Australian Rainfall & Runoff

Revision Projects

PROJECT 11

Blockage of Hydraulic Structures

STAGE 2 REPORT

P11/S2/021

FEBRUARY 2013

Australian Government

ENGINEERS AUSTRALIA
Water Engineering

PROJECT 11: BLOCKAGE OF HYDRAULIC STRUCTURES

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Project Project 11: Blockage of Hydraulic Structures	**AR&R Report Number** P11/S2/021
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Authors W. Weeks G. Witheridge E. Rigby A. Barthelmess and G. O'Loughlin	**Verified by**

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FOREWORD

AR&R Revision Process

Since its first publication in 1958, Australian Rainfall and Runoff (AR&R) has remained one of the most influential and widely used guidelines published by Engineers Australia (EA). The current edition, published in 1987, retained the same level of national and international acclaim as its predecessors.

With nationwide applicability, balancing the varied climates of Australia, the information and the approaches presented in Australian Rainfall and Runoff are essential for policy decisions and projects involving:

- infrastructure such as roads, rail, airports, bridges, dams, stormwater and sewer systems;
- town planning;
- mining;
- developing flood management plans for urban and rural communities;
- flood warnings and flood emergency management;
- operation of regulated river systems; and
- estimation of extreme flood levels.

However, many of the practices recommended in the 1987 edition of AR&R are now becoming outdated, no longer representing the accepted views of professionals, both in terms of technique and approach to water management. This fact, coupled with greater understanding of climate and climatic influences makes the securing of current and complete rainfall and streamflow data and expansion of focus from flood events to the full spectrum of flows and rainfall events, crucial to maintaining an adequate knowledge of the processes that govern Australian rainfall and streamflow in the broadest sense, allowing better management, policy and planning decisions to be made.

One of the major responsibilities of the National Committee on Water Engineering of Engineers Australia is the periodic revision of AR&R. A recent and significant development has been that the revision of AR&R has been identified as a priority in the Council of Australian Governments endorsed National Adaptation Framework for Climate Change.

The Federal Department of Climate Change announced in June 2008 $2 million of funding to assist in updating Australian Rainfall and Runoff (AR&R). The update will be completed in three stages over four years with current funding for the first stage. Further funding is still required for Stages 2 and 3. Twenty one revision projects will be undertaken with the aim of filling knowledge gaps. The 21 projects are to be undertaken over four years with ten projects commencing in Stage 1. The outcomes of the projects will assist the AR&R editorial team compiling and writing of the chapters of AR&R. Steering and Technical Committees have been established to assist the AR&R editorial team in guiding the projects to achieve desired outcomes.

Project 11: Blockage of Hydraulic Structures

There is considerable debate at present regarding appropriate advice on design blockages that should be assumed for various hydraulic structures in urban drainage systems. While a number of studies were undertaken in the Wollongong area in response to the widespread blockage of hydraulic structures during the 1998 flood that have developed criteria for the assessment of blockage for new hydraulic structures, these studies only relate to catchments whose characteristics are similar to those in the Wollongong area. Hence, there is a need to extend these previous studies and to extend their suitability so that appropriate guidance on design blockage for hydraulic structures can be developed for Australia.

For the purposes of this project, the term hydraulic structures refers to culverts and small bridges over drainage channels (rather than major bridge structures) and to inlet structures (i.e. pits) to urban drainage systems.

The aim of Project 11 is to provide design guidance on the blockage of structures during flood events. It is intended that these guidelines will incorporate the uncertainty associated with blockage so that appropriate risk management practices can be applied by users.

Mark Babister
Chair Technical Committee for
ARR Research Projects

Dr James Ball
ARR Editor

AR&R REVISION PROJECTS

The 21 AR&R revision projects are listed below :

ARR Project No.	Project Title	Starting Stage
1	Development of intensity-frequency-duration information across Australia	1
2	Spatial patterns of rainfall	2
3	Temporal pattern of rainfall	2
4	Continuous rainfall sequences at a point	1
5	Regional flood methods	1
6	Loss models for catchment simulation	2
7	Baseflow for catchment simulation	1
8	Use of continuous simulation for design flow determination	2
9	Urban drainage system hydraulics	1
10	Appropriate safety criteria for people	1
11	**Blockage of hydraulic structures**	**1**
12	Selection of an approach	2
13	Rational Method developments	1
14	Large to extreme floods in urban areas	3
15	Two-dimensional (2D) modelling in urban areas.	1
16	Storm patterns for use in design events	2
17	Channel loss models	2
18	Interaction of coastal processes and severe weather events	1
19	Selection of climate change boundary conditions	3
20	Risk assessment and design life	2
21	IT Delivery and Communication Strategies	2

AR&R Technical Committee:

Chair: Mark Babister, WMAwater
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Professor Martin Lambert, Chair NCWE, University of Adelaide
Dr Rory Nathan, SKM
Dr Bill Weeks, Department of Transport and Main Roads, Qld
Associate Professor Ashish Sharma, UNSW
Dr Bryson Bates, CSIRO
Steve Finlay, Engineers Australia

Related Appointments:
ARR Project Engineer: Monique Retallick, WMAwater
Assisting TC on Technical Matters: Dr Michael Leonard, University of Adelaide

PROJECT TEAM

- Bill Weeks, AR&R TC Project Manager, Queensland Department of Main Roads (Brisbane).
- Grant Witheridge, Catchments & Creeks (Brisbane).
- Ted Rigby, Rienco (Wollongong).
- Anthony Barthelmess, Cardno Forbes Rigby (Wollongong).
- Geoff O'Loughlin, Anstad (Sydney).

This report was independently reviewed by:

- Ian Joliffe, GHD

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1. INTRODUCTION

1.1 BACKGROUND

Flooding is one of the most costly of natural disasters in Australia. As our population growth continues, and as we in turn urbanise and modify catchments, we have a need to create engineering structures in our catchments, floodplains and watercourses. These structures include piped and open channel drainage networks, flood control systems and waterway crossings.

During storms, material located throughout the catchment can be mobilised and transported towards various hydraulic structures. This material can be as variable as the catchment from which it is sourced. Forested areas generate material such as trees, leaf litter and logs and other rural areas can generate sediments and other vegetative matter. Urban areas can generate a range of domestic debris including litter, garbage bins, cars, household rubbish and building materials, as well as vegetation and sediment similar to rural catchments.

As this material is mobilised and transported downstream it may be conveyed through drainage structures or it may be captured by hydraulic structures it encounters, thereby partially or fully blocking the structure from conveying flow. Blockage causes a reduction in the capacity of hydraulic structures and drainage systems in which they lie, especially if the blockage occurs prior to or around the flood peak. Blockage of structures also has the potential to divert flows into adjacent streams or catchments, thereby altering flood levels and flood-related damage.

Blockage can be a design issue from the smallest of inlet structures to the largest of culverts and bridges. While in some catchments the consequences can be severe, there are regions of Australia where the blockage of hydraulic structures is not a major design issue. The reasons for this can be due to the limited availability of blockage matter within the catchment, the ability of the blockage material to pass through the waterway or the effects of proactive urban planning resulting in few private or public assets being susceptible to the adverse effects of blockage.

The impacts of blockage can be hard to quantify, or even to observe. The extent and consequences of blockage often vary dramatically from one location to another, even when these locations are in close proximity. In addition, the degree of structure maintenance and the type and extent of materials transported by flood events can also vary widely from one event to another.

1.2 OVERVIEW OF REPORT

This report represents Stage 2 of Project 11 of the Australian Rainfall & Runoff projects, and follows the Stage 1 report published in November 2009. The Stage 1 report (Weeks et al, 2009) provided the background to the problem, but did not include guidance for those who design flood control and drainage systems. This report adds to the previous material and includes some guidance based on available information.

Hydraulic blockages can occur within a variety of structures including stormwater inlets and pipes, cross drainage structures, especially culverts and bridges, overland flow paths, drainage channels and waterways, dams and weirs. The principal areas of interest within this report are culverts and bridges as cross drainage structures and the inlets and pipes of urban drainage systems.

The issues addressed within this report include:

- *Design of drainage systems:* This discussion focuses on how to account for blockage in the design of new or refurbished drainage systems. It includes guidance on assessment as well as how to analyse the impacts of blockage.
- *Evaluation of the performance of existing systems:* This discussion outlines the analysis of existing drainage systems and waterway structures, the determination of flood levels and the analysis of historic storm and flood events.
- *Management of blockage:* This discussion focuses on how to manage and minimise the impact of blockage on a drainage system through appropriate design and maintenance. It also includes discussion on how to modify existing systems to better manage blockage events.

Understanding the issue of blockage has been found to be a difficult problem, and there are many aspects and differing opinions expressed across Australia and internationally on how blockages should be accommodated or even if they are a problem. There is also very limited recorded or observed data to allow a quantitative estimate of the risks of blockage at a given location, even though a significant number of photographs exist of blockages taken after flood events. This lack of relevant recorded data is one reason for the lack of national agreement on the best approach to the estimation and management of structure blockages.

Similarly there is limited quantitative guidance on this issue internationally. There are, however, some guidelines and publications that indicate similar concerns to those encountered in Australia, though again there are few detailed guidelines on the analysis of blockage in hydraulic structures. Unfortunately even if there was detailed guidance, there are problems in applying overseas guidelines to Australian conditions because of very different climatic conditions, levels of catchment development, and variations in drainage structure types, standards and practices.

Consequently, the recommendations presented within this report are based on limited observed data supplemented with theoretical analysis, published reports and guidelines and the experience of relevant practitioners.

1.3 TERMINOLOGY

Blockage refers to the presence of debris within or immediately adjacent to a waterway and drainage structure that reduces that structure's hydraulic capacity.

Blockage matter refers to the material that is likely to form the primary 'blockage', i.e. the material primarily causing the interference to hydraulic flow. Such material is unlikely to cause full blockage of a structure without the presence of suitable 'bridging matter'.

Bridging matter refers to the material of sufficient size and strength to bridge across the opening (inlet) of a structure and on which blockage matter can collect, thus potentially resulting in the full or partial blockage of a structure. Bridging matter can be as small as leaves caught on a debris screen, or as large as logs, cars and mattresses trapped at culvert inlets.

Blockage mechanism refers to the combination of parameters needed to effectively describe a structure blockage. Depending on the structure type, these parameters include:

- The blockage type (floating (raft), non-floating (depositional), porous plug or mixed).
- The blockage location (inlet, barrel, outlet or handrails).
- The blockage porosity (floating rafts and plugs can be quite porous, which means that while there may be an apparent blockage material, water can still flow through the "blockage", though probably with some constriction).
- The blockage timing (the blockage time-series – particularly when it starts and peaks).

Debris availability refers to the presence and quantity of particular types of debris within the source area. The critical types of debris are related to the geometry of the various hydraulic structures located within the catchment and more than one type of debris may need to be considered.

Debris mobility refers to the ease with which the available debris is initially mobilised, then transported across overland flow paths into streams and then towards structures.

Debris potential refers to a qualitative measure (high, medium, low) of the likely debris load at a structure derived from consideration of debris availability, debris mobility and debris transportability.

Debris source area refers to that part of the catchment from which most of the debris reaching the structure will be sourced. In small catchments this will likely be the full upstream catchment, but in larger catchments the source area may be only the catchment up to the next major structure.

Debris transportability refers to the ease with which the mobilised debris is transported down a stream or along a drainage channel to the structure.

Design blockage refers to the most likely blockage conditions that can be expected to occur during a design storm of a given frequency. It is noted that the assessed level of blockage for a

10 year ARI storm may be different from that expected during a 100 year ARI storm. This amount of blockage can be applied in the calculation of design flood levels.

Severe blockage refers to the extent of infrequent blockage that is considered possible during the design life of a given structure, say during exceptionally large floods, but is unlikely to occur on a frequent basis. Though termed 'severe', such blockage may not necessarily represent total blockage of the structure, or even a condition likely to result in severe consequences.

Structure interaction refers to the interaction between debris arriving at a structure and the structure itself. It is highly influenced by the quantity and quality of debris arriving at the structure and specific aspects of a structure, such as inlet diameter or waterway width, as these govern the propensity of the structure to block. This is also affected by specific designs of any countermeasures such as debris deflectors that are planned to limit the impact of blockage.

1.4 EXISTING PRACTICES

Most councils and infrastructure agencies in Australia, including road and rail authorities as well as local authorities, incorporate some reference to the blockage of structures within their drainage codes, but the broader impact of stream and structure blockages on flooding and flow diversions is generally not addressed.

Blockage has been noted in drainage guidelines for agencies in Australia as well as overseas. These guidelines recognise that there may be a problem caused by blockage that limits the effectiveness of the drainage system, but data to support this conclusion has been limited and the final recommended design guides are uncertain in how this information should be applied.

For example, the United States Army Corps of Engineers and the United States Federal Highway Administration (USDOT, 2005), mention blockage as being important, but do not provide detailed or quantitative methods for defining limits or anticipated blockage conditions for designing various hydraulic structures. This publication mainly deals with bridges but there is material relevant to culverts. It identifies debris types and sources and provides a method for assessing quantities of debris in rural contexts. It presents possible blockage mechanisms and shows how these can be modelled using HEC-RAS. It also defines countermeasures for bridges and culverts and provides design guidelines and culvert examples.

A recent and comprehensive international publication that deals with blockage issues associated with waterway culverts is CIRIA (2010) which addresses the issue in association with a risk-based procedure. This manual is more oriented to maintenance and renewal works, but does have relevant material. While there are some relevant design guidance and procedures included in this report, however the climatic conditions and drainage criteria for culverts in the United Kingdom are quite distinct from those in Australia so this guidance is generally of limited value for Australian conditions, though in some regions of Australia it could be applicable.

The 1986 NSW Floodplain Development Manual discusses issues associated with the hydraulic modelling of floods, but does not comment on the need for consideration of structure blockages or the consequences of flow diversions. It has generally been standard practice in flood mapping exercises across Australia to assume all structures are clear (i.e. no blockage), except for the blockage of handrails and the blockage assumptions made during the simulation of historical floods. The 2005 NSW Floodplain Management Manual raises the need to consider blockages in design or analysis of major drainage systems, but for the most part repeats the 1986 manual's guidance on hydraulic analysis (Rigby and Silveri, 2001).

The Queensland Urban Drainage Manual (Department of Natural Resources and Water, 2008) provides recommended blockage factors for drainage inlets, but does not provide guidance on floodplain management or flood modelling issues. The document does indicate that blockage must be considered when assessing the impacts of drainage systems on urban areas; however, no guidance is provided on assessing the risk or degree of blockage of overland flow paths or waterway structures.

Wollongong City Council's Drainage Design Code (1993) used the major/minor drainage system concept and introduced a requirement for blockage consideration (Rigby et al, 2002). This policy required the consideration of a minimum 50% blockage of inlet grates if the trunk drainage system is prone to blockage by debris.

Following the floods of 1998, Wollongong City Council developed a 'Conduit Blockage Policy' (2002). The policy's objective is "to more accurately predict flood behaviour in real events as a result of blockage of bridges and culverts across waterways". The policy applies to all watercourses including creeks, floodways and trunk drainage systems within the Wollongong City Council local government area. The policy lists the following blockage factors to be applied to structures across all watercourses when calculating design flood levels:

(a) 100% blockage for structures with a major diagonal opening width of less than 6 m.

(b) 25% bottom-up blockage for structures with a major diagonal opening of 6m or more.

(c) 100% blockage for handrails over structures covered in (a) and for structures covered in (b) when overtopping occurs.

1.5 DATA COLLECTION ISSUES

Blockage issues are highly variable across the country and even across individual catchments or between events. The appropriate incorporation of a design procedure for blockage into drainage design and floodplain management is dependent on the collection and interpretation of local data and this data is also essential to develop regional methodology. The recommendations presented within this paper have been development with a national focus, but the final outcomes ultimately rely on the application of local knowledge. Unfortunately, there are several reasons why such data can be difficult to collect and interpret.

The collection of data on blockage of drainage structures is often conducted by observing the condition of the structure after the flood has receded and noting the extent of blockage. Observations of actual blockage during events are difficult so are rarely undertaken. Further complicating the issue is the fact that flooding is often caused by short duration thunderstorms in the late afternoon or early evening when light restrictions prevent clear observation and recording of blockage conditions. Access and safety issues to both the public and maintenance personnel can also prevent the observation of reliable 'peak of flood' data. Thus the most common method of observing blockage is the evidence remaining after the flood has receded.

Blockage can also be observed by measuring the maximum flood levels upstream and downstream of the culvert, which are the flood levels for the peak of the flood. These measurements can then be compared with the theoretical water level difference assuming no blockage and the effect of the blockage can then be estimated.

Debris blockage of drainage structures, especially the major impacts, generally occurs during significant flood events with less impact for smaller floods. These events often occur without warning and for short durations. Because of the speed of occurrence, it is unlikely that trained observers will be on-site to make the necessary observations. Photographs and videos taken by locals and news organisations can be very useful, but rarely show the detail needed to identify the extent of blockage or the impacts. In fact, some videos may show debris passing through structures with limited hindrance near the peak of the flood, but then debris is observed in the structures after the flood has receded.

Blockage data collection during floods can identify some important details including:

- Floating debris typically collects around culverts and bridges when flood levels approach the deck of the crossing. This debris then builds in a top-down fashion prior to flows passing over the structure causing debris to collect around handrails and traffic barriers. As the flood recedes, debris collected against the face of the structure often falls to the bed where it can be partially swept through the structure. Often what is left behind after the flood is just the debris wrapped around piers and/or legs of the structure and material wrapped around railings and barriers. Unfortunately, debris can be removed by road maintenance staff before floodplain managers arrive to do their inspections or photos are taken. This means that even the debris observed after the flood may differ between events and locations depending on the extent of this clearing.
- Non-floating debris, such as sediment and gravels, often collects at structures only during the falling limb of the flood hydrograph, thus the observations made at the end of the flood may not be representative of 'peak of flood' conditions and do little to provide an understanding of the temporal pattern of blockage throughout the event or the impacts at the flood peak.

The effect of maintenance staff and even the public removing debris during or immediately after a flood is difficult to quantify. In most cases, the removal of debris from major culverts and bridges during a flood is not possible due to safety risks but debris removal from minor structures is common during floods as demonstrated in Photo 1.

Photo 1: Post-flood debris deposited on an overland flow path adjacent to residential properties and trimmed mid-storm by residents concerned about flooding

To supplement the observations of the appearance of the floodwater at the structure, it is also useful to measure the difference in water levels across the structure. With a known discharge and information on the type and location of the blockage that has formed, these level differences can then be used to establish the porosity or extent of blockage at the time of measurement. If available at all, this data will typically only be available for conditions at the flood peak, providing no information on the temporal variation throughout the event, though the peak of the flood is most important.

2. BLOCKAGE ISSUES

2.1 INTRODUCTION

As noted above, data on blockages is very difficult to obtain and there are several reasons for this. Blockage, even at a single location, can vary greatly from event to event. Blockage may result from the accumulation of floating and/or non-floating debris and this debris can collect across the inlet, within the barrel or at the outlet (if screened). During a single event, the degree of blockage may vary from a single piece of floating debris jammed across the inlet of a structure to a fully blocked structure. Even when apparently fully blocked, the debris may be relatively porous providing some residual flow capacity. The timing of the blockage can also be highly variable, with debris arriving progressively or rapidly in a pulse. Blockages involving floating debris may arrive or build up as a floating raft that rises with the floodwater and is only deposited over the inlet as floodwater recedes. Blockages involving deposition of large quantities of non-floating natural material such as sediment will typically transport most debris at the peak of the flow, but deposition will typically be greatest on the flood recession as velocities drop. Irrespective of the debris type, it is difficult to infer the extent and impact of blockage during the flood or at the flood peak from what remains and is observed after the event.

When the structure affected by blockage is owned by a government agency or other large organisation, there is often a significant separation between the designer, asset management and maintenance personnel. This means that designers may not be aware of practical problems related to blockage or other issues that may arise during operation or an asset. This is a particular issue for government agencies which own significant assets. However it also occurs with privately developed infrastructure, such as culverts in a large subdivision. Councils, which are ultimately responsible for the asset, are strict in the assessment of design assumptions.

The sensitivity of the hydraulic capacity of structures to variations in the blockage mechanism (location, type, timing, porosity) was explored by Rigby and Barthelmess (2011) in a theoretical assessment using hydraulic modelling. This work demonstrated that major changes in flood levels and discharges can occur at a structure, depending on the blockage mechanism triggered.

2.2 TYPES OF DEBRIS

2.2.1 Introduction

Blockages can result from a wide range of materials as outlined in Table 2.1.

Table 2.1: Types and sources of debris

Type of debris	Typical sources of debris
Litter	• General urban litter (e.g. cans, plastic bags, takeaway food containers) • Litter originating from recreational, sporting and commercial areas • Litter from building and construction sites
Leaves	• Local trees as a result of strong winds or leaf drop
Grass	• Cut grass from rural and urban properties or public open spaces • Grass stripped by water from overbank areas
Garden mulch	• Garden mulch from overland flow paths within urban areas • Natural mulch from bushland areas
Reeds	• Aquatic reeds from urban and rural creeks
Woody debris	• Storm damage of trees and shrubs • Flood damage of riparian vegetation
Sediment	• Building and construction sites • Road surfacing material • Erosion of catchment, gullies and watercourses • Sand from gully erosion or normal bed load movement associated with alluvial (sand-based) streams
Gravels and boulders	• Gravel from gully erosion or normal bed load movement associated with alluvial (gravel-based) streams • Boulders from landslips and gully erosion
Building material	• Loose building material from building and construction sites • Large debris from flood damage to buildings • Loose objects washed from residential and commercial properties
Cars	• Cars and other vehicles swept into and down waterways by floodwaters
Sundry urban debris	• In urban areas, a wide variety of debris is available and can be mobilised and washed into the drainage system

2.2.2 Floating Debris

Debris may be classified as floating (e.g. trees), non-floating or depositional (e.g. sediment) and urban (e.g. cars and mattresses). Floating debris can be further categorised as small, medium or large.

Small floating debris, less than 150 mm long, can include small tree branches, sticks, leaves and refuse from yards such as litter and lawn clippings and all types of rural vegetation. This type of debris can also be introduced into a stream by earlier windstorms, bank erosion, landmass failures or from seasonal leaf falls. It is important to note that this material is available in both urban and rural catchments, and is usually available for transportation at any time.

Medium floating debris, typically between 150 mm and 3 m long, consists of tree limbs and large twigs. This material is usually introduced into the flow path by channel erosion undermining riparian vegetation or through wind gusts during storms.

Large floating debris, more than 3 m long, consists of logs or trees, typically from the same sources as for medium floating debris. Transport and storage of this material depends on discharge, channel characteristics, the size of the drift pieces relative to the channel dimensions, and the hydraulic characteristics (depth and slope) of the system. In small and intermediate size channels, this material is not easily transported and can easily become snagged mid-stream acting as a collection point for smaller material (i.e. a debris raft or log-jam). Whole trees can be retained within streams, temporarily anchored either to the bed or banks of the stream. Large floating debris is usually transported during larger floods or prolonged periods of high river-stage where the floodplain is engaged and the ability of the debris to become snagged is reduced. This type of debris can cause significant problems at bridge structures.

Photo 2: Debris blockage of culvert outlet

Photo 3: Debris blockage of culvert inlet

2.2.3 Non-Floating Debris

Non-floating debris is usually sediment of all types.

Fine sediments (silt and sand) typically consist of particles ranging from 0.004 to 8 mm (Standards Australia, AS-1348-2002). The deposition of the finer clay-sized particles is normally a concern in tidal areas, with lower velocities. This type of debris is either transported along the streambed as bed load or within the water column as suspended load. Such material is normally sourced from sheet and rill erosion, landslip and landmass failures, and channel erosion. Yield rates for this material can be significantly influenced by the conditions of, and changes to, a catchment due to urbanisation and/or rural land use practices.

Gravels and cobbles consist of rock typically ranging in size from 4.75 to 75 mm and 60 to 300 mm respectively (Standards Australia, AS-1348-2002). The source of this material may be from gully formation, channel erosion, landslips or land mass failure. Once mobilised, gravels and cobbles are primarily transported as bed load within high gradient streams. The deposition of cobbles can readily block the entrance of culverts or reduce the flow area under bridges.

Boulders comprise rocks greater than 300 mm. The source of boulders is gully and channel erosion, landslips and the displacement of rocks from channel stabilisation works. This material can readily block the entrance to a structure and/or cause damage to the structure from the force of impact/collision.

Photo 4: Sediment blockage of stormwater pipes

Photo 5: Boulder sourced from an upstream rock chute, now deposited in a culvert

2.2.4 Urban Debris

Urbanisation of catchments introduces many different man-made materials that are less common in rural catchments and which can cause structure blockage. These include building materials, mattresses, garbage bins, large industrial containers and vehicles (Rigby and Silveri, 2001). Garbage bins can easily be washed down a street and into a stream or drainage structure, a situation made worse if a large rainfall event occurs on the same day as rubbish collection within the catchment, when bins are placed in streets for collection.

Rigby and Silveri (2001) report that small to medium floating debris is often mobilised in the Illawarra region via a pulse-like delivery of urban refuse, building materials, fences, sheds and the like, swept into streams by overland flows or overbank flows associated with flooded streams. A similar situation is likely to occur elsewhere.

Some examples of urban debris from Wollongong and Newcastle are shown in Photos 5 and 6.

Photo 6: Cars in a culvert inlet – Newcastle

Photo 7: Urban debris in Wollongong

2.3 TYPES OF STRUCTURES AND DRAINAGE SYSTEMS

The types of structures or drainage elements affected by blockages can generally be grouped as follows:

(a) *Bridges and Culverts:* These cross drainage structures carry roads, railways, pipelines or other infrastructure across watercourses. These structures can be affected by a number of different types of blockage mechanisms, resulting in consequences including increased flood levels, changes to stream flow patterns, changes to erosion and deposition patterns in channels, and physical damage to the structure.

(b) *Drainage system inlets and pipes:* This includes components of urban drainage systems located within road reserves and urban overland flow paths. Frequently blockage in this type of system is generally less likely to cause the same extent of damage associated with blockage of bridges and culverts, but the consequences can still be serious from a traffic and safety perspective, and can cause serious inconvenience and nuisance. However in certain circumstances, in densely developed urban areas, pit blockage can cause significant monetary damage due to flooding of buildings upstream.

(c) *Open channels and waterways:* Blockage of natural and constructed waterways can occur at any location, typically as a result of large debris snagged against bank vegetation, or debris passing slowly down the channel. The consequences of such blockage are increased flood levels, diversion of surface flows and the possible relocation of the waterway channel as a result of severe bank erosion.

(d) *Overland flow paths:* This category covers various surface flow paths that are not normally recognised as drainage channels but do act to convey surface flows in larger events. Blockage of these flow paths can result from the deposition of sediment or the material blockage of structures built across the flow, such as property fences blocked by litter and grass clippings.

(e) *Weirs and dams:* Debris can cause blockage within the spillways of weirs and dams, especially where there is a significant constriction to the flow area. This could increase the water level in the storage, possibly threatening the security of the structure. The sudden release of large debris rafts from dam spillways can cause significant damage to downstream road crossings.

This report focuses mainly on structure types (a) and (b) since these are the most important and can be analysed with typical hydraulic analysis procedures. While some limited comment is provided on blockage of the other structure types, their behaviour when blocked is even more poorly documented and is less likely than for the bridges, culverts and pipe drainage systems. In addition, control of blockage at these sites should normally be managed by planning processes.

2.4 IMPACTS OF BLOCKAGE

2.4.1 Overview

Blockages cause changes to water level, flow direction and velocity so therefore cause damage to the affected hydraulic structure, but more importantly, blockages can often cause damage to separate but nearby public and private assets, as well as increased safety risks to both the public and emergency and maintenance personnel. Table 2.2 outlines typical impacts arising from the blockage of various hydraulic structures.

Table 2.2: Likely impacts of blockages of hydraulic structures

Hydraulic structure	Typical impacts
On-site detention systems	• Increased maintenance requirements of surface and underground outlet structures • Increased frequency and severity of overland flow through property
Overland flow paths	• Increased property flooding • Damage to property fences • Damage to landscaping
Stormwater inlets (kerb and field inlets) and pipes	• Increased overland flow down roads and associated safety risks • Flooding of roads and intersections restricting usage • Property flooding and damage resulting from bypass flows
Stormwater outlets, including surcharge chambers	• As above for stormwater inlets • Structural damage to outlet screens • High cost associated with de-silting coastal outlets
Detention/retention basins	• Increased risk to community from deeper and faster water level rise • Increased property flooding due to the failure of the structure to fill or de-water in accordance with desired operational performance • Structural damage to outlet structure • Safety risk to maintenance personnel during post-storm maintenance
Fishways	• Restrictions to fish passage during period of blockage • Potential long-term changes to upstream aquatic habitats
Waterway bridges, culverts and causeways	• Increased flooding and damage to adjacent properties caused by increased frequency or depth of overtopping and bypass flows • Safety risk to maintenance personnel during post-storm maintenance • Increased cost of post-storm debris removal • Structural damage to pedestrian safety fencing and handrails • Bed erosion resulting from debris collection around bridge piers • Restrictions to fish passage even during period of minor bed-level debris blockage • Blockages in causeways particularly rural causeways, resulting in long-term changes to upstream water levels with a number of issues.

Estimating the impacts of blockages in a design event requires consideration of the following issues on a site-by-site basis for different storm probabilities or average recurrence intervals:

- The quantity and type of debris that would reach the structure in the design event.
- The type, location, porosity and timing of a blockage at the structure, and the likely extent and coincidence of such blockages across the catchment.

- The impacts of likely blockage mechanisms on the hydraulic behaviour of the structure, particularly in regard to changes in flood levels and discharges both at the structure and in adjacent water courses if blockage could cause or modify flow diversions.
- The impacts of likely blockage on the catchment, community assets, and public safety.
- The environmental impact of blockage, such as interference to fish passage.

When considering the likely impacts of debris blockage on major waterway structures such as bridges and larger culverts, appropriate analysis should also be made of the following matters:

- The consequences of blockages in excess of the adopted level.
- The consequences of flow in excess of the adopted design discharge.
- The likelihood and consequences of damage to the structure as a result of blockage.
- The likelihood for unrepairable asset damage (e.g. damage to historical sites, or severe erosion that threatens the structural integrity of public or private assets).
- The likelihood for above floor level flooding (residential and commercial) upstream and adjacent to the structure, including the sensitivity of flooding to the adopted design conditions (i.e. the potential for significant changes to the number of affected properties resulting from only minor changes in the adopted design conditions).
- The likely impact on both the value and use of adjacent land.
- The likelihood of changes in the flow paths for bypass and overtopping flows e.g. overland flows that may pass through downstream properties before re-entering the waterway channel, and flows that may exit the waterway and enter an adjacent roadway, such as shown in Figure 2.1, or enter an adjoining catchment as in Figure 2.2.

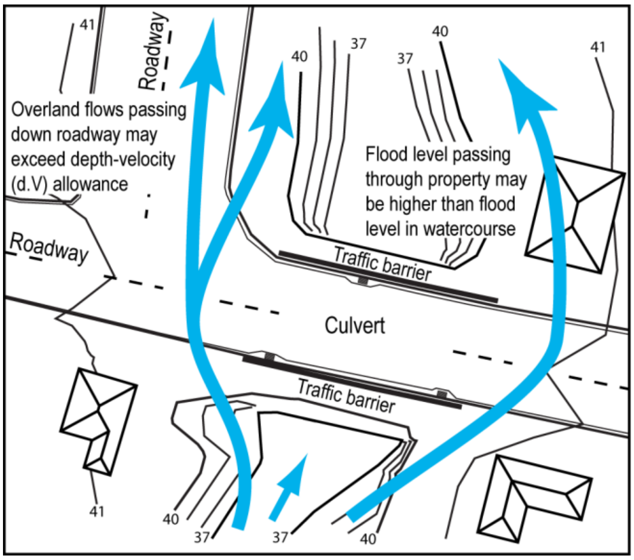

Figure 2.1 Overland flow paths of bypass flows (Catchments & Creeks Pty Ltd)

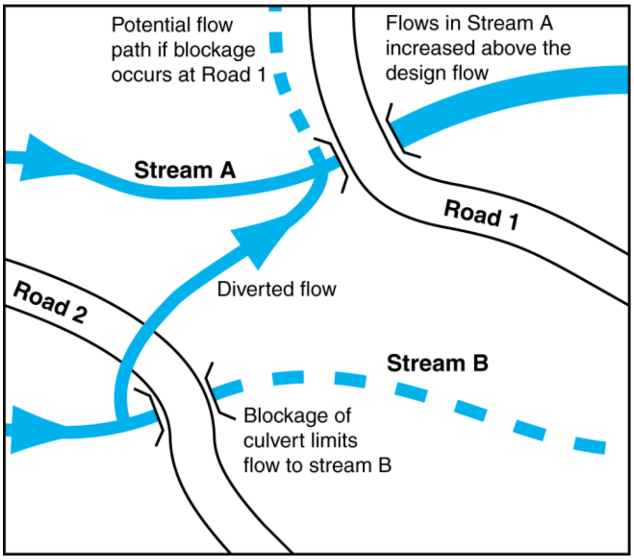

Figure 2.2: Diversion of flow into an adjacent catchment (after Rigby & Silveri, 2001)

2.4.2 Hydraulic Impacts

Waterway structures are designed to convey water at both high and low flows and the blockage of these structures can significantly reduce their capacity. The most common impact of this reduced capacity is an increase in flood levels upstream of the structure, which may cause anything from nuisance flooding to the inundation of public and private structures.

If the blockage affects low flows, the increase in water level may be relatively small, but water will tend to pond for long periods, causing environmental concerns. At high flows, a partial blockage of the structure can cause increased flow velocities leading to increased channel erosion and/or damage to the structure or adjacent infrastructure. Such conditions can also increase the hazard to pedestrians and traffic as a result of increased overtopping flow depths and velocities.

In major floods it is not uncommon for structures to back up flow to the point where overland flow paths develop at some points allowing flows to divert into adjacent catchments (Figure 2.2). These diverted flows may eventually return to their original stream or become permanently retained within the adjacent catchment. Blockages have the potential to increase both the frequency of occurrence and magnitude of such diverted flows in adjacent flow paths.

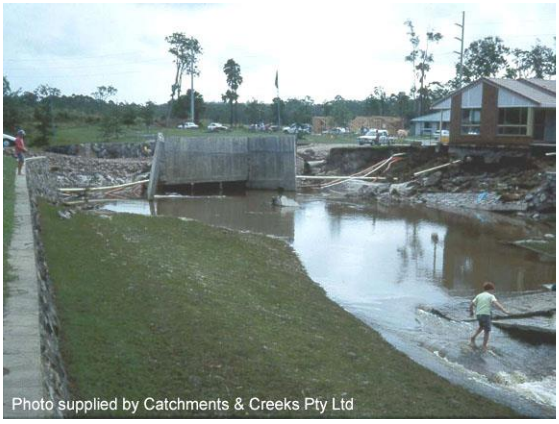

Photo 8: Damage to culvert caused by debris blockages and flows diverted from an adjoining catchment

Photo 9: House adjacent to culvert (left) undermined by flows bypassing the culvert

Blockages can also alter stream discharges by altering the height-storage-discharge relationship of water impounded above a structure. For example, if the blockage of a culvert or detention basin outlet structure occurs early within a flood, then the available flood storage could fill before the peak of the flood hydrograph arrives. The resulting outcome of early blockage is usually an increase in the peak discharge downstream of the structure. Conversely, partial blockage of a structure that does not normally overtop can lead to a decrease in peak discharge downstream of the structure. The impact of different blockage mechanisms on the hydraulic behaviour of a culvert was explored by Rigby and Barthelmess (2011).

2.4.3 Geomorphology Impacts

Geomorphic impacts may involve damage to stream channels and their aquatic environments. In many cases these geomorphic impacts are not fully appreciated until a new channel is formed. Without remediation works, the altered flow paths may become permanent.

2.4.4 Economic Impacts

Financial impacts are usually very important and can usually be measured more accurately than many of the other impacts. These impacts include direct physical damages as well as indirect costs such as those associated with traffic delays. Even if there is no clear physical damage, the indirect costs associated with traffic inconveniences or nuisance flooding may be significant.

2.4.5 Social Impacts

It is noted that whilst floods may not be the most costly in terms of financial loss, they are the most costly in terms of loss of life and injury. There are also social impacts, including the stress suffered by residents and businesses affected by debris-induced flooding.

The blockage of stormwater inlets causes ponding on roads potentially resulting in traffic delays as well as inconvenience to pedestrians.

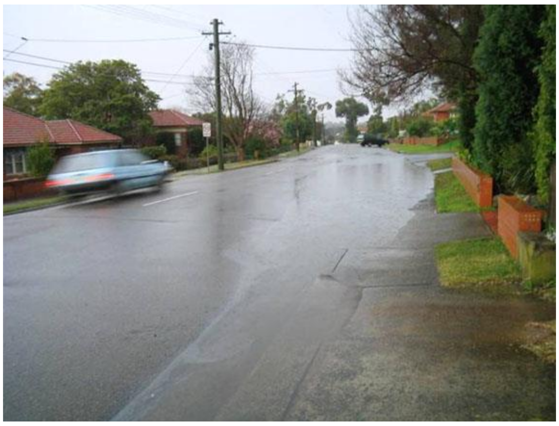

Photo 10: Ponding on street caused by blocked inlet pit (G O'Loughlin)

Photo 11: Temporary blockage of kerb inlet causing road flooding

Debris flows can also have fatal consequences. In 1988 a natural slope and railway embankment located in Coledale, New South Wales failed after blockage of a critical drainage pipe beneath the embankment caused water to surcharge the embankment, triggering a debris flow that impacted on a house, killing a mother and child (Flentje et al., 2001).

2.4.6 Environmental Impacts

Blockages and resulting changes in flow patterns can affect the environment in one of several ways. Blockages may cause ponding along flow paths close to the inlets of drainage systems or culverts. This ponding may persist for long periods causing health concerns such as those arising from breeding of mosquitos and biting insects.

Debris blockage of bridges and culverts can also interfere with essential fish passage and the movement of terrestrial wildlife. Riffles and pools in watercourses can also become inundated with sediment damaging aquatic habitats and altering the movement pattern of low flows.

2.5 MECHANICS OF DEBRIS BLOCKAGE

2.5.1 Overview

Key factors influencing the hydraulic impact of blockages are:

- blockage type.
- blockage location.
- blockage porosity.
- blockage timing and extent.

These factors are collectively referred to in the following sections as describing the blockage mechanism. Each factor is discussed further in the following section, grouped initially by blockage type. In the following sections, source area refers to that part of the catchment from which most debris reaching the culvert is sourced.

2.5.2 Floating Material (Raft) Blockages

Floating material or raft blockages are mostly associated with source areas with a high number of fallen limbs or trees growing close to the bank line. In urban areas, debris rafts can also be created by floating cars, drums, crates and construction timber. Floating debris typically restricts flow as a blockage from the water surface downward, as a 'Top Down' blockage, and is typically associated with blockages of the culvert inlet. Characteristics of such a blockage in respect to its location, porosity and timing are listed as follows:

- **Inlet** This is common and typically of variable porosity. Timing can be expected to commence when flows are sufficient to mobilise and transport floating material into the stream. For culverts, the greatest upstream raft depth typically develops on the recession when floodwater stops surcharging the culvert and velocity subsides. In culverts that are not overtopped, debris will typically accumulate throughout the event although some (or most in some cases) floating debris will likely be washed through the culvert during the event. Whether overtopped or not, once the flood subsides, the settling debris from the raft will likely appear as a full culvert inlet blockage. Timing is therefore very difficult to establish after the event, and due to submergence of the inlet by floodwater, very difficult to confirm during the event. It is possible that the settled raft may have been floating above the obvert level of the culvert inlet at the flow peak, with little if any impact on peak conveyance through the culvert. Inlet blockage with floating material (during or at the end of the event) is a common mechanism in highly vegetated rural areas. It can also occur in urban areas where material such as timber planks, timber fencing or sealed containers are present within the source area.

- **Barrel** This is a possible but improbable mechanism.
- **Outlet** This is a possible but improbable mechanism unless the inlet is open and the outlet is grated.
- **Handrails** This is a common mechanism. Depositional material would not normally reach handrails. Handrail blockage, when it does occur, is typically from a floating debris raft caught on the handrails as the rising floodwater overtops the structure. Blockage tends to develop progressively from the handrail base upward with the rising floodwater, as the embankment overtops and because the greatest amount of floating debris is usually on the rising limb of the flood hydrograph. Once blocked the handrails tend to stay blocked. This blockage cannot commence until the floodwater begins to overtop the structure. While this discussion is concerned with handrails on bridges crossing water courses, there are also cases where there is a footpath or bikeway under a bridge with handrails. These structures can be in the path of the water flowing under the bridge well before the bridge is overtopped and can also collect debris. In this case, the handrail acts similarly to a pier or culvert wall.

2.5.3 Non Floating (Depositional) Blockages

Non floating (depositional) blockages are mostly associated with streams with unstable beds or banks, or source areas where significant granular material (such as sand, gravel, mine products) are stored close to the stream banks. These materials typically accumulate from the inlet or barrel invert upward, as a ‘Bottom Up’ blockage. Characteristics of such a blockage in respect to its location, porosity and timing are listed as follows:

- **Inlet** This is a common mechanism associated with depositional barrel and outlet blockages. It tends to occur progressively when flows are sufficient to mobilise and transport bed/bank material, peaking on the recession after the flow peak. An inlet only blockage can occur however when depositional debris is of comparable size to the culvert inlet. Blockage of the inlet can develop rapidly if a pulse of depositional material is washed into an inlet, for example from a nearby bank collapse. The process is typically dynamic with some material being washed through the inlet while it remains only partly blocked. Depositional inlet blockage is a common mechanism in areas where bed/banks are unstable/erodible or in urban areas where granular materials are stockpiled in the source area.
- **Barrel** The characteristics are as outlined for ‘Inlet’.
- **Outlet** The characteristics are as outlined for ‘Inlet’.
- **Handrails** This is a possible but improbable mechanism that has occurred in water courses with comparatively small cross sections delivering a very high depositional debris load of large relative dimensions.

2.5.4 Porous Plug Blockages

Porous plug blockages tend to occur downstream of heavily vegetated source areas or where urban debris can rapidly mobilise and be transported. Such blockages typically occur in steeper areas where overland and stream velocities are relatively high. They typically begin to form once flows are sufficient to mobilise and transport floating debris, creating a relatively porous mat of larger floating material bridging across an inlet that in turn quickly entraps smaller material, increasing the thickness and decreasing the porosity of the plug. The addition of fine depositional material to the plug mix can further reduce porosity. Unlike floating raft and depositional blockages, a porous plug blockage forms initially across the full waterway area and tends to decrease in porosity with time.

- **Inlet** This is a relatively **c**ommon mechanism for rapid inlet blockage in rural areas where floating and non-floating debris become entangled at the inlet. Blockages often occur on the rising limb of a flood hydrograph as a consequence of an initial pulse-like delivery of the more easily mobilised debris once sufficient flow develops to initiate mobilisation and transportation Such debris is also common in urban areas where material such as cars, bins or containers for example are mobilised towards inlets as the flood rises. Porosity varies considerably depending on the characteristics of the trapped material and length of time the plug has been in place and the reasons for this variability are unknown. Observation of such blockages suggests mixed rural plugs tend to be of low porosity whereas urban plugs are frequently more porous.
- **Barrel** This is an uncommon mechanism that can occur in smaller culverts when an object (such as tree limb or plank for example) enters the culvert lengthways, but then twists and wedges in the barrel, trapping other material behind it as time passes. This is quite a random process with no predictable timing. Where such blockages have been observed, they have typically resulted in a low porosity blockage of the barrel.
- **Outlet** This mechanism is improbable.

2.5.5 Mixed Mode Blockages

All blockages are likely to be of a mixed mode to some degree and the character of debris reaching a structure will often vary throughout a flood event. Depending on the range of materials involved, mixed mode blockages can exhibit any of the preceding characteristics, and while visual observations are common, they are still very difficult to characterise and quantify.

2.6 BLOCKAGE OCCURRENCE

The occurrence of structure blockage is relies on the following factors (Barthelmess and Rigby, 2009):

- **Debris availability –** the presence of particular types of debris within a catchment.

- **Debris mobility –** the process by which debris is initially mobilised from overland areas, floodplains or the banks or beds of streams. The factors influencing the initial mobilisation of debris can be different from the factors that influence the transportation of debris down the stream to the structure.
- **Debris transportability** – the process by which debris is transported down the stream to the structure.
- **Structure interaction** – the processes by which debris interacts with the structure to pass through or form a blockage at that structure.

It is the combination of the potential quantity of blockage material within the catchment, and the triggers for the initial displacement and transportation of this material that ultimately influence the quantity of material entering a drainage line, waterway, bridge or culvert. Therefore, a large quantity of catchment vegetation does not necessarily result in a high risk of blockage if there are no triggers for the initial displacement of the organic matter. Such triggers could be a strong windstorm or the actions of channel erosion undermining the vegetation.

Similarly, a car park full of cars is not necessarily a potential source of culvert-blocking debris unless floodwaters reach sufficient elevation and/or shear stress to mobilise the cars.

The availability of debris in a source area strongly relates to land use and catchment management activities within that area. The mobilisation and transportation of that debris usually relates to the severity of winds, channel shear stress, and the elevation of floodwaters across floodplains. The latter two factors are closely linked to the average recurrence interval (ARI) of the flood. The transportation of material can also be linked to the slope of the catchment, especially in regards to the transportation of larger material such as cobbles and boulders.

Table 2.3 provides an overview of key factors likely to influence the availability, mobilisation, and transportation of various forms of debris.

Table 2.3 Summary of factors influencing debris blockage potential at a structure

Debris Type	Factors Influencing Debris Potential		
	Availability	**Mobility**	**Transportability**
Leaves	Degree of tree cover Density and location of deciduous trees Frequency of street sweeping	Severity of winds Seasonal factors relating to leaf fall from deciduous trees	Stream Power Gradient of watercourse Waterway width and depth relative to material dimensions for floating debris Bed and bank irregularity for non-floating debris
Grass and garden mulch	Percentage grass cover Collection of grass clipping following mowing	Shear stress of overland flow	
Reeds and other aquatic vegetation	Regional factors relating to growth opportunities, including annual rainfall and canopy cover of the upstream waterway	Shear stress of in-bank flow Frequency of bankfull flows	
Woody matter	Density of riparian tree cover	Severity of winds Stability of waterway channel (often related to changes in catchment hydrology) Severity of flood event	
Litter	Land use (residential, sporting, recreational and commercial) Degree of building activities Regional factors Frequency of street sweeping	Severity of winds Shear stress of overland flow	
Building debris	Extent and control of building activities Land use (commercial)	Severity of winds Shear stress of overland flow Inundation of floodplain	
Sediment	Extent and control of building and construction activities Geology of watercourse Degree of sediment control measures	ARI of flood event Stability of waterway channel (often related to changes in catchment hydrology)	
Rocks and boulders	Geology of watercourse Gradient of watercourse Stream power	ARI of flood event Landslips and landslides Stability of waterway channel (including natural channel migration)	
Urban debris	Land use (car parks) Population (car) density Density of buildings within floodplain	Inundation of floodplain Depth of flooding Velocity of flood flows	

2.7 DEBRIS AVAILABILITY

2.7.1 General

The following factors affect the availability and supply of debris material within a source area.

- *Potential for soil erosion: S*oil erosion exposes soil and rock particles, thus increasing their availability. The potential for soil erosion is dependent on a number of factors including soil erodibility, rainfall erosivity, slope length and gradient, vegetation cover and changes in catchment hydrology, often closely linked to the effects of urbanisation. A change in catchment hydrology is one of the main causes of gully erosion, which is in turn a major contributor to the supply of sediment of all sizes.
- *Local geology:* The geology of the debris source area, and particularly the exposed geology of the watercourse, influences the availability of materials such as clay, silt, sand, gravel, rocks and boulders. Different types of waterways produce different quantities of bed load material. Alluvial streams, such as sand and gravel-based waterways, typically experience significantly more sediment flow than fixed-bed, clay or rock based waterways.
- *Source area:* Increasing the area supplying debris typically increases the quantity of available blockage material. It is noted however, that once blockage occurs at a given structure, the debris source area for the next downstream structure may be much less than that of the contributing catchment area.
- *Amount and type of vegetative cover:* This cover can vary from grasses and shrubs to thick forests and plantations as well as a variety of crops and agricultural uses. Some types of vegetation are easily uprooted by overland flow and others are not. Strong winds can produce significant quantities of leaf matter as well as twigs and larger branches.
- *Urbanisation:* Such areas make available a wide range of debris typically influenced by the extent of flood inundation, thus making this a manageable factor linked to town planning and drainage design.
- *Land clearing:* This is associated with both rural and urban land use practices. Deforestation and urbanisation can alter the long-term flow regime of streams and may lead to gully erosion and channel expansion. As a result, significant quantities of sediment and riparian vegetation can be made available for mobilisation in both rural and urban streams.
- *Preceding wind and rainfall:* The occurrence of frequent flood events typically reduces the availability of debris present in the catchment from time to time, however, the occurrence of frequent windstorms typically increases the quantity of debris present in the catchment. Debris availability as a result of windstorms and cyclones can be managed through frequent rubbish collection and catchment clean-ups.

2.7.2 Landslips and Landslides

Landslips and landslides are a source of sediment for streams in steep country throughout Australia. Slope stability depends on many factors such as flood and drainage behaviour, the underlying geology, and the intensity and duration of rainfall. These factors may individually or in combination produce a slope failure. Young (1978) has observed that in the Illawarra region of New South Wales, while underlying geology and slope material are significant contributors to potential landslips, runoff is a more crucial factor than rainfall.

Young's work was extended by Flentje (1998), who identified a relationship between the percentage exceedance of antecedent rainfall and slope failures. The study concluded that the timing and failure of a landslide correlated to antecedent rainfalls over periods of 90 and 120 days.

2.7.3 Land Use Characteristics

Land use characteristics affect the availability of debris that could potentially cause structure blockages. Urban catchments contain various sources of floating and non-floating debris. Non-urban land uses can include forested and rural catchments. Forested catchments contain large areas of tree stands and understorey shrub growth. Rural areas are often dominated by short native grasses that can be mobilised in large quantities by winds and overland flows, whether or not they are mechanically cut or disturbed by grazing.

2.7.4 Preceding Windstorms or Rainfall

The effects of preceding windstorms or rainfall are difficult to quantify with certainty, but it is considered reasonable that the effects could be significant. On one hand, if a catchment first experiences a 5 year ARI flood event, followed days later by a 20 year ARI flood event, then the degree of blockage in the latter event would be expected to be lower because the previous flood had probably cleared the catchment of much of its available debris. However, the impacts would depend on the degree of structure maintenance that occurred during the intervening days.

For example, an event in western Brisbane during 2008 demonstrated that a strong windstorm preceding a heavy rainfall event can significantly increase the amount of debris availability (and subsequently blockage). The first event stripped trees of leaves and branches depositing this material throughout the catchment and within the various drainage paths. The second event, which was dominated by heavy rainfall, resulted in debris mobilisation and significantly more debris blockage than would normally have been expected by such a rainfall event occurred due to the previously mobilised debris.

2.8 DEBRIS MOBILITY

The following factors affect the mobilisation of debris material within the catchment (Barthelmess and Rigby, 2009):

- *Rainfall erosivity:* Different areas of the country experience different frequencies of rainfall intensity, and in general, those areas that experience more intense rainfall have a greater potential to mobilise debris than areas of lower rainfall intensity. This however, is somewhat offset by the 'cleansing' nature of frequent flooding within these high rainfall intensity areas, which means that debris does not accumulate to he same extent.
- *Soil erosivity erodibility:* This can vary from weathered rocks to cohesive clays, all soils have different abilities to become eroded, entrained and available for mobilisation.
- *Slope:* With respect to sediment and boulder movement, there is a relationship between the mobilisation of such debris and the slope of the catchment, both with respect to overbank areas where debris may be sourced and the stream channel which conveys the debris.
- *Storm duration:* The mobilisation of materials generally increases with increasing storm duration.
- *Vegetation cover:* Sparse vegetation cover can increase sediment mobility.

When large quantities of sediment are mobilised, debris flows, where significant amounts of sediment move down slope, can develop. These can occur in a variety of geologic, geomorphic and climatic environments and there are a variety of conditions and factors that govern the mobility of a detached mass of earth and/or rock forming a debris flow (Flentje et al., 2001). The dominant factors in the triggering of a debris flow are centred around the geological and geomorphic aspects of the catchment, as well as the hydrologic conditions preceding the debris flow. Debris flow provides a supply of debris to streams for further transportation downstream, and can be in some areas an important consideration with regard to factors affecting structure blockage (Van Dine, 1996).

2.9 DEBRIS TRANSPORTABILITY

Once debris has been mobilised, it then needs to be transported down the stream if it is to present a hazard to downstream structures. Stream power, velocity, depth, presence of snags and bends and the overall dimensions of the water course play a large part in determining whether the mobilised debris lodges where it first enters the stream or is transported downstream to a receiving structure. There is a reasonably strong correlation between the waterway width and the maximum size of floating debris that a stream can transport. The transportation of non-floating debris is also heavily influenced by stream power, which is a function of velocity and depth. The event magnitude is also a major factor in controlling the quantity of debris transported. Rarer events produce deeper and faster floodwater able to transport large quantities and larger sizes of debris, smaller events may not be able to transport larger bridging material at all.

2.10 STRUCTURE INTERACTION

The likelihood of blockage at a particular structure depends on whether or not debris is able to bridge across the structure's inlet or become trapped within the structure. As bridging occurs, the clear expanse of each opening reduces, thus increasing the likelihood of further bridging and further blockage by smaller or similar material.

Most blockage matter is unlikely to cause full blockage of a structure without the presence of suitable bridging matter, the material that bridges across the opening or inlet of a structure. Bridging matter can be as small as leaves caught on a kerb inlet grate, or as large as logs, cars and shipping containers caught at a culvert inlet.

Exposed services attached to the face of culverts or bridges or obstructing the culvert waterway opening can significantly increase the risk of blockage (Photo 12). Similarly, some through-culvert features introduced to improve fish passage can also collect and hold debris causing internal blockage problems (Photo 13).

Photo 12: Debris collected around exposed pipes

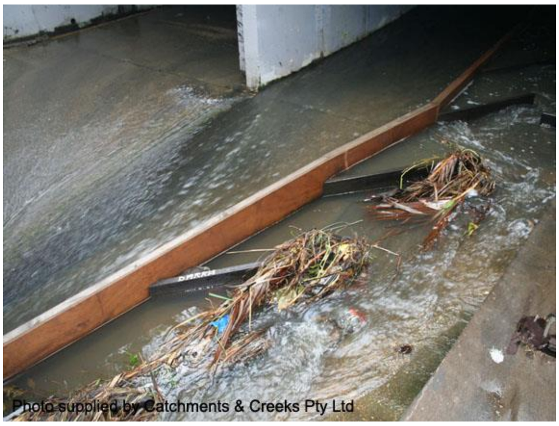

Photo 13: Debris can be trapped by fish passage baffles

2.11 BLOCKAGE TIMING AND EXTENT

The timing of a blockage is critical in the hydrologic analysis of a structure and/or flood event. For example, the timing of a blockage in an outlet of a detention basin can be most important, as it can significantly impact peak flood discharges from the structure and flood levels upstream. A substantial blockage early on in a storm event will likely cause any available storage in the structure to fill prior to the peak, reducing the ability of the storage to attenuate peak flows during the main 'burst' (Rigby and Silveri, 2001).

This issue of timing is governed by the different mobilisation patterns of different blockage material. For example fine sediment and small to medium floating debris generally can be mobilised during any part of a flood event, but is typically deposited only during the falling limb of the hydrograph. Conversely, boulders may only be mobilised for a short time during rare, large flood events and are most likely to block structures around the flood peak. Stream morphology suggests that most coarse sediment is likely to be associated with near-bankfull flows when channel erosion and stream meandering processes are at their maximum. The mobilisation of urban debris is associated with the timing of overbank flows of sufficient depth and/or velocity to move the debris across the overbank area and into the stream.

If, during a given event, structure blockages predominantly occurred during the low energy, falling limb of a flood hydrograph, then any post flood observations may give a false impression of the degree of blockage that actually existed during the peak of the flood. For example, sediment deposits often exist within culverts and beneath bridges before flood events even commence. Similar or even greater degrees of deposition may also exist after a flood, but during the peak of the flood when flow energy is greatest, culverts can be flushed clean of sediment and bed levels below bridges can be several metres below normal bed level. This phenomenon is well known in alluvial streams where there is often considerable movement of the bed material during floods that cannot be easily observed during periods of low flow.

Rigby and Barthelmess (2011) reported on the effects that variations in the timing of blockages have on discharge released from hydraulic structures such as detention basins, culverts and bridges. The findings of this paper are summarised below:

- If there is minimal flood storage upstream of the structure, then the structure will overtop, and the discharge downstream of the structure is generally independent of the timing and degree of blockage, unless of course such blockage results in a flow diversion away from the downstream waterway. Flood levels upstream of the structure, however, may still be dependent on the timing and degree of blockage.
- If there is significant flood storage upstream of the structure, and the blockage occurs early within the flood cycle, then the available flood storage can fill before the flood peak arrives resulting in the discharges downstream of the structure mimicking the upstream (inflow) discharge (unless of course such blockage results in flow diversion).
- If there is significant flood storage upstream of the structure, and the blockage occurs during the peak of the flood, then the induced flood storage becomes most effective, resulting in a reduction in peak discharge downstream of the structure.
- If there is significant flood storage upstream of the structure, and the blockage occurs late in the flood event, then the flood storage that occurs upstream can be used as designed and peak discharges downstream of the structure. In both this and the previous case, peak flood levels upstream of the structure are often dominated by the overtopping flow conditions as floodwaters pass over or around the blocked structure.

The timing of blockages depends on many variables including the type of blockage material, the timing of initial mobilisation, and the transportation time form source to structure. Table 2.4 provides a general guide to the likely timing of initial mobilisation of various types of blockage material.

Table 2.4: Likely timing of peak debris mobilisation

Debris Type	Likely timing of peak mobilisation of debris
Leaves	• Pulse like mobilisation in early stages of flood if leaves were originally displaced by recent windstorm or by seasonal leaf-fall, otherwise progressively during rising limb of a flood hydrograph.
Grass and garden mulch	• Commencement of overland flow, especially in rural areas.
Reeds, woody matter and other aquatic vegetation	• Progressively during rising limb of a hydrograph with most mobilisation coinciding with peak within bank flow.
Litter	• Progressively during rising limb of a flood hydrograph once overland flows develop
Building debris	• Often pulse-like delivery once significant overbank or overland flow develops.
Sediment	• Progressively during the event with peak mobilisation typically occurring on the rising limb of a flood hydrograph around bankfull discharge. Peak deposition normally occurs on the falling limb as velocities reduce.
Rocks and boulders	• As for sediment.
Urban debris	• Peak movement is likely to coincide with period of significant overbank flow (when depth*Velocity >= 0.3 along overland flow paths)

The timing of blockages at bridges and culverts also depends on where the blockages occur. Blockages around piers and legs can occur progressively throughout the flood, while top-down blockages begin to form once flood levels approach the obvert of the structure. The blockage of handrails and traffic barriers begins to occur once overtopping flows commence.

3. BLOCKAGE ANALYSIS AND ASSESSMENT

3.1 INTRODUCTION

This report considers two components of the issues related to blockage of drainage structures. The first of these is to include blockage in the calculation of design flood levels in flood investigations and the second is concerned with the consideration of risk of blockage when planning and designing drainage systems. There are different considerations for each method.

Thus the assessment of blockage issues does not just involve an assessment of the likelihood of blockage material passing down a waterway or drainage line, but also involves an integrated assessment of the combined effects of the 'likelihood' of blockage and the 'consequences' of such blockage as used in risk assessment. The likelihood of blockage is related to the availability of blockage material, the forces likely to mobilise and transport the material, and the likelihood of the material being captured by a structure. Likelihood is therefore dependent on both the type and quantity of material arriving at a structure and the type and design of that hydraulic structure.

Consequences concern the possible damage or inconvenience caused by the blockage. If consideration of different levels of blockage causes minor changes in flood level with no adverse flooding on any property, the consequences are minor or even nonexistent, but if blockage of a culvert causes significant flow diversions and damage to residences, the consequences are severe. Therefore, while assessment of the design flood level may rely on a certain level of blockage, severe consequences should require modifications to the drainage design.

3.2 BLOCKAGE CONDITIONS

3.2.1 Overview

Analysis of blockage in hydraulic design should consider the following blockage conditions:

- **Design blockage:** This is the blockage condition that is most likely to occur during a given design storm and will vary from one event to another. It is also noted that actual blockage levels vary greatly from event to event with a potential spread from all clear to fully blocked even in floods of comparable magnitude. Antecedent catchment conditions and pure chance are major factors in determining blockage levels in an actual event. The selected design blockage must aim for AEP neutrality (the concept of ensuring that the average recurrence interval of the design flood discharge is the same as the ARI of the design rainfall input) so design floods are appropriate for the particular circumstances. As with other similar aspects of design flood estimation, such as losses, each individual historical flood may have quite different amounts of blockage compared to the design event.

- **All Clear:** As previously noted an 'all clear' condition is possible and in many cases at least as likely as the most likely blocked condition. Depending on conditions, many drainage systems may have a low probability of blockage and this condition may be the most likely.
- **Severe blockage:** The level of blockage that is considered possible during the design life of the structure, but unlikely to occur on a frequent basis during any given design storm. Though termed 'severe', such blockage may not necessarily represent total blockage of the structure, or even a condition likely to result in severe consequences, but only occurs in extreme or unusual flood events. However if there are serious consequences, severe blockage should be considered in the planning and design of drainage systems, but may not be the condition required for design purposes.

Flood mapping is an exercise in probabilities that involves the estimation of 'average' catchment conditions for various storm and flood frequencies to ensure that the rainfall of the defined probability produces the flood peak of the same probability. In such work, *design blockage* conditions must be considered when predicting flood levels of a given frequency. However such *design blockage* conditions may not be acceptable when assessing 'design flood levels' in situations where the consequences of blockage are high. In such circumstances it may be necessary to consider a less likely 'severe' level of blockage to retain the risk at a comparable level to that where a similar culvert is designed in an area with minimal consequences when blocked. Consideration of this severe blockage does affect the probability of the flood levels. Consideration of severe blockage will increase flood levels so the calculated flood level will be for a lower probability flood.

The degree of structure blockage assumed within a drainage catchment also affects in-stream flood storage and the exchange of flood waters between adjacent catchments. Adopting severe blockage conditions throughout a catchment is neither appropriate in all circumstances, nor is it necessarily conservative. In some cases, the increase in flood storage and the inter-catchment exchange of flood waters within the upper catchment can significantly reduce waterway discharges within the lower catchment.

The appropriate degree of blockage to be considered in the analysis of design floods, whether 'all clear', 'design' or 'severe', depends on consideration of the combined risk of blockage and the consequences of such blockage, but design blockage is needed for calculation of design flood or planning levels.

3.2.2 Determination of Design Flood Levels

Design flood level or the *Defined Flood Event* is the flood level used in floodplain management for the purpose of setting critical design levels, such as minimum fill levels for urban development and minimum floor levels for residential building approvals, traditionally the 100 year ARI flood level.

Due to the random and highly variable nature of debris blockage, the 100 year flood ARI level obtained from a long-term, multi-event model simulation (e.g. Monte Carlo modelling) may be different from the flood level obtained from single event modelling in which ‘average’ or ‘most likely’ blockage conditions are normally assumed. The reason for this is that at some structures, the flood level obtained from a 1 year ARI discharge assuming severe blockage conditions can be higher than the flood level obtained from a100 year ARI discharge assuming the most likely blockage conditions. Such a case is demonstrated in Figures 3.1 and 3.2, where Figure 3.1 shows the long-term average flood levels upstream of a culvert operating under the most likely blockage conditions and Figure 3.2 shows the flood levels that would exist during infrequent severe blockage conditions.

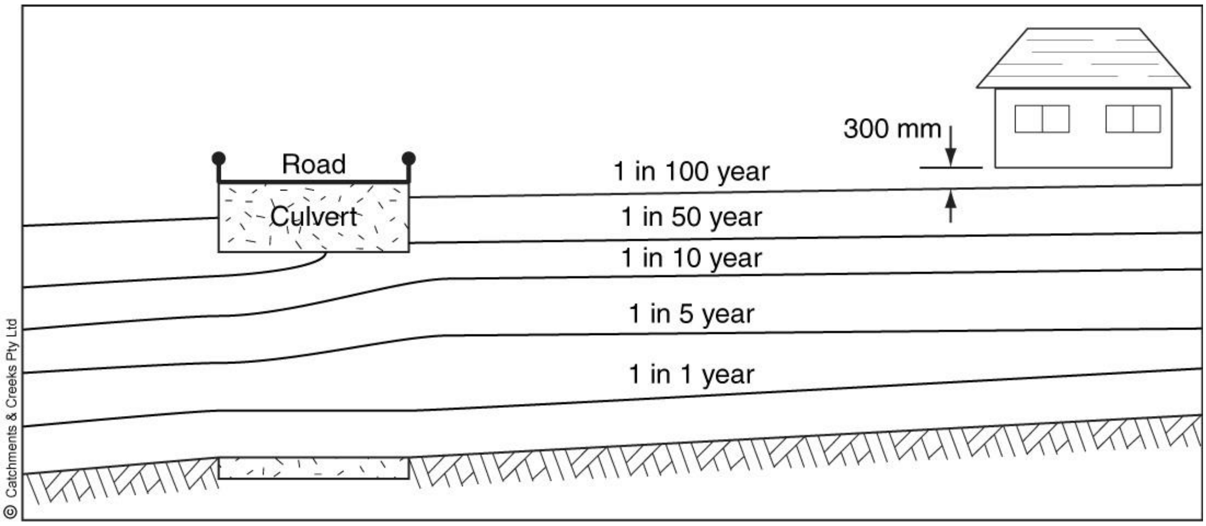

Figure 3.1: Long-term average flood levels based on average blockage conditions

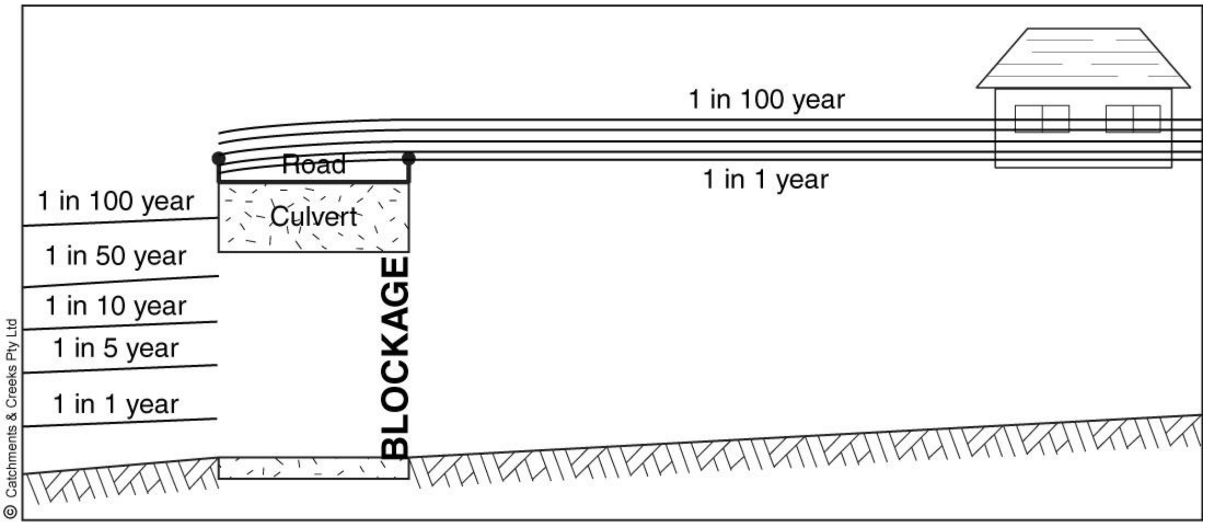

Figure 3.2: Flood level based on 100% blockage of the culvert

If design flood levels were based on the long-term average flood levels resulting from a 100 year ARI storm with average blockage conditions (Figure 3.1), there would be severe consequences if severe blockage occurs (Figure 3.2), though the probability of this event is much less.

3.3 ASSESSMENT OF BLOCKAGE

Assessment of the risk approach and the most appropriate methodology for assessment of design flood levels with an appropriate allowance for blockage is a difficult problem, and one where the investigations and review carried out in this project has not indicated a clearly superior approach. No clear methodology has been developed for inclusion of blockage in the calculation of design flood levels or for assessment of severe blockage for consideration of risk assessments.

Based on the reviews, two different approaches have been developed and both offer some advantages. These two approaches are presented in this report. After further consideration and testing of these methods, one or other of these can be modified and adopted or the two methods can be merged and combined in an appropriate manner.

In Section 3.4 a methodology, labelled Scheme A, for accommodation blockage in design or analysis is presented, based on the various papers by Barthelmess, Rigby, Silveri and others. In Section 3.5 an alternative methodology labelled Scheme B by Witheridge is presented.

3.4 ASSESSMENT OF BLOCKAGE – SCHEME A

3.4.1 Overview – Scheme A

This procedure is based on a qualitative assessment of debris likely to reach a structure, and the likely interaction between that debris and the structure regarding the potential for blockage. It is based on the various papers prepared by Barthelmess, Rigby, Silveri and others.

The procedure involves a series of decisions on the likelihood of debris reaching a structure in a 100 year ARI event based on consideration of:

- Debris availability.
- Debris mobility.
- Debris transportability.

This debris potential is then adjusted as required for greater or lesser event probabilities and used in conjunction with details of the structure to establish the 'most likely' and 'severe' blockage levels for that event. The location and timing of the blockage is then determined from consideration of the dominant type of debris material reaching the structure.

When applied with the resulting 'design' blockage level, this procedure provides an AEP neutral response.

To move this procedure into a risk based format, the consequences of blockage then need to be quantified and used to establish a blockage level commensurate with the agreed level of risk.

These steps are discussed further and set out procedurally in the following Section 3.4.2.

3.4.2 Assessment Procedure for an AEP Neutral Blockage Level – Scheme A

This is an appropriate level of blockage for calculation of design floods, but may not reflect conditions for specific historical events.

The availability of particular debris within a catchment limits the level of debris that can be mobilised and transported to a structure. These characteristics are given descriptively, so there is some judgement required in the evaluation. Table 3.1 describes typical source (upstream catchment) area characteristics and a corresponding ranking for the likely availability of debris.

Table 3.1: Debris Availability

Availability	Typical Source Area Characteristics
High	• Dense forest, thick vegetation, difficult to walk through. • Considerable fallen limbs, leaves and high levels of floor litter. • Non-cohesive soils and boulder/cobble based streams with steep slopes and steep banks showing signs of past bed/bank movements. • Areas where annual rainfall is high and/or temporal distribution of annual rainfall is irregular. • Arid areas, where loose vegetation and exposed soils occur and vegetation is sparse. • Urban areas where a significant number of cars and stored loose material etc., are present on the floodplain close to water courses.
Medium	• State forest areas, grazing land with stands of trees. • Source areas generally falling between the High and Low categories.
Low	• Rural lands, grazed paddocks, mown parklands. • Areas where temporal distribution of annual rainfall is uniform. • Streams with moderate to flat slopes and stable banks. • Urban areas where debris source areas (urban development) are located a considerable distance from watercourses (and culverts).

The ability for debris to become mobilised has an effect on the amount of debris that can be transported to a structure. Table 3.2 describes typical source (upstream catchment) area characteristics and a corresponding rank for the likely mobility of debris.

Table 3.2: Debris Mobility

Mobility	Typical Source Area Characteristics
High	Steep catchments with fast response times and high annual rainfall and/or storm intensities and arid areas subject to high rainfall intensities with sparse vegetation cover.
Medium	Moderate rainfall intensities and moderately sloped catchment areas. Source areas generally falling between the High and Low categories.
Low	Low rainfall intensities and large, flat catchment areas.

The ability for debris to be transported downstream to a structure has an effect on the amount of debris arriving at a structure. Table 3.3 describes typical source (upstream catchment) area characteristics and a corresponding rank for the likely transportability of debris.

Table 3.3: Debris Transportability

Transportability	Typical Source Area Characteristics
High	• Steep bed slopes (> 3%). • Wide streams relative to expected debris load dimensions. • Banks prone to scour during a design event. • Streams with permanent water. • High annual rainfall.
Medium	• Moderate bed slopes (1 - 3%). • Stream size comparable to expected debris load dimensions.
Low	• Flat bed slopes (< 1%). • Narrow streams relative to debris load dimensions. • Banks not prone to scour during a design event. • Regular rainfall distribution.

Where data is available on the quantity and type of debris typically present at a structure, this can be used to directly quantify the debris potential. Where such data is not available, the potential quantity of debris reaching a structure at a site from a contributing source area can be estimated from Table 3.4. If there is a significant quantity of more than one type of debris in the source area that could induce blockage, this should require more than one type of debris potential to be estimated.

Table 3.4: At Site Base Debris Potential

Debris Potential	Combinations of the Above (any order)
High	HHH or HHM
Medium	MMM or HML or HMM or HLL
Low	LLL or MML or MLL

Observation of debris conveyed in streams strongly suggests a correlation between event magnitude and debris potential at a site. This is accommodated in Table 3.5 as follows.

Table 3.5: At Site Debris Potential - Adjustment for ARI

Event ARI	**Base Debris Potential**		
	High	**M**edium	**L**ow
ARI < 20 year	**M**edium	**L**ow	**L**ow
20 year ≤ ARI ≤ 200 year	**H**igh	**M**edium	**L**ow
>200 year	**H**igh	**H**igh	**M**edium

Research into culvert blockage in Wollongong showed a correlation with blockage and opening diameter / width (Rigby and Silveri, 2001), termed here control dimension, W. As such, it is important to recognise this as a major factor influencing blockage in any design procedure. The ratio of the width of the controlling openings of structures (e.g. grate clear spacing, kerb inlet height, diameter or width of the culvert or bridge pier spacings) to the length of the longest 10% of debris that could arrive at the site (termed here as L_{10}) is used in Table 3.6 to quantify the likelihood of this material bridging the openings and triggering a blockage. The L_{10} value must be estimated approximately from sampling of typical debris loads. In conjunction with the quantity of debris likely to arrive at the site, Table 4.6 provides an estimate of the 'most likely' blockage level should a blockage form. This blockage level is the percentage of blockage to be used in the design. It should be noted that the random nature of blockage will produce a structure that does not block in some events, despite being prone to do so. This 'all clear' condition may be possible needs to be included in any procedure that reflects blockage, as the 'all clear' condition can significantly alter downstream conditions from that of the 'blocked' condition.

Table 3.6: Most Likely Blockage Levels - B_{DES}

Control Dimension	**At-Site Debris Potential**		
	High	Medium	Low
$W < L_{10}$	100%	50%	25%
$W \geq L_{10} \leq 3{*}L_{10}$	20%	10%	0%
$W > 3{*}L_{10}$	10%	0%	0%

While the above provides a means of estimating a realistic value for the magnitude of a likely (ARI neutral) blockage, it does not address the other characteristics required to properly describe the blockage mechanism (viz type, location and timing).

While the number of possible blockage mechanisms is considerable, there appears to be a strong correlation between the dominant debris type arriving at a structure and the blockage mechanism it triggers (Rigby and Barthelmess, 2011). It should be noted that both Tables 3.6 and 3.7 are not based on quantitative data and it is therefore important that they be refined as further data comes to hand. In Table 3.7, T_P is the time of peak discharge and $T_{O/T}$ is the time the structure overtops.

Table 3.7: Likely Blockage Timing

DOMINANT SOURCE MATERIAL	SUPPLY RATE	BLOCKAGE LOCATIONS			
		Inlet	**Barrel**	**Outlet**	**Handrails**
FLOATING	**Progressive**	$1.5T_P$ to B_{DES} at $2.0T_P$	Unlikely	Unlikely[2]	$T_{0/T}$ to B_{DES} at T_P
	Pulse[1]	B_{DES} @ $0.5T_P$	Unlikely	Unlikely	$T_{0/T}$ to B_{DES} at T_P
NON FLOATING	**Progressive**	$0.5T_P$ to B_{DES} at T_P	$0.5T_P$ to B_{DES} at T_P	$0.5T_P$ to B_{DES} at T_P	Unlikely
	Pulse[1]	Unlikely[3]	Unlikely	Unlikely	Unlikely

1. Pulse blockages are more likely in systems subject to infrequent flooding

2. Unlikely - but could become likely if inlet is open and outlet grated.

3. Unlikely – but could become likely if upstream bed/banks unstable and/or prone to scour

The above procedure can now be applied to establish flood behaviour in an AEP neutral manner for a structure where blockage is seen as possible.

3.4.3 Risk Based Assessment of Blockages – Scheme A

The preceding section presents a procedure for establishing an AEP neutral analysis of the hydraulic behaviour of a structure considering blockage. In order to move design or analysis into a risk based procedure, it is necessary to consider both the probability of an event occurring and the consequences of that event occurring (risk = f {probability, consequences}). Without consideration of consequences, the flooding risks communities could be exposed to from two similarly designed culverts might be significantly different. If one was in a rural area with no nearby development, the consequences of blockage elevating upstream flood levels might be minimal. Blockage of a similarly designed culvert in a highly built up area could have major consequences and therefore present a much higher risk to the community. Consideration of risk in flooding is a relatively complex matter as there is a strong relationship between the event magnitude (probability) and the consequences of that event occurring. Smaller events (high probability) typically are associated with lesser consequences and risk reflects the product of the two.

Historically, the profession has chosen a design ARI for hydraulic structures that indirectly reflects the consequences associated with 'failure' of that structure. This will continue, so that risk in terms of blockage only needs to consider the implications of structures being designed or analysed for a given ARI event.

To design or analyse these structures with risk (rather than ARI) in mind, then the higher consequences environment needs to be coupled with a less probable flood event. In the context of this report this would require an estimate of blockage that is higher than that 'most likely'. An improbable but possible ('severe') blockage level is therefore proposed to be coupled with the otherwise neutral AEP event where the consequences of a 'severe' blockage are very high. It is suggested that as an interim value, a blockage level of twice the 'most likely' level would represent a likely value for such an improbable but possible blockage. To complete the procedure a high probability level is also required to couple with low consequence AEP neutral events, but it is considered that until there are data to justify other values, the 'all clear' or 0% blockage can serve in this situation.

This process is set out in Table 3.8. To equalise risk for the design or analysis of a structure to accommodate a specific ARI event, the design or analysis should be undertaken with blockage levels adjusted as set out in the following table.

Table 3.8: Risk Based Blockage Assessment

Consequences of Severe Blockage				
Very High	High	Moderate	Low	Very Low
Severe[1]	Design[2]	Design[2]	Design[2]	0%

1. 'Severe' estimated as 2* B_{DES}
2, 'Design' B_{DESS} as per Table 4.6

3.4.4 Assessment of Multiple Structures – Scheme A

Structures should generally not be designed or analysed in isolation. Even when the objective is the design or analysis of a single hydraulic structure it is possible that it lies downstream of other structures which may be prone to blockage and subject to flow diversions of many hydraulic structures, an impractical number of combinations of blocked and clear structures develops, with flow being maximised or levels minimised in each reach depending on where and what degree of blockage is assumed to occur. It is therefore important to exercise judgement in considering those patterns that are likely to occur and restricting analysis to those patterns.

It should be noted that the envelope of design flood peak levels that comes from analysis of several patterns will not normally be reached in an event of the target ARI, as only one actual blockage pattern will be present. Given the probabilistic nature of blockages it is however likely that at some locations the envelope flood levels could be exceeded.

3.5 ASSESSMENT OF BLOCKAGE – SCHEME B

3.5.1 Blockage risk – Scheme B

This alternative approach provides a numerical estimate of the qualitative assessment described in Scheme A.

The likelihood of structure blockage can be determined using an appropriate risk analysis procedure. If sufficient long-term records exist (which is probably unlikely), based on the memory of locals, maintenance personnel or other records, then the risk should be based on historical conditions at the site rather than a generic procedure, as provided in this section. In such cases, Table 3.9 can be used to assess the likelihood scale for 100% or near-100% blockage conditions.

A generic risk assessment procedure based on key catchment and structure conditions is presented in Table 3.9. A ranking of high, medium or low (representing a likelihood scale of A, B and C) is determined by the designer based on a simple numerical procedure. In some circumstances, just one catchment or structure condition can trigger a high-risk ranking for the site—thus the final assessment relies heavily on experience and judgement.

Installed debris control features associated with the design of a hydraulic structure can affect this scale.

Table 3.9: Example of a likelihood scale for 100% or near-100% Blockage Conditions Based on Blockage History

Likelihood scale	Description [1]	Blockage frequency [2]
A (High)	High risk of blockage	Once a year
B (Medium)	Blockage is not likely to occur on a frequent basis, but has occurred in recent memory or is likely to occur infrequently during severe storms	Once every 10 years
C (Low)	Blockage is considered possible, but unlikely, or is considered possible only when a combinations of unlikely events occur simultaneously	Once every 100 years

[1] The severity of the blockage depends on the degree of blockage relative to that assumed in the design.

[2] Likelihood of blockage significantly greater than that assumed within the design.

Table 3.10 gives a numerical estimate of the descriptive assessment described in Scheme A. These numerical values are based on experience of Grant Witheridge, but testing and trial application will be needed to determine whether they are appropriate.

Table 3.10 a: Example generic procedure for the assessment of likelihood scale

Description	Points	Score
1. Inlet dimensions		
• Clear opening height greater than 3 m, and • Clear opening width greater than 5 m	0.8	
• Clear opening height less than 3 m, but width greater than 5 m, or • Clear opening height greater than 3 m, but width less than 5 m	1.0	
• Clear opening height less than 3 m, and/or • Clear opening width less than 5 m	1.2	
2. Upstream reach length		
• Distance to next upstream structure that will retain debris is less than 1 km	0.8	
• Distance to next upstream structure that will retain debris is 1 to 10 km	1.0	
• Distance to next upstream structure that will retain debris is greater than 10 km	1.2	
3. ARI of storm causing submergence of the structure's inlet without blockage		
• Inlet is submerged during flows of a frequency greater than 1 in 50 years	0.9	
• Inlet is submerged during flows of a 1 in 50 year frequency or less	1.0	
• Inlet is submerged during flows less than a 1 in 5 year frequency	1.1	
4. Predominant catchment land use		
• Urban with most overland flow passing through well-maintained drainage reserves • Rural with low potential debris flow	0.9	
• Urban with significant overland flow passing through formal drainage easements within private properties • Rural with high potential debris flow (e.g. grasses)	1.0	
• Urban, commercial or industrial with significant overland flow passing through properties	1.1	
5. Existence of large floating urban debris		
• Low risk of large floating urban debris	0.9	
• Medium risk of large floating urban debris (default value if unknown)	1.0	
• High risk of large floating urban debris	1.1	
6. Potential for landslips within the drainage catchment		
• Low risk of landslides or landslips	0.9	
• Medium risk of landslides or landslips (default value if unknown)	1.0	
• High risk of landslides or landslips	1.1	
7. Frequency of strong winds		
• Strong winds that strip branches and leaves from trees are rare	0.9	
• Strong winds are common, but the resulting debris is well-maintained	1.0	
• High stream flows typically coincide with periods of strong wind • Strong winds are common and the resulting debris is poorly-maintained	1.1	

Table 3.10 b: Example generic procedure for the assessment of likelihood scale

Description	Points	Score
8. Risk of upstream gully erosion and channel erosion		
• Low risk of ongoing gully erosion • Minimal recent urban or rural growth within catchment upstream of hydraulic structure • Small drainage catchments not subject to gully or channel erosion	0.9	
• Medium risk of ongoing gully erosion • Significant recent or ongoing water-sensitive urban growth • Significant clearing for rural development	1.0	
• High risk of ongoing gully erosion • Significant recent or ongoing non water-sensitive urban growth	1.1	
9. Risk of sedimentation		
• Low risk of significant sedimentation at the structure • Minimal urban growth	0.9	
• Medium risk of significant sedimentation at the structure • Significant ongoing urban growth with good sediment control • Default value if sediment risk is unknown	1.0	
• High risk of significant sedimentation at the structure • Significant ongoing urban growth with poor sediment control	1.1	
10. Expected frequency of maintenance		
• Prompt, regular and efficient maintenance of structure	0.9	
• Maintenance typically only after significant event, with limited maintenance between events (default value if unknown)	1.0	
• Poor structure maintenance that is likely to contribute to ongoing blockage problems	1.1	
11. Exposed services or high-risk fauna passage features		
• Low risk of debris blockage of exposed services or features	0.9	
• Medium risk of debris blockage of exposed services or features	1.0	
• High risk of debris blockage of exposed services or features	1.1	
12. Existence of design features that reduce the risk of blockage		
• Effective blockage control features incorporated into the design	0.9	
• Low-efficiency blockage control features incorporated into the design	1.0	
• Significant blockage is possible and no blockage control features incorporated into the design	1.1	

Blockage risk classification	Total score range	Total score
High (likelihood scale A)	>12.2	
Medium (likelihood scale B)	11.7 to 12.2	
Low (likelihood scale C)	< 11.7	

Table 3.11 provides an example of the ‘consequence scale’ that could be used in the assessment process for both the design of individual hydraulic structures and the determination of design flood levels adjacent a hydraulic structure. Table 3.12 provides an example of a risk assessment matrix.

Table 3.11: Example of consequence scale [1]

Level [2]	Consequence type					
	Damage	**Health**	**Environment**	**Social**	**Community**	**Legal**
V	> $10M	Multiple fatalities	Very serious, long-term environmental impairment of ecosystem functions	Significant irreversible damage to cultural values	Serious public or media outcry with international coverage	Significant prosecution and fines including class action
IV	$1M to $10M	Single fatality and/or severe irreversible injuries to one or more persons		On-going serious social issues, or significant, but mostly reversible damage to cultural values	Serious public or media outcry	Major breach of regulations or risk of litigation
III	$100K to $1M	Moderate irreversible injuries to one or more persons	Serious medium-term environmental effects	On-going moderate social issues, or moderate, but reversible damage to cultural values	Significant adverse national media or public attention	Serious breach of regulations with moderate fines possible and compensation
II	$10K to $100K	Objective but reversible disability requiring hospitalisation	Moderate, short-term effects by not affecting ecosystem functions	On-going social issues, or minor, reversible interference to cultural values	Significant adverse local media or public attention	Minor legal issue with low risk of fines
I	< $10K	No medical treatment required	Minor effects on biological or physical environment	Short-term social issues, or reversible interference to cultural values	Minor adverse local media or public attention	Minor legal issue

[1] The consequences of an under-estimation of the design discharge may be significantly different from the consequences of debris blockage. The consequence scale should be determined from an assessment of the consequences of:

- an under-estimation of the design discharge when assessing hydrologic conditions; or
- the consequences of debris blockage in excess of that assumed within the design when assessing design flood levels adjacent an individual hydraulic structure.

[2] Adopt the highest value achieved for any of the consequence types.

Table 3.12: Example risk matrix providing 'risk level'

Likelihood scale	Consequence scale				
	I	**II**	**III**	**IV**	**V**
A	Medium	High	High	Very high	Very high
B	Medium	Medium	High	High	Very high
C	Low	Medium	Medium	High	High

3.5.2 Risk Assessment for Determining Design Discharge for Hydraulic Structures

One of the first tasks performed in the design of hydraulic structures is the determination of an appropriate design discharge. For minor hydraulic structures such as kerb inlets, the design discharge is usually determined using hydrologic procedures that do not directly take into account blockage conditions within the drainage catchment. Upstream conditions, such as diversions caused by upstream blockage, could influence the design discharge.

Consideration of the hypothetical effects of upstream blockage on the design discharge for an individual hydraulic structure is usually more critical in the design of culverts because of changes in the flow arriving at the downstream culvert. In such cases, an appropriate risk analysis procedure should be used to assess the risk level associated with under-estimating or over-estimating the design discharge.

It is also important that designers **not** perform unnecessarily complex hydrologic analysis if the consequences of under-estimating or over-estimating the blockage conditions are negligible.

Table 3.13 provides example procedures for use in the hydrologic analysis of individual hydraulic structures.

Table 3.13: Example evaluation of blockage risk for the hydrologic estimation of the design discharge of individual hydraulic structures

Risk level [1]	Issues for consideration during hydrologic evaluation [2]
Low	• Adoption of a specific blockage condition within the drainage catchment is not critical given the low risk level.
Medium	• Assume minimal blockage of upstream structures where such blockage would increase upstream flood storage and thus reduce the design discharge at the structure being designed.
High or Very high	• Assume minimal blockage of upstream structures where such blockage would reduce the design discharge at the structure being designed. • Assume severe blockage of structures in adjacent catchments where such blockage is likely to divert flows into the drainage catchment of the structure being designed. Adjacent catchments being evaluated for the same storm frequency as the principal catchment being evaluated.

[1] Risk level based on the consequences resulting from an under-estimation of the design discharge for the hydraulic structure being designed.

[2] Provided recommendations are a guide only. Designers must assess appropriate hydrologic procedures on a case-by-case basis, and where appropriate, adopt hydrologic procedures different from those recommended above.

3.5.3 Risk Assessment for the Hydraulic Design of Individual Structures

The degree of blockage assumed in the design of hydraulic structures is not only different for different types of structures, but may also be different for the design of different components of a given structure. For example, in the design of a water course culvert, the degree of blockage assumed when assessing the effects of overtopping flows may be different from that assumed when assessing the flood immunity of the crossing, when the culver is not overtopped.

Similarly, if two identical waterway culverts, in identical drainage catchments, were required to have 50 year ARI flood free trafficable conditions, then it would be expected that both culverts would be designed using the same degree of assumed blockage. However, if significant adverse consequences resulted from the severe blockage of one of these culverts, then it would be reasonable to expect that a greater degree of blockage would be assumed during the analysis of discharges in excess of the 50 year ARI design discharge for that culvert.

This assessment would not alter the design flood level but would be useful in determining the appropriate culvert design because of risk.

The design outcomes for the above high-risk culvert may be the provision of a larger culvert waterway area, the acquisition of a more extensive overland flow easement, and/or the setting of higher minimum development fill levels adjacent to the culvert to minimise any adverse consequences resulting from overtopping flows. Other options include debris barriers or deflectors or embankments can be designed for overtopping. This means that for both culverts a blockage of, say 25%, may be assumed during the analysis of the 50 years ARI discharge, while for the analysis of overtopping events, the same 25% blockage may be adopted for the low-risk culvert while 100% blockage may need to be adopted for the high-risk culvert.

Tables 3.14 and 3.15 provide example risk evaluation tables for use in the hydraulic analysis of individual hydraulic structures.

Table 3.14: Example evaluation of blockage risk for the hydraulic analysis of individual drainage structures (not cross-drainage structures)

Risk level [1]	Issues for consideration during hydrologic evaluation [2]
Low	• Adopt 'design' blockage conditions for both minor and major flows.
Medium to very high	• Adopt 'design' blockage conditions for both minor flows. • Adopt 'severe' blockage conditions for both major flows.

[1] Risk level based on the consequences resulting from **'severe'** blockage of the structure.

[2] Provided recommendations are a guide only. Designers must assess appropriate hydraulic design procedures on a case-by-case basis, and where appropriate, adopt hydraulic design procedures different from those recommended above.

Table 3.15: Example evaluation of blockage risk for the hydraulic analysis of individual cross-drainage structures

Risk level [1]	Issues for consideration during hydrologic evaluation [2]
Low	• Adopt zero blockage for fish passage flow area design considerations. • Adopt ‘design’ blockage conditions for assessment of flood immunity of crossing.
Medium	• Adopt zero blockage for fish passage flow area design considerations. • Adopt ‘design’ blockage conditions for assessment of flood immunity of crossing. • Adopt ‘severe’ blockage conditions for the design and assessment of overtopping flood events.
High	• Adopt zero blockage for fish passage flow area design considerations. • Adopt ‘design’ blockage conditions for assessment of flood immunity of crossing. • Adopt ‘severe’ blockage conditions for the adopted major event (even if this discharge will not cause overtopping during ‘design’ blockage conditions). • Adopt ‘severe’ blockage conditions for the design and assessment of overtopping flood events.
Very high	• Adopt zero blockage for fish passage flow area design considerations. • Adopt ‘severe’ blockage conditions for assessment of flood immunity of crossing. • Adopt ‘severe’ blockage conditions for the adopted major event (even if this discharge will not cause overtopping during ‘design’ blockage conditions). • Adopt ‘severe’ blockage conditions for the design and assessment of overtopping flood events.

[1] Risk level based on the consequences resulting from **‘severe’** blockage of the structure.

[2] Provided recommendations are a guide only. Designers must assess appropriate hydraulic design procedures on a case-by-case basis, and where appropriate, adopt hydraulic design procedures different from those recommended above.

As previously discussed, it is considered inappropriate to assume severe blockage conditions exist at all culverts and/or bridges when performing most flood mapping exercises. Such widely distributed severe blockage conditions are most unlikely.

During the development of hydrologic models for the preparation of Master Drainage Plans or flood maps, designers should assume ‘design’ blockage conditions exist within the catchment. ‘Design’ blockage conditions should be determined separately for each type and location of structure based on an appropriate risk assessment procedure. Table 3.16 provides a guide for such blockage conditions.

Table 3.16: Suggested 'design' and 'severe' blockage conditions for various structures

Type of structure		Blockage conditions	
		Design blockage	**Severe blockage**
Pipe inlets and waterway culverts	*Inlet height < 3 m, or width < 5 m:*		
	Inlet	20%	100% [2]
	Chamber (culverts)	[1]	
	Inlet height > 3 m and width > 5 m:		
	Inlet	10%	25%
	Chamber (culverts)	[1]	[1]
	Culverts and pipe inlets with effective [6] debris control features	As above	As above
	Screened pipe and culvert inlets	50%	100%
Bridges	Clear opening height < 3 m	[3]	100%
	Clear opening height > 3 m	0%	[4]
	Central piers	[5]	[5]
Solid handrails and traffic barriers associated with bridges and culverts		100%	100%

[1] Adopt 25% bottom-up sediment blockage unless such blockage is unlikely to occur.

[2] Degree of blockage depends on availability of suitable 'bridging' matter. If a wide range of bridging matter is available within the catchment, such as large branches and fallen trees, then 100% blockage is possible for such culverts.

[3] Typical event blockage depends on risk of debris rafts and large floating debris.

[4] Blockage considerations are normally managed by assuming 100% blockage of handrails and traffic barriers, plus expected debris matter wrapped around central piers.

[5] Typical event blockage depends on risk of debris wrapped around central piers. The larger the piers, the lower the risk normally associated with debris wrapped around piers.

[6] Whether a control feature is "effective" is hard to define, though monitoring trial measures may give some guidance.

4. DESIGN AND ANALYSIS OF DRAINAGE SYSTEMS

4.1 OVERVIEW

The earlier sections of this report have outlined issues concerning blockage and indicated the possible implications for this on drainage systems. Therefore blockage should be accounted for in the design of new or refurbished drainage systems. An appropriate accounting for blockage within the design process will ensure that drainage systems convey design flows through the system at an accepted level of risk, and design flood levels are appropriate to that level of risk.

Overestimating the extent of blockage can be as damaging as underestimating blockage conditions. Overestimating blockages typically elevates upstream design flood levels, a result that may appear conservative, but can also result in higher modelled upstream flood storage and cause flow diversions. The end result can be underestimation of the design discharge and flood levels immediately and for some distance downstream of the blockage. Conversely, underestimating blockage conditions tends to understate upstream design flood levels while overstating discharges and flood levels at some other location.

During floods, culverts may remain clear or may be blocked to some extent. It is therefore necessary that design or analysis of a given probability flood event considers both the most likely blocked and the clear scenarios in determining discharges and flood levels of a comparable probability. Adopting blockage factors that are either too high or too low can both be a concern for design and operation of drainage systems.

In urban areas, setting of minimum floor levels and/or minimum fill levels for new developments are often closely linked to flood studies. Designers need to be aware of those circumstances where a minor variation in the likely level of blockage could result in an unacceptable increase in asset and property damage. In general, the design or analysis of drainage systems should appropriately consider the consequences of flows in excess of the design flow, and blockage conditions in excess of expected long-term averages. To maintain comparable levels of risk with respect to blockage, this consideration may lead to design in a low consequence (of blockage) environment being coupled to a lesser level of blockage and design in a high consequences (of blockage) environment being coupled to a higher level of blockage.

4.2 MAJOR/MINOR DRAINAGE SYSTEM

The procedures for planning and design of the major drainage system should account for the flow conveyed in the underground minor drainage system, and for the consequences of blockages in the system. It is also important to demonstrate that it is possible to design and construct an inlet system for the minor drainage network that can operate under appropriate levels of debris blockage, otherwise appropriate adjustments need to be made to the design discharge of the major drainage system.

The design of major underground pipe systems with no overland flow component should only be adopted where overland flow is either impracticable or unacceptable. Prior to adopting a major underground pipe system that does not incorporate an overland flow component, the planner or designer should consider the following:

- How design flows enter the underground drainage system under likely blockage conditions.
- Effects of flows in excess of the design flow, including the consequences of flows up to the Probable Maximum Flood (PMF).
- Management of debris blockages, including likelihood of pre- and post-storm maintenance.
- Impact on discharges and flood levels of debris blockages in excess of or less than that considered likely.

Each of the drainage system elements needs to consider this approach and the following sections provide guidelines for the assessment procedures required for each element.

4.3 ANALYSIS OF PAST SYSTEMS AND EVENTS

Existing and historic drainage systems need to be analysed for various reasons, perhaps to determine design flood levels for an existing system, or to analyse the performance of an existing or historic system during a past flood event for the purposes of assessing damage levels or to calibrate a hydraulic model. In analysing a historic event it is important to not only estimate the location and type of blockage that actually occurred, but also the likely timing and extent of the blockage. In the case of a porous plug blockage, an estimate of the porosity (and its variation over time) is also required. Given the considerable impact that error in these estimates can have on flows and levels, the correlation between modelled and recorded flows or levels will often be relatively poor. As previously noted, the actual blockage in a particular event may be different from the most likely design blockage, and may vary substantially from one event to another.

When analysing historical events, the timing of a flood level rise is often considered a critical aspect of model calibration. Modellers need to be aware that flood level rise, as recorded upstream of a bridge or culvert, can reflect both changes in discharge as well as changes in structure blockage. Useful information can sometimes be obtained from event records (i.e. requests to remove blockages) held by emergency services organisations and/or the asset manager.

5. PIT BLOCKAGE

5.1 PIT INLET CAPACITIES

The capacities of pit inlets to collect stormwater depend on the type and size of the inlet, and on other factors. The most common pit types are kerb inlets (side entry pits), grated pits, and combination kerb inlet and grated pits, illustrated in Photo 14. There are many variations on these, and other types of inlet are sometimes employed, such as end, slotted and culvert-type inlets.

Kerb Inlet, Grate and Combination Inlets

Direct Entry Pit, Channel Inlet and Culvert Type Inlet

Photo 14: Types of Pit Inlets

Capacities also depend on the location of a pit. Most inlet pits are located on a slope, in a street gutter or channel. Depending on their widths and velocities, flows can run over and around pits, so that all of the flow is not captured and a bypass flow occurs, as shown in Figure 5.1. The capacity of an on-grade pit therefore depends on the geometry of the road upstream of the pit, as well as the characteristics of the pit itself. There are also many locations where a barrier, usually the raised crown of a road, creates a pond over a pit in a depression or sag.

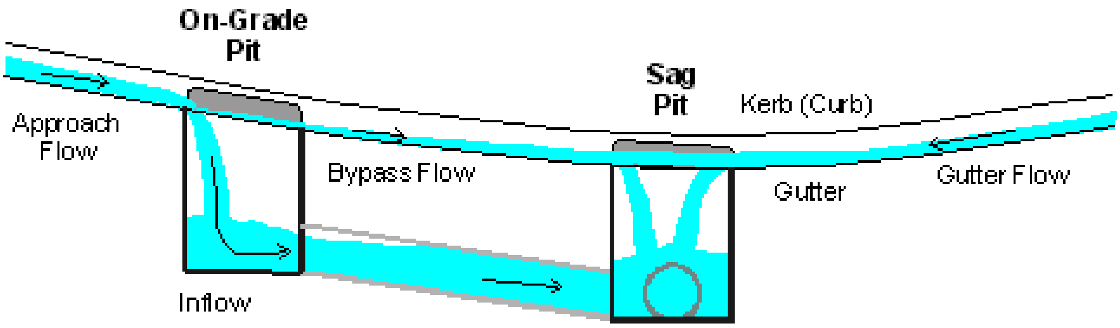

Figure 5.1: On-Grade and Sag Pits

The hydraulic behaviour of on-grade and sag pits is quite different. There is no simple theory for on-grade pits, and only one general procedure for determining inflow capacities has been published, the procedure in the US Federal Highway Administration's Hydraulic Engineering Circular 22 (2009). In most cases, however, inlet capacities have been developed experimentally using laboratory rigs such as those at Manly Hydraulics Laboratory, NSW, and at the University of South Australia. The relationships obtained from most tests do not extend far enough to model flowrates that may occur in extreme flood events such as 100 year ARI or probable maximum floods, so relationships must be extrapolated.

Sag pit inflows are governed by weir and orifice equations, depending on the depth of ponding. The weir equations apply to flows that enter the pit at its edges, or the edges of bars in a grate. The orifice equations apply to the available opening when a pit is fully submerged, usually at depths exceeding 0.2 m.

As the depth of ponding increases it eventually reaches a threshold level at which water will overflow from the ponded storage over a sag pit, passing over a 'weir' such as a road crown, driveway hump or wall. So both on-grade and sag pits can experience bypass flows.

Pit capacity relationships are available from road authority and council sources, such as those provided by VicRoads and Brisbane City Council, for example.

A 'generic' spreadsheet implementing the HEC 22 procedures is available from http://www.watercom.com.au/utilities.html and many inlet capacity relationships can be extracted from the demonstration version of the DRAINS program (www.watercom.com.au). The HEC 22 procedures should be used in preference to the sag pit Equations 14.5 to 14.8 in *Australian Rainfall and Runoff* (1987).

Inlet capacity relationships are an essential part of the design of piped drainage systems, because they determine the magnitudes of bypasses. Designers are concerned that flow widths and depths are within appropriate limits, both upstream and downstream of a pit. Widths may be limited to 2 to 2.5 m or one traffic lane at a 'minor' ARI of 5-10 years. Depths may be limited to kerb height, or to the height of a water-excluding hump on driveways, plus an appropriate freeboard. Velocities may also need to be limited, to keep depth × velocity within limits that are safe for vehicles and pedestrians, as recommended by Cox et al. (2010) and Shand et al. (2011). These factors can be controlled by locating pits at suitable places, and by limiting flowrates by providing inlets of sufficient sizes. Similar limits may also apply at a 'major' ARI of 50 or 100 years, in calculations that test the safe operation of the system under severe conditions.

Most authorities have a range of standard inlets of various sizes, for which capacity relationships are available, or can be estimated from the HEC 22 calculations. It is also possible to employ combinations of pits, such as two or three standard pits end-to-end. It usually is not possible to obtain accurate inflow capacity relationships for these.

5.2 PIT BLOCKAGES

Obviously, blockage or clogging (the term used in the US and Europe) will reduce the inlet capacity of pits and cause more water to flow on the surface that the designers of piped drainage systems intended. We have ample evidence that such blockages occur, and designers have allowed for this by applying blockage factors such as those recommended in *Australian Rainfall and Runoff* (Institution of Engineers, Australia, 1987) and the *Queensland Urban Drainage Manual*, 2008).

Photo 15 shows some examples of blocked sag pits. Instances of blocked on-grade pits are much harder to find.

Blockage is usually associated with the visible surface inlet, and this is assumed to be the hydraulic control that limits flows into the drainage system. However, blockage can also occur within pits and pipe systems, due to foreign objects (such as car engine blocks) being put into pits and to accumulations of sediment and debris.

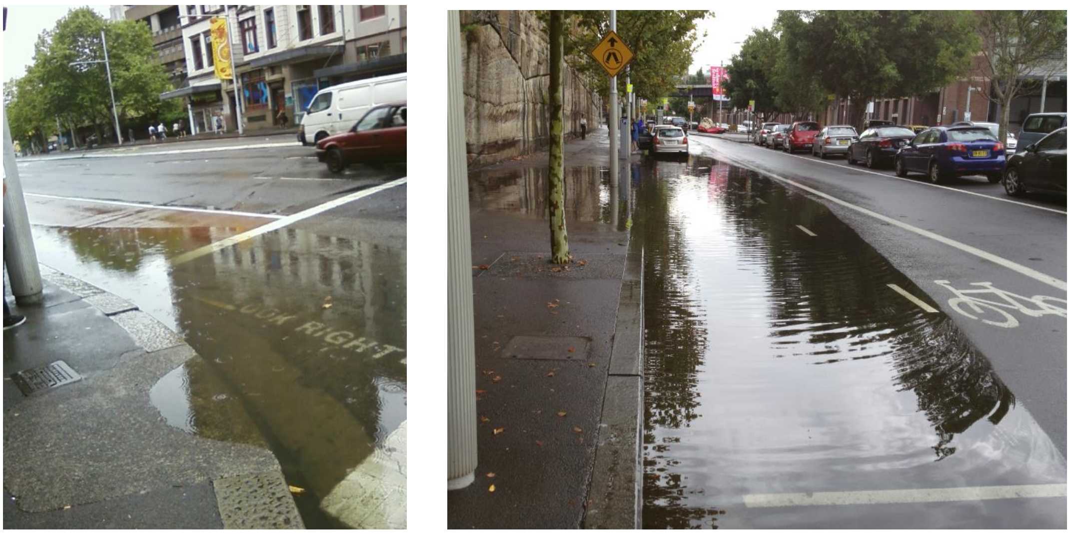

Photo 15: Water Ponding Over Blocked Sag Pits, Sydney 2012

The mechanisms that cause pit blockage have not been extensively researched. A recent, unpublished study from Spain found that grated pits can be blocked by an accretion of hard material on bars of grates and deposits of material such as leaves.

Some examples of these types of blockage are shown in Photo 16.

Photo 16: Examples of Pit Blockages, Sydney and Melbourne

Partial or full blockages can be caused by:

- accretion of road grit material,
- deposition of leaves, particularly in Autumn and after wind storms,
- litter,
- in larger rainstorms, gross material and sediments washed from rubbish bins, gardens and construction sites,
- other causes, such as vehicles parking over pits, malicious blockages and accidents.

A number of mechanisms might be involved. For kerb inlets, blocking mechanisms are likely to be similar to the ways in which culverts are blocked, with a large object bridging a gap, and smaller material lodging against this, possibly forming a mat.

The supply of blocking material is important. This will be greater than usual in:

- heavily-trafficked roads,
- areas with a large cover of deciduous or non-deciduous trees,
- heavily built up areas, with larger populations and larger amounts of rubbish,
- commercial areas with large litter-generation potential,
- industrial areas with outdoor materials storage and handling.

Mobility and transportation of blocking materials will be greater than usual in steeply-sloping catchments, and possibly, in those with high impervious area percentages.

Obviously, the size and type of the inlet will affect the blockage potential. From observations such as those shown in Photo 17, grates are more likely to block than kerb inlets, although clear grates have greater inlet capacities, in both on-grade and sag locations. If accumulations of debris like those in Photo 18 are large enough, kerb inlets can be blocked as well.

Photo 17: Examples of Grated Pit Blockages, Sydney

Photo 18: Examples of Kerb Inlet Pit Blockages, Sydney

In addition to environmental and physical factors, maintenance is a highly important factor in avoiding blockages, both on the surface and within pits and pipes.

In some cases, blockages may be deliberately induced, notably to prevent sediments from entering newly-constructed pits while construction works are still proceeding on land developments. Some examples are shown in Photo 19. These measures are commonly applied in new subdivisions, but are also implemented for individual infill developments in established areas, where the potential for damaging impacts due to deliberate blockage is higher.

Photo 19: Deliberate Blockages for Sediment and Erosion Control

The consequences of blocking pits in piped drainage networks are usually not severe. Some nuisance will be caused to traffic and pedestrians, but unless water enters properties, there will be no damage or risks to persons. However, there have been instances where blocked or undersized pits have caused water to enter houses and garages, causing significant damage.

Blockages will also divert bypassing flows to other parts of a piped drainage network, causing it to operate differently from the designer's assumptions. Downstream pits may be 'overloaded', receiving greater flowrates than intended. Unless a designer has the resources to examine many scenarios, the possibility of blockages will make the outcomes of simulations more uncertain. This will result in more conservative designs.

5.3 PITS IN OPEN AREAS

In addition to locations on streets, pits are often used to drain open areas such as parklands, as shown in Photo 19A. While there is usually considerable debris in such areas, the consequences of flooding are usually small.

Photo 19A 'Letter Box' Pits in an Open Area and a Bioretention System

5.4 PITS IN STORMWATER TREATMENT AND WATER-HARVESTING SYSTEMS

Pits are used as components in stormwater treatment systems. For example, grated, raised pits are commonly used as overflow and inspection devices in bioretention basins. Design procedures such as those developed by the Queensland Healthy Waterways – Water by Design organisations deal adequately with potential blockage issues from loose material.

5.5 PIPE BLOCKAGES

There is evidence that blockages can also occur in pipes as well as pits. These may be due to sediments or to objects washed into pipes. Photo 20 shows the effects of a blockage observed at Penshurst, NSW. Water formed a pond over a sag pit, affecting traffic and potentially entering an adjoining property. The problem was traced to the pipe system, and material was removed from the next pit downstream of the sag pit.

Photo 20: Pipe Blockage Incident, Penshurst, June 2009

Little is known about the incidence of such events, as councils and road authorities operate individual recording systems, of varying degrees of detail.

There is little literature on stormwater drainage system asset management, with the main Australian example being the paper by Coombes et al. (2002), which does not expressly deal with blockages. There have been studies of chokes or blockages in sanitary sewer systems and occasionally in stormwater systems, such as that by Tran et al. (2006), but these are mainly concerned with the prediction and control of chokes using mathematical optimisation techniques.

5.6 SURVEYS

Two attempts have been made to obtain, through surveys, information on pit blockages, in tandem with a survey on culvert blockages, but only a few responses were obtained from industry. These were of good quality and provided new information, but the overall data obtained were insufficient to make definite conclusions.

5.7 PIT BLOCKING FACTORS

Blocking or clogging factors are usually applied as a multiplier F_b, between 0.0 and 1.0, in the equation:

$$Q_{in,adj} = F_p.Q_{in} \qquad \text{… (5.1)}$$

where $Q_{in,adj}$ is the adjusted inlet capacity of the pit (m^3/s),

F_p is the factor, representing the proportion or fraction of the inflow that is not blocked, and

Q_{in} is the inlet capacity estimated from the pit inlet capacity relationship being used (m^3/s).

Some other forms of factor may also be used. If F_b is the proportion of the inflow that is blocked, then $F_p = (1 – F_b)$. A divisor $D_p = 1/F_p$ is also used. F_p and F_b may also be expressed as percentages. With these alternatives, care needs to be taken when specifying and interpreting blockage factors.

In Australian practice, there is little formal guidance on suitable factors. *Australian Rainfall and Runoff* (1987) stated that:

> In major flow calculations, it may be inappropriate to employ the usual pit entry capacity relationships. Extraordinary flow depths, velocities and debris loads will occur. It is likely that pit entry capacities will be reduced. In the absence of observations or experimental results, choke factors of 0.5 for sag pits and 0.8 for pits on grade are tentatively recommended, reducing inlet capacities to 50% to 80% of those normally adopted.

and the 1992 and 2008 versions of the *Queensland Urban Drainage Manual* state:

7.05.2 Provision for blockage

Local authorities may indicate the percentage of blockage that is to be applied to the theoretical inflow capacity of inlets.

Where such guidance is not provided the recommendations in Table 7.05.1 should be adopted. Where the invert of the kerb is depressed at the inlet the capacity of the inlet should be adjusted accordingly.

Table 7.05.1 Provision for blockage at kerb inlets [1]

Condition	Inlet Type	Percentage of Theoretical Capacity Allowed
Sag	Kerb inlet	80%
	Grated	50%
	Combination	[2]
Continuous Grade (On-Grade)	Kerb inlet	80%
	Longitudinal bar grated	60%
	Transverse bar grate or longitudinal bar grate incorporating transverse bars	50%
	Combination	90% [3]

Notes:

[1] This table does not prevent local authorities from setting alternative blockage factors for site specific inlet designs.

[2] In a sag the capacity of a combination inlet should be taken to be the theoretical capacity of the kerb opening, the grate being assumed to be blocked.

[3] On a continuous grade the capacity of a combination inlet should be taken to be 90% of the combined theoretical capacity of the grate plus kerb opening.

Blocking factors are incorporated into the pit inlet capacity relationships provided a standard drawings by the Brisbane City Council. Relationships provided by other councils and by road authorities do not usually include allowances for blockage, but it is advisable for designers to check for this.

Similar, but less definite relationships are proposed in US practice. The Denver Urban Drainage and Flood Control District *Urban Storm Drainage Criteria Manual* (2001) states:

3.3.6 Inlet Clogging

Inlets are subject to clogging effects (see Photographs ST-5 and ST-6). Selection of a clogging factor reflects the condition of debris and trash on the street. During a storm event, street inlets are usually loaded with debris by the first-flush runoff volume. As a common practice for street drainage, 50% clogging is considered for the design of a single grate inlet and 10% clogging is considered for a single curb-opening inlet. Often, it takes multiple units to collect the stormwater on the street. Since the amount of debris is largely associated with the first-flush volume in a storm event, the clogging factor applied to a multiple-unit street inlet should be decreased with respect to the length of the inlet. Linearly applying a single-unit clogging factor to a multiple-unit inlet leads to an excessive increase in length. For instance, a six-unit inlet under a 50% clogging factor will function as a three-unit inlet. In fact, continuously applying a 50% reduction to the discharge on the street will always leave 50% of the residual flow on the street. This means that the inlet will never reach a 100% capture and leads to unnecessarily long inlets.

It then presents procedures developed by Guo (2000, 2006) that allow for clogging of pits made up of multiple units joined together.

The US FHWA HEC 22 manual (2009) makes no exact recommendations, but a 50% clogging factor is used for sags. The manual is vague about on-grade pits.

The California Department of Transportation *Highway Design Manual* (2009) states, on page 830-16, that for sag pits:

> The HEC 22 charts neglect the effects of debris and clogging on inlet capacity. In some localities inlet clogging from debris is extensive, while in other locations clogging is negligible. Local experience should dictate the magnitude of the clogging factor, if any, to be applied. In the absence of local experience, design clogging factors of 33 percent for freeways and 50 percent for city streets may be assumed.

No allowance is recommended for on-grade inlets or kerb inlets, but a 50% factor may be applied to grates with closely-spaced bars for safety of bicycles.

Little information is available from UK practice.

The Hong Kong Government (1994) used the following inflow reduction factors for blockage of pits by debris, based on UK research:

Roads / Road Sections	RF_{debris}
Expressways	
longitudinal gradient less than 0.5% & near sag points	10%
other sections	0%
Other Roads	
longitudinal gradient less than 0.5%	15%
longitudinal gradient 0.5% or more	10%
near sag points or blockage blackspot, e.g. streets with markets or hawkers	20% or more

It appears that there is a movement towards more exact estimates of blockage factors, but that information is still lacking and guidance is vague.

The only field surveys of the effects of blockage appears to be those carried out recently in Spain, and not yet published. Almedeij et al (2006) have analysed effects of clogging factors on pit capacities in Kuwait.

Laboratory tests on blockages have been carried out by Despotovic et al. (2005) and by Spanish researchers. These were on grates that differ from those commonly used in Australia, but the indicative results are interesting. Covering of on-grade grates will significantly reduce capacities, as shown in the diagram in Figure 5.2.

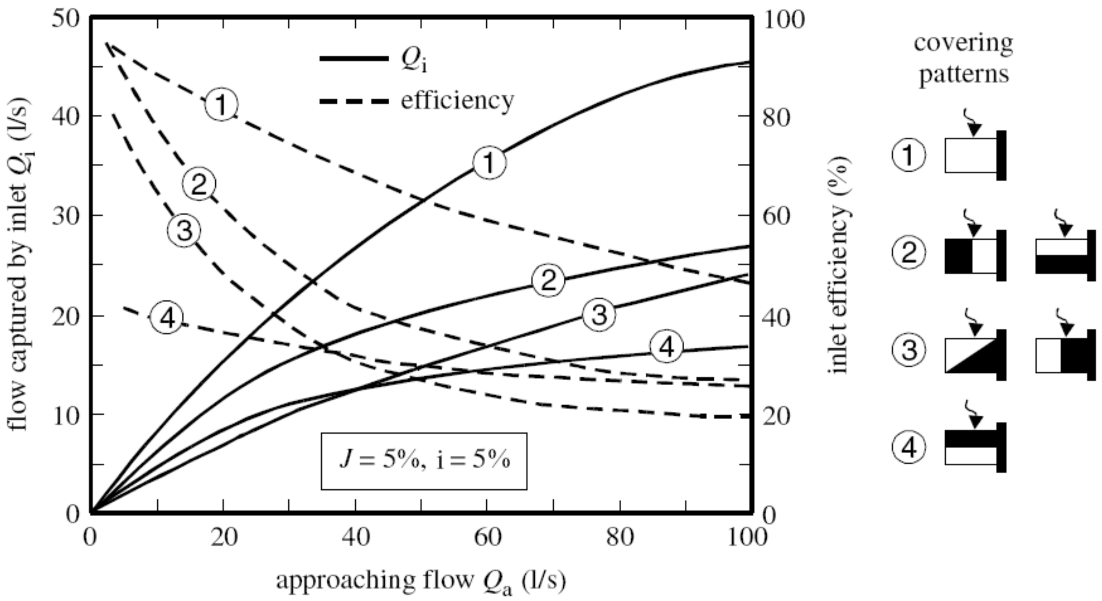

Figure 5.2: Effects of Clogging of On-Grade Grated Pits (Despotovic et al., 2005

Laboratory tests on debris were also conducted as part of the US Federal Highway Administration *Bicycle-Safe Grate Inlets Study* (Burgi and Gober, 1977). However, the emphasis was not on loss of capacity due to blockages, but on the tendency of debris to cling to grates rather than to be washed into pits or to be swept away with bypass flows. Debris handling efficiency was measured as the proportion of 150 paper ‘leaves’ that clung to the bars of grates during tests of given durations. Grates with widely-spaced bars performed better than those with close spacings.

There is scope for further research into aspects such as the applicability of a simple multiplier. This may be appropriate for a grated pit in a sag, where the grate can be physically covered by leaves or a cardboard box. However, the blockage of an on-grade kerb inlet will be more complex, and a simple multiplier will probably be inappropriate. The blockage factor is likely to be progressive, being lower for small approach flowrates and then increasing with flows up to a given flowrate. Supposing that a blocking factor F_o applies at a flowrate Q_o and at higher rates. Assuming a straight-line relationship, the on-grade relationship, illustrated in Figure 5.3, will be:

$$Q_{in,adj} = [1 + (F_o - 1).Q_{in}/Q_o] \,.\, Q_{in} \qquad \text{where } Q_{in} < Q_o$$

$$= F_o \,.\, Q_{in} \qquad \text{where } Q_{in} \geq Q_o \qquad \ldots (5.2)$$

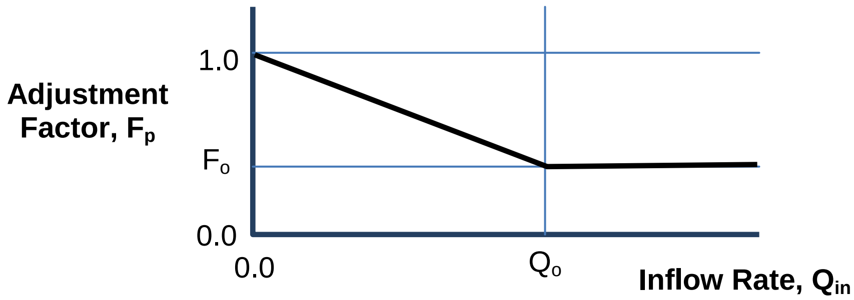

Figure 5.3 Progressive Blockage Factor for an On-Grade Kerb Inlet

The likely progressive relationships for Australian pits are unknown.

5.8 BLOCKAGE MANAGEMENT FOR PIPED DRAINAGE SYSTEMS

5.8.1 Design of New Systems

Authorities responsible for assessing designs need to establish general blocking factors applying to on-grade and sag pits, while allowing designers the scope to vary these in circumstances where special conditions apply. Since designers tend to be cautious, it is unlikely that they will adopt less-conservative factors than the standard ones.

There is little available evidence at this stage to go beyond the advice provided in current manuals, although this may change with research findings. The advice in *Australian Rainfall and Runoff* 1987 to use a blockage factor F_p = 0.8 for on-grade pits and 0.5 for sag pits was based on perceptions in the 1980s. The author of this advice now recommends a F_p = 1.0 zero-blockage for on-grade pits with kerb inlets, as he has seen little evidence of blockage of such pits. He would retain the F_p values of 0.8 for on-grade grates and 0.5 for all types of sag pit.

These estimates are less conservative than the values in the *Queensland Urban Drainage Manual* (2008), which recommends F_p = 0.8 (20% blockage) for on-grade kerb slot inlets, and 0.5-0.6 for grates, depending whether bars are longitudinal or transverse. For on-grade combination pits, the following instruction applies "On a continuous grade the capacity of a combination inlet should be taken to be 90% of the combined theoretical capacity of the grate plus kerb opening."

For sag pits, the *Queensland Urban Drainage Manual* (2008) recommends that a blockage factor F_p = 0.8 for kerb inlets and 0.5 for grates. For combination inlets, the following provision applies: "In a sag the capacity of a combination inlet should be taken to be the theoretical capacity of the kerb opening, the grate being assumed to be blocked."

The *Queensland Urban Drainage Manual* recommendations are accepted in Table 7.1 of this report. The authors of the original 1992 *Queensland Urban Drainage Manual* indicated that the estimates were derived from observations of blockages, particularly those caused by fallen leaves, and a literature review.

More work and debate needs to be conducted to resolve differences and to come up with a definitive set of recommendations. Until then, authorities will probably follow their current guidelines with are usually based on the parts of *Australian Rainfall and Runoff* (1987) and the *Queensland Urban Drainage Manual (2008).*

Designers need to identify locations where the risks of blockage are greater than normal, and to apply higher blocking factors at these locations. This might be done subjectively, with limited documentation, or a cut-down version of Schemes A or B in Sections 4.4 and 4.5 might be applied. In most cases, elaborate methods will not be appropriate because designers of most greenfield subdivisions have incomplete knowledge of the exact building development that will occur once a subdivision is completed. Exceptions may occur where it is known that a specific property may house vulnerable persons or activities, such as schools, aged persons' homes and police stations.

In such situations, blockage prevention and the management of overflows from pits should be addressed in detail. Some drainage authorities have applied requirements for overflow paths located above pipelines that might block, where the overflows pass through properties rather than run along roadways. For example, a flow path may need to carry the greater of:

(a) overflow that will occur in 100 year ARI storms, assuming that upstream inlets are clear,

(b) overflow that will occur in 5 year ARI storms, assuming that upstream inlets are completely blocked.

These are usually applied on an arbitrary basis, and it is desirable that requirements of this type be assessed in order to develop consistent, widely-applicable requirements.

(In the future, pipe system designs and analyses may be carried out using Monte Carlo analysis, with hundreds of sets of rainfall-runoff calculations being performed with randomly-generated design storms. The results would be assessed statistically, from this large sample of possible ‘futures’. In such circumstances, blockage factors might also be randomly generated from an assumed probability distribution based on observations of the incidence of blockages. The sheer number of simulations performed in such an analysis would ensure that critical combinations of events would be identified.)

5.8.2 Analysis of Existing Systems

The purposes of an analysis of an existing piped drainage system are usually to define current flood hazards, and to explore remedies for these. Under these circumstances, blocking factors need to be realistic and not conservative. Because pipe systems are interconnected networks of surface and pipe flows, high blockage factors will create higher than average flows in one part of a network, but will also cause lower than average flows in other parts. (This is not such a problem in greenfield design, because pipes can be sized according to the expected flows, although there will be some overdesign.)

With existing systems, the analyst would be aware of particularly vulnerable properties and would have some records of flooding complaints.

5.8.3 Asset Management

Many instances of poor maintenance have been observed, as shown in Photo 21. Drainage authorities need to operate appropriate asset management programs, ensuring that pits are regularly cleaned.

Photo 21: Poor Pit Maintenance

5.9 RESEARCH NEEDS

As with all aspects of blockage, hard information is lacking on pit blockage or clogging. Guidance on blocking factors is available from manuals but this is sometimes contradictory, and needs to be re-assessed by a panel of experienced engineers to achieve a consensus position. The differences between kerb inlet, grate and combination inlets need to be considered. For combination inlets it may be appropriate to apply different blockage factors to the kerb inlet and grate components.

The form of blocking factors needs to be considered. For kerb inlets a simple multiplier is probably simplistic, and a variable factor such as that proposed in Equation 5.2 is probably appropriate. The matter can be settled fairly simply by commissioning tests typical Australian pits using the laboratory rigs available in Australia.

Finally, a more comprehensive and well-publicised survey needs to be made on the experience of engineers and technologists with blockage, possibly combined with the release of this Stage 2 Report on Blockage of Hydraulic Structures. This will yield new material relevant to design and analysis, but more importantly, it will provide information relevant to maintenance and blockage mechanisms and consequences, which is limited at present.

6. MANAGEMENT OF BLOCKAGE

6.1 INTRODUCTION

There are a number of approaches to the management of structure blockages and the possible impacts these blockages can have on drainage and flooding. As in many aspects of engineering, the various management options can be classified into the following basic groups:

(a) Avoid the problem. These options do not alter the problem or the outcomes, but focus on avoiding any potential outcomes. Such management options include:

- Avoiding or at least minimising the placement of structures in locations where blockages could occur—an option not often practicable for culverts and bridges.
- Retro-fitting existing structures to minimise the risk of blockages occurring.
- Appropriate town planning that locates public and private assets away from floodplains and other regions where blockage issues exist.

(b) Defuse the problem. These options focus on modifying the problem, not the outcomes. Such management options include:

- The removal or at least minimisation of potential sources of blockage matter, such as the removal of loose woody matter from streams, preventing the storage of floatable objects within floodplains and overland flow paths, and the minimisation of gully and channel erosion within regions likely to supply excessive sediment, cobbles and boulders.
- Installing debris collection structures than help to minimise the delivery of blockage matter to downstream hydraulic structures.
- Maintaining hydraulic structures such that ongoing sedimentation is managed to acceptable levels and debris blockages are promptly removed after each event.
- Educating the community to minimise their contribution to the supply of blockage matter.

(c) Control the outcomes to an acceptable level. These options focus on modifying the outcomes not the problem. Such management options include:

- Designing hydraulic structures with an appropriate allowance for blockage.
- Providing counter measures such as debris deflectors, screens or racks.
- Retro-fitting existing structures to either minimise the risk of blockage and/or control any adverse outcomes.
- Installing adequate flow bypass systems to allow the structure as a whole to function even when substantial blockages occur.

(d) Learn to live with the problem. Such management options include the ‘do nothing’ approach and aspects of community education. In some regions of Australia debris blockages are not recognised as a significant social or economic issue. Continuing maintenance may be necessary in these situations.

This section discusses the above management options commencing with the design of new structures, the retro-fitting of existing structures, the use of debris control structures, debris reduction programs, community education and finally structure maintenance.

6.2 DESIGN CONSIDERATIONS

6.2.1 Introduction

The likelihood and impacts of blockages can be reduced through appropriate planning and design of hydraulic structures. The following section outlines a range of recommendations that should be given appropriate consideration during the planning and design of hydraulic structures.

6.2.2 All hydraulic structures

The appropriate consideration of maintenance issues is an important aspect of engineering design. Such consideration includes:

- Designing to minimise the need for and cost of maintenance.
- Designing maintenance procedures to be compatible with the personnel and equipment available.
- Provision of safe and functional access to perform necessary maintenance, including site inspections.
- Providing any site specific maintenance requirements or procedures to maintenance personnel.

Further design issues relating to structure maintenance are discussed later in Section 6.7.

6.2.3 Stormwater inlets

Stormwater inlets are especially prone to blockage and there are several ways that this can be managed. If the inlet is screened, then the likelihood of blockage increases significantly. In such cases, the adverse effects of debris blockages can be reduced by:

- Increasing the effective flow area of the screen to reduce the risk that blockages will reduce the capacity of the inlet to less than the capacity of the downstream drainage system.
- Incorporate maximum 150 mm wide clear slots around the base of the screen.
- Integrating the inlet debris screen with the functions of a safety fence/screen set well back from the inlet (Photo 22).

- Incorporating a safety screen separate to the inlet debris screen—the aim of in this option is to capture most of the debris at the safety screen which is set well back from the inlet screen (Photo 23).

Photo 22: Combined debris and safety screen surrounding a field inlet

Photo 23: Safety screen surrounding screened detention basin outlet

To avoid confusion within the industry, inflow capacity (design) charts for stormwater inlets should reflect the theoretical or measured capacity of the inlet (i.e. zero blockage condition), to which appropriate blockage factors may be applied. The effects of blockage should not be included within these design charts. In the design of stormwater inlets, suggested design blockage conditions are presented in Table 3.16.

Photo 24: Dome inlet screen with minor blockage

Photo 25: Horizontal screened field inlet with scour control concrete lip

At field (drop) inlets, the impacts of debris blockage can be delayed, if not reduced, through the adoption of 'dome' screens (Photo 24) instead of the more traditional horizontal screens. Also, the concrete lip formed around field inlets should have sufficient width to minimise the risk of grass growing over the grate, or causing blockage of the grate (Photo 25).

6.2.4 Stormwater outlets

Blockages of stormwater outlets are normally associated with one or more of the following occurrences:

- Sediment deposition, resulting from sediment passing through the pipe (Photo 4), sediment passing down the receiving waterway, or sediment entering the pipe through tidal action.
- The establishment of thick vegetation blocking the free discharge of stormwater from the pipe.
- Progressive blockage of a gross pollutant trap established at or near the outlet.
- Blockage of an outlet screen (Photo 2).

Screens are increasingly being placed on stormwater outlets to prevent public access. While this may be part of a risk minimisation strategy, it should be noted that such screens should not be installed unless the accidental entry of persons into the upstream stormwater network during storm events can be prevented.

Design considerations include the following:

- To minimise sedimentation in pipes, a minimum 1 year ARI flow velocity of 1.2 m/s.
- Elevating the outlet may reduce the risk of sediment blockages associated with sediment passing down the receiving waterway, and also allow maintenance inspection of the pipe; however, such pipe elevation should not be allowed to cause excessive erosion.
- Use of flap-gates or similar to prevent the intrusion of salt water and/or sediment into the pipe. In coastal regions, these flap-gates may need to be located within the first access chamber set back from the beach to protect its operation from vandalism, wave attack, debris and sand blockage. Alternatively flap-gates may need to be located at the end of the pipes for ease of maintenance.
- Stormwater outlets discharging to grass-lined swales/channels should have an invert level at least 50 mm above the design invert of the outlet channel, or as appropriate, to allow for expected sedimentation and grass growth without causing either blockage of the outlet or water to pond within the pipe.
- Stormwater outlets discharging to open channels should consider the likelihood of blockage of the outlet by heavy reed growth within the outlet channel. Where appropriate, consideration may need to be given to the inclusion of an elevated, dry, bypass channel that is not susceptible to reed growth. Typically, reed growth is not expected to cause significant backwater problems when the discharging pipe has a diameter of 1200 mm or greater.
- Outlet screens should not be used in circumstances where an unauthorised person could either enter, or be swept into, the upstream pipe network.

- Under normal circumstances, 100% blockage of outlet screens should be assumed during the design storm, thus 100% flow bypassing should be accounted for in the design of the major drainage system.
- Outlet screens should be structurally designed to break away under the conditions of 50% blockage (or lower if needed to prevent undesirable backwater flooding) during the pipe's design storm event.
- Outlet screens on pipe/box units up to 1800 mm in width should be designed such that the full width of the outfall pipe/box can be accessed for periodic maintenance.
- Consideration should be given to the use of top hinged outlet screens installed at an angle (say, 10 degrees to the vertical) to restrict unauthorised entry, but allow the passage of water during conditions of significant debris blockage.
- Prior to incorporating a surcharge chamber into a drainage line, the following should be considered:

(i) Potential surcharge of the upstream system and resulting flooding problems caused by blockage of the outlet screen.

(ii) Safe maintenance access to allow removal of debris trapped within the surcharge chamber.

6.2.5 Detention/retention basins

Most of the design considerations previously presented for stormwater inlets (Section 5.2.3) also apply to the outlets of detention/retention basins. Appropriate consideration should also be given to the following issues and recommendations:

- Detention/retention basin outlet structures (Photo 19) should be protected against expected debris blockages, and appropriately designed to minimise safety risks to persons swept toward the outlet structure during flood events.
- The degree of protection must commensurate with the consequences of failure caused by such blockages, and the estimated blockage frequency.
- Consideration should be given to the consequences of a fully blocked low-level outlet structure during the designated minor storm.
- Best results are often achieved when the debris control trash racks are separated from the safety control screens (Photo 23). This allows both the trash rack and safety screen to be designed for the optimum location, size and bar spacing.
- Debris screens placed on basin outlets are typically required to satisfy the following design outcomes: restriction of debris entry into the conduit, and prevention of the total collapse of the debris screen while under heavy debris loading. The latter design outcome helps in the

post flood drainage of the basin. Without such structural integrity, the debris screen and the associated debris can enter the outlet conduit making maintenance and basin de-watering difficult.

- The design of debris screens must take appropriate consideration of the maintenance equipment likely to be available to the asset owner.
- Trash racks should be large enough that their partial blockage will not adversely restrict flows reaching the outlet control device. Typically the trash rack area should be at least 10 times larger than the control outlet orifice.
- The use of inclined vertical bar rack is most effective for the lower stage outlets. Such rack designs allow the removal of accumulated debris with a rake while standing on top of the structure. Cage type racks or racks with horizontal members generally inhibit this type of debris removal.
- The spacing of trash rack bars must be proportioned to the size of the smallest outlet protected. This may require the use of a separate, close bar-spaced rack in front of the smaller outlets.
- To facilitate removal of accumulated debris and sediment from around the outlet structure, the trash racks should have hinged connections wherever practicable.
- To avoid sediment blockage and sediment entrainment into the lowest staged water quality outlet, the outlet chamber (i.e. the chamber invert between the flow control orifice and the entrance to the primary outflow pipe) should be recessed below the lowest outlet a distance at least equal to the diameter of the outlet.
- Wherever practicable, trash racks and bar screens should be designed to shed debris and assist the egress of persons trapped in the basin. Guidelines on the design of trash racks and bar screens that allow the egress of persons are provided by the Queensland Department of Natural Resources (2007).

6.2.6 On-site detention (OSD) systems

In additions to the design considerations presented for stormwater inlets (Section 6.2.3) and detention/retention basins (Section 6.2.5) the following issues and recommendations also apply to the outlets of on-site detention systems.

- Best self-cleaning effects are created when the length of the pit containing the outlet control orifice and debris screen (measured from the screen to the rear wall) is made only just large enough to incorporate the inlet pipe (entering tangential to the screen).
- The available screen area should be as large as possible in order to prevent blockage.
- The inflow pipe should enter the pit at 90 degrees to the direction of outflow through the orifice and tangential to the screen.

- Self-cleaning is improved if surface inflow (inflow via screened drip pit) falls directly onto an inclined, vertically slotted, screen (Photo 27).

Photo 26: Detention basin outlet chamber

Photo 27: Outlet screen of an on-site detention pit viewed from the screened surface inlet (visible in reflection)

6.2.7 Watercourse crossings

Even though causeways and ford crossings can be subject to blockage issues, by far the greatest attention is given to the management of blockages at culvert and bridge crossings.

To minimise the adverse impacts of debris blockages on bridges the following design considerations should be given appropriate consideration:

- Minimise the number of instream piers.
- Minimise the exposure of services (i.e. water supply pipelines) on the upstream side of the bridge, and/or minimise the likelihood of debris being captured on exposed services.

To minimise the effects of debris blockage on culverts the following design consideration should be noted:

- Take all reasonable and practicable measures to maximise the clear height of the culvert, even if this results in the culvert's hydraulic capacity exceeding the design standard. This minimises the likelihood of debris being caught between the water surface and obvert, and also minimises the risk of a person drowning if swept through the culvert (i.e. the culvert is more likely to be operating in a partially full condition).
- The risk of debris blockage can also be reduced by using single-cell culverts, or in the case of floodplain culverts, spacing individual culvert cells such that they effectively operate as single-cell culverts without a common wall/leg (Photos 29 and 29).

Photo 28: Series of floodplain culverts

Photo 29: Floodplain culvert

- One means of maintaining the hydraulic capacity of culverts in high debris streams is to construct debris deflector walls (1V:2H) as shown in Figure 6.1 and Photo 29. The purpose of these walls is to allow the debris that normally collects around the central leg to rise with the flood, thus maintaining a relatively clear flow path under the debris. Following the flood peak, the bulk of the debris rests at the top of the deflector wall allowing easier removal (Photo 31).

Photo 30: Debris deflector walls

Photo 31: Post flood collection of debris on top of deflector walls

- Sedimentation problems within culverts may be managed using one or more of the following activities:
  - Formation of an in-stream sedimentation pond upstream of the culvert.
  - Formation of a multi-cell culvert with variable invert levels such that the profile of the base slab simulates the *natural* cross section of the channel (Photo 32).
  - Installation of *sediment training walls* on the culvert inlet (Figure 6.1 and Photo 33). Sediment training walls reduce the risk of sedimentation of the outer cells by restricting minor flows to just one or two cells.

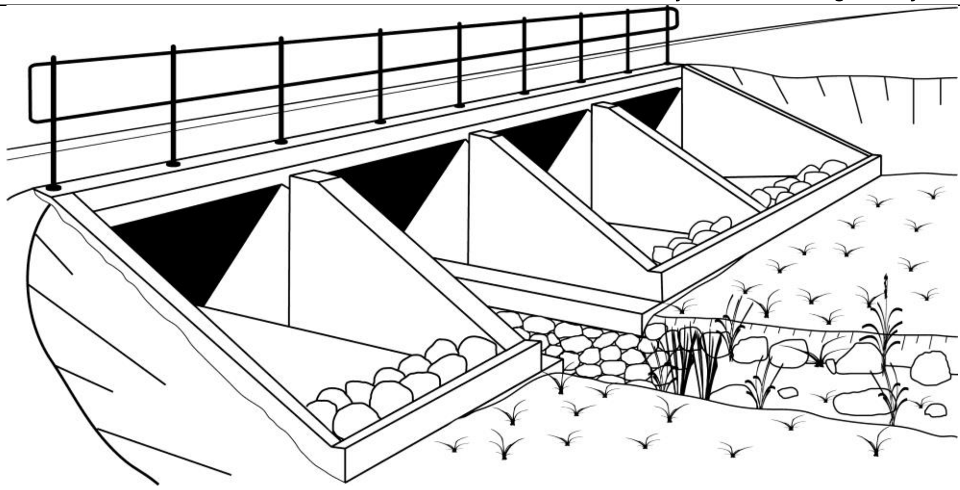

Figure 6.1: Sediment training walls incorporated with debris deflector walls (Catchments & Creeks Pty Ltd)

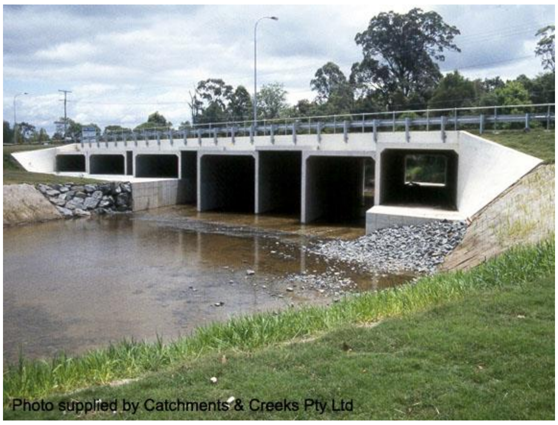

Photo 32: Multi-cell culvert with different invert levels

Photo 33: Debris deflector walls and sediment training wall added to existing culvert

- Where space allows, a viable alternative to increased culvert capacity (in response to the effects of debris blockage) may be to lengthen the roadway subject to overflow (i.e. the effective causeway weir length).
- Where high levels of floating debris are present and frequently become trapped on hand rails, collapsible hand rails may be considered. Such systems typically include pins or bolts designed to fail when water becomes backed up by the handrails and therefore require ongoing maintenance. If to be used as traffic barriers, the downstream rail fixing can be problematic. They can however limit rises in floodwater levels upstream of the structure.

6.3 RETRO-FITTING EXISTING STRUCTURES

Structures can be modified to allow debris to be directed through the structure with a reduced risk of blockage. These modifications can include improved inlet performance through the use of debris deflection walls and/or sediment training walls (Photo 31) or an increase in the size of the structure.

6.4 DEBRIS CONTROL STRUCTURES

Debris control structures are structural measures provided in a watercourse or immediately upstream of critical structures to collect debris before it reaches the structure and causes problems. These can be (a) fences, posts or rails providing a much larger 'interception area' for debris than a pipe or culvert entrance, (b) storages or dry basins in which boulders or other debris can collect as on the Hobart Rivulet, or (c) diversion structures designed to provide safe bypass of debris or water. Such structures can occasionally be incorporated into a water quality management plan for a catchment.

6.5 DEBRIS REDUCTION PROGRAMMES

Woody debris can be generated by a variety of sourced, including tree poisoning, gully erosion and natural regeneration processes. Preliminary evidence suggests that a significant proportion of the woody debris that passed through Queanbeyan during the November 2010 flood was generated by the willow eradication program previously conducted within the upstream catchment. Snag removal is a controversial issue that requires the generation of a well-researched management plan, but authorities should be allowed to collect and remove woody debris associated with weed eradication programs.

While debris reduction programs may be difficult to implement, the reduction of the source of blockage material is an excellent means of reducing the damage and inconvenience caused by blockage of hydraulic structures. This can be implemented in catchment management plans that include specific measures to reduce the sourcing of problem debris. Debris reduction programs can be implemented in conjunction with community awareness programs.

In addition to debris reduction programs, steps can be taken to reduce the 'accelerated' supply of sediment, gravels and boulders. Management programs can include:

- Minimising the risk of accelerated channel erosion by minimising changes to the frequency, duration and peak discharge of flows released from modified catchments.
- Replenishing previously lost vegetation from the tops of catchments and riparian areas.
- Implementation and policing of effective erosion and sediment control programs within developing catchments.
- Formation of permanent in-stream sediment collection and extraction points to manage excessive sediment loads already contained within degraded waterways (such practices have several adverse side effects that generally make this option one of last resort).

6.6 COMMUNITY AWARENESS

Education awareness programs can be implemented in conjunction with planning procedures to ensure that the community is aware of the risk and consequences of debris movement in watercourses and how they can take active measures to reduce the potential supply of woody and urban debris.

6.7 MAINTENANCE OPTIONS

6.7.1 Introduction

The likelihood and impacts of blockages can in some cases be reduced through appropriate maintenance of hydraulic structures. The following section outlines a range of recommendations relating to the maintenance of hydraulic structures.

Maintenance is necessary to reduce the impact of blockages in stormwater drainage. When designing for maintenance the following essential criteria must be considered.

(a) Whole of life costs

When comparing alternatives for structures, whole of life costs must be compared rather than just the initial costs. Whole of life costs include maintenance and replacement cost over the anticipated life of the structure.

(b) Physical access

Access to the structure must be provided for maintenance purposes. Such access must provide for the most efficient way of maintaining the structure. This may include all-weather roads or tracks to access the structure with trucks, 'bob cats' or other equipment to maintain the structure and remove collected material. The grade and width of access tracks must be appropriate for the equipment used and the likely conditions it is used in.

(c) Legal access

Local authorities require the legal right to access waterway structures and maintain them. This can be achieved by appropriate easements, including drainage easements and access easements from public roads.

(d) Workplace health and safety

An understanding of workplace health and safety laws and the reasons for them is essential when designing for maintenance. The laws restrict the size and weight of grates, height of access walkways, depths of manholes etc. A maintenance plan will be rendered inoperable if it contravenes relevant state or territory workplace health and safety acts.

(e) Frequency and trigger points for maintenance

A maintenance plan should be developed at the design stage to guide maintenance personnel with regard to both the essential and desirable works. The timing and frequency of the maintenance work is an important part of the maintenance plan. The plan should provide sufficient information to help in the estimation of maintenance costs. It is also important that procedures are put in place to ensure that such plans are made available to the asset managers and not just archived with the design files.

(f) Unintended risks to children and others

Water courses attract children and hydraulic structures can challenge children, so this must be taken into account when designing stormwater structures. The location of the structure, the anticipated age of the children, the likelihood of adult supervision, and the possible consequences of an accident are other factors that must be taken into account when considering the design and maintenance of waterway structures.

(g) Design life and replacement of structures

Water course structures often consist of components with limited lives. The appropriate replacement of these components must be taken into account at the design stage. The structure must be able to be replaced in the future without causing inordinate disruption and expense.

(h) Environmental issues

In important fish habitats, the prompt removal of bed-level debris blockage can be essential in maintaining fish passage along the waterway. Such debris blockages may appear insignificant from a flood control perspective (Photo 4), but can be critical in the sustainable management of aquatic habitats.

(i) Design for the local environment

It is always important to design hydraulic structures for the local conditions, rather than the 'blind' adoption of standard drawings or universal solutions. In some cases this may require the development of non-standard solutions that reflect either the unique knowledge or abilities of the future asset manager, or the unique characteristics of the local environment.

Typical examples include the following:

- *Mangrove areas* – Increase the width of concrete aprons and maintenance access paths to prevent mangroves growing back and blocking structures.
- *Natural channels* – When designing vegetated channels be aware of the growing public interest in revegetating water courses. In general, design should include a sensitivity analysis based on a minimum Manning's 'n' roughness of 0.15 within riparian areas to allow for future planned and unplanned revegetation.
- *Vegetated catchments* – Consider trapping debris at a more appropriate upstream location where it will cause less damage and/or be easier to collect.

- *Tidal areas* – Allow for the normal accumulation of silt within channels and culverts (say, 150 mm) between expected maintenance periods.
- *Low bikeway bridges* – Consider the incorporation of collapsible handrails.
- *Tide gates* – Consider the benefits of installing tide gates within the first access chamber rather than at the outfall.
- *Pipes and culverts* – Observe minimum sizes of pipes, culverts, inlets and other structures.

6.7.2 Maintenance of specific structures

The selective maintenance clearing of riparian vegetation upstream or downstream of a bridge or culvert must be assessed on a case-by-case basis, but is likely to be warranted in the following situations:

- Hydraulic or environmental benefits have been demonstrated by past clearing operations.
- Woody vegetation is restricting flood flows from leaving the upstream floodplain and entering the bridge or culvert.
- Woody vegetation is restricting the flow of floodwaters exiting the bridge or culvert from entering into the downstream floodplain.
- Woody or inflexible vegetation is growing within an area defined by one culvert/bridge width upstream of the bridge or culvert (Figure 6.2).
- The vegetation is considered noxious or damaging to the ecological integrity of the downstream watercourse.

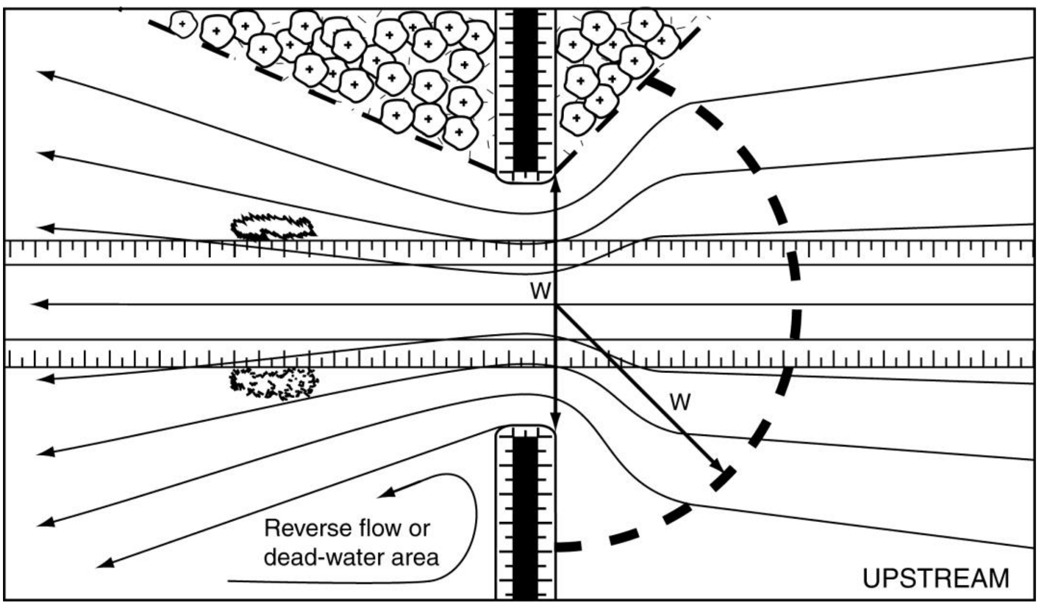

Figure 6.2: Critical inflow control zone (Catchments & Creeks Pty Ltd)

6.8 FLOW PATH BLOCKAGE

This report has principally concentrated on blockage of culverts and urban drainage systems. Another aspect of blockage that has not been considered in any detail is the blockage of overland flow paths. These are mainly an issue in urban areas, but can also be found in rural regions as well.

In this case, there is a flow path, often an overland flow path that may be blocked by a fence or other construction. In this case, the flow path may not be immediately obvious and the overland flow may not be clear. When this flow path is blocked, water may be diverted into regions where flow is not expected and it may also pond to a depth that is an inconvenience.

In this case, planning should ensure that these flow paths are not blocked. The flow paths should be identified by either review of historical flood patterns or by hydraulic modelling.

7. GENERIC BLOCKAGE FACTORS

In the absence of any other information, generic blockage factors can be applied to drainage elements. Details are presented in Table 7.1.

Table 7.1: Suggested 'Design' and 'Severe' Blockage Conditions for Various Structures

Type of structure		Blockage conditions	
		Design blockage	**Severe blockage**
Sag kerb inlets	Kerb slot inlet only Grated inlet only Combined inlets	0/20% 0/50% [1]	100% (all cases)
On-grade kerb inlets	Kerb slot inlet only Grated inlet only (longitudinal bars) Grated inlet only (transverse bars) Combined inlets	0/20% 0/40% 0/50% [2]	100% (all cases)
Field (drop) inlets	Flush mounted Elevated (pill box) horizontal grate Dome screen	0/80% 0/50% 0/50%	100% (all cases)
Pipe inlets and waterway culverts	*Inlet height < 3 m, or width < 5 m:* Inlet Chamber (culverts)	 0/20% [3]	 100% [4]
	Inlet height > 3 m and width > 5 m: Inlet Chamber (culverts)	 0/10% [3]	 25% [3]
	Culverts and pipe inlets with <u>effective</u> debris control features	As above	As above
	Screened pipe and culvert inlets	0/50%	100%
Bridges	Clear opening height < 3 m Clear opening height > 3 m Central piers	[5] 0% [7]	100% [6] [7]
Solid handrails and traffic barriers associated with bridges and culverts		100%	100%
Fencing across overland flow paths		[8]	100%
Screened stormwater outlets		100%	100%

[1] At a sag, the capacity of a combination inlet (kerb inlet with grate) should be taken to be the theoretical capacity of the kerb opening with 100% blockage of the grate.
[2] On a continuous grade the capacity of a combination inlet should be taken to be 90% of the combined theoretical zero-blockage capacity of the grate plus kerb opening.
[3] Adopt 25% bottom-up sediment blockage unless such blockage is unlikely to occur.
[4] Degree of blockage depends on availability of suitable 'bridging' matter. If a wide range of bridging matter is available within the catchment, such as large branches and fallen trees, then 100% blockage is possible for such culverts.
[5] Typical event blockage depends on risk of debris rafts and large floating debris.
[6] Blockage considerations are normally managed by assuming 100% blockage of handrails and traffic barriers, plus expected debris matter wrapped around central piers.
[7] Typical event blockage depends on risk of debris wrapped around central piers. The larger the piers, the lower the risk normally associated with debris wrapped around piers.
[8] Typically 50 to 100% blockage depending on debris availability.

In addition to these two conditions, zero blockage should also be tested and adopted if considered appropriate in the context of the risk of blockage for the particular location.

8. RECOMMENDED FURTHER INVESTIGATIONS

This report has been prepared using the best information available to the authors at the time. It became clear during the research carried out that the factual data concerning blockage and the impacts of this blockage on the performance of drainage systems was very limited. This has meant that the recommendations contained in this report have been based on experience of the authors as well as consultation with industry practitioners.

There are two aspects of the further research that could improve this analysis.

The first is related to the hydraulic analysis. However this topic is reasonably well understood and additional work in the area will not add significantly. The results from the second component of these recommendations should then be assessed with the available hydraulic models to improve analysis.

The major concern is with the collection of factual data on blockage and its impacts in different regions.

Most "data" on blockage consists of observations of debris left deposited after the flood has receded. While these observations show significant material in drainage lines as well as culverts and bridges, it is not certain that the blockage has affected the flood levels at the peak of the flood, where design issues become significant.

Data that must be collected are summarised as follows.

- Observations and photos of debris deposited at the end of the flood.
- Estimate of the debris in the culvert at the flood peak.
- Maximum flood levels on the upstream and downstream side of the culvert. These indicate the flood levels and the drop in water level across the culvert at the flood peak, and can be used to calculate the flow through the culvert at the flood peak.
- Catchment parameters as outlined in Section 4 of this report that are used in the risk assessment.
- Any observations of debris or catchment properties that are seen as relevant.

Once this data is collected, the actual flow of the culvert can be compared with the theoretical flow on the assumption that the culvert was not blocked at all and the blockage factor can be calculated.

These investigations must be carried out for a range of different catchments in a variety of regions and also for a range of storm magnitudes. The data should be published and coordinated.

Efforts have been made in the past to gather information on the current practices of local authorities and other agencies on the current treatment of blockage and current practices by the use of surveys. These have not resulted in adequate useful information to this time. Further efforts should be made to progress these surveys

As well as the assessment of blockage risk, a range of different mitigation measures have been applied but the relative performance of these is unknown. Further investigation into the performance of deflector systems and other mitigation measures is also recommended.

9. CONCLUSIONS AND RECOMMENDATIONS

Blockage has been identified as an important aspect of drainage planning and design, but one that is little understood and often poorly managed. Blockage can have significant impacts on the drainage system and can lead to costly and sometimes dangerous impacts on the community.

Preparation of this report has drawn together experts in the field from a number of agencies around Australia and developed an understanding of current issues and procedures. Notwithstanding, we note that the conclusions of this report are subject to revision as relevant data becomes available.

Because of this uncertainty, two different approaches to the determination of blockage to be used in design have been presented. These can be considered together or separately, and following further testing, a combination of these two approaches may be developed. For the current time however, adoption of these two approaches should allow a logical consideration of blockage in design of drainage structures.

Considering the perceived significance and impacts of blockage, it has been surprising that blockage effects are often totally neglected. One consequence has been that so little data has been collected and the other is that the proposed procedures are so different.

This report provides a background review of many of the issues that are needed for the evaluation and design of hydraulic structures subject to blockages.

This report has followed on from Stage 1 of the project and has indicated recommended design guidance for the incorporation of blockage into the planning, design and management of drainage systems. While the report has gathered relevant data and drawn conclusions from this data, there are still considerable uncertainties and further research will be needed to improve these recommendations.

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