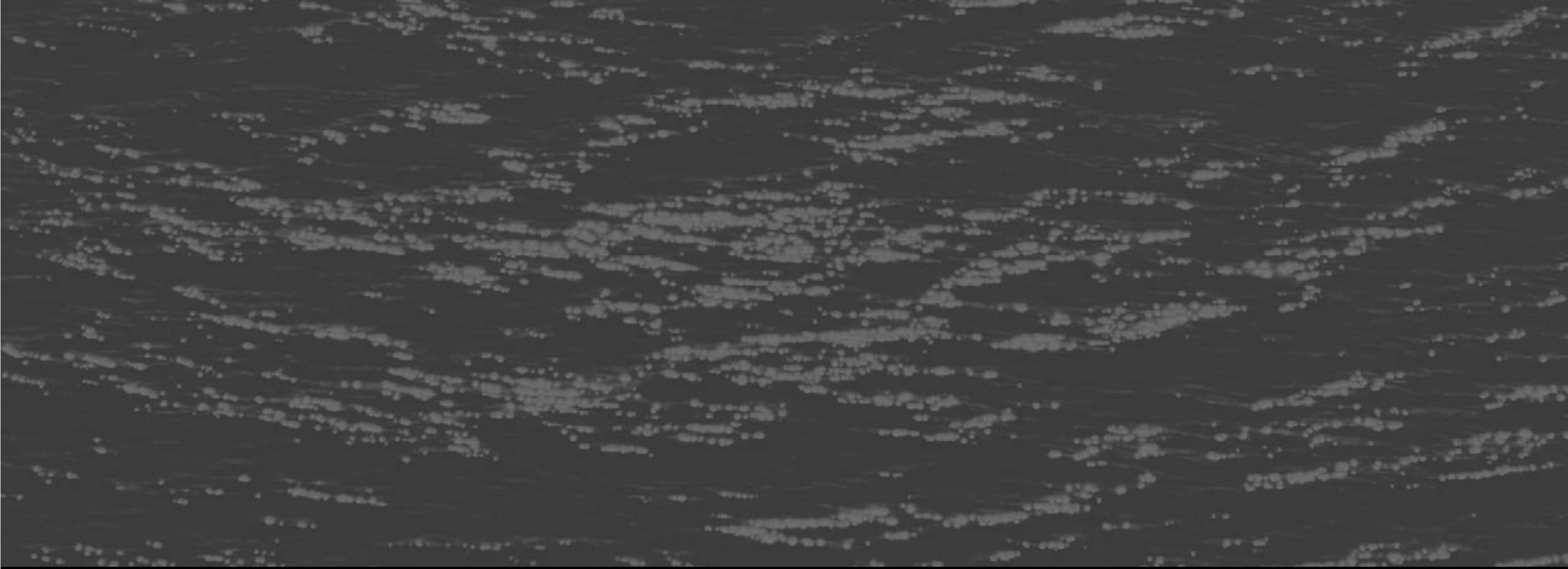

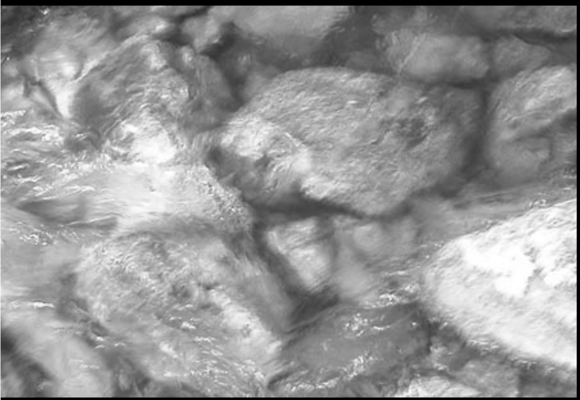

Urban stormwater and the ecology of streams

CRC FOR
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COOPERATIVE RESEARCH CENTRE FOR
CATCHMENT HYDROLOGY

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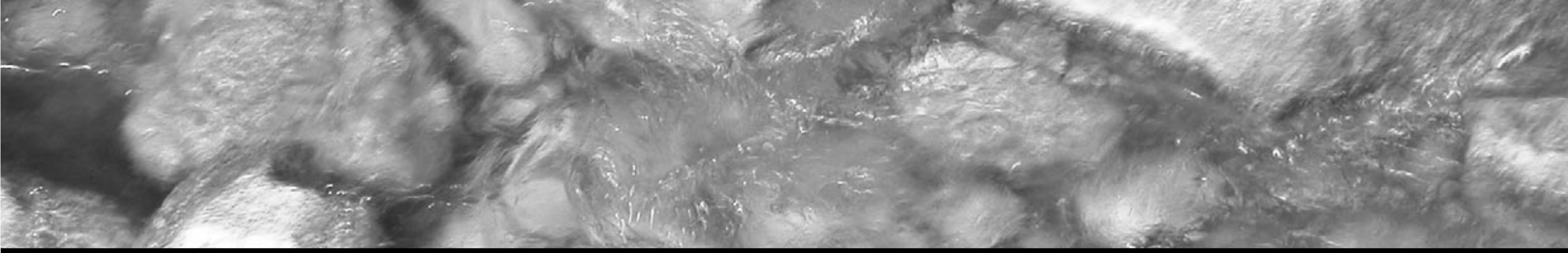

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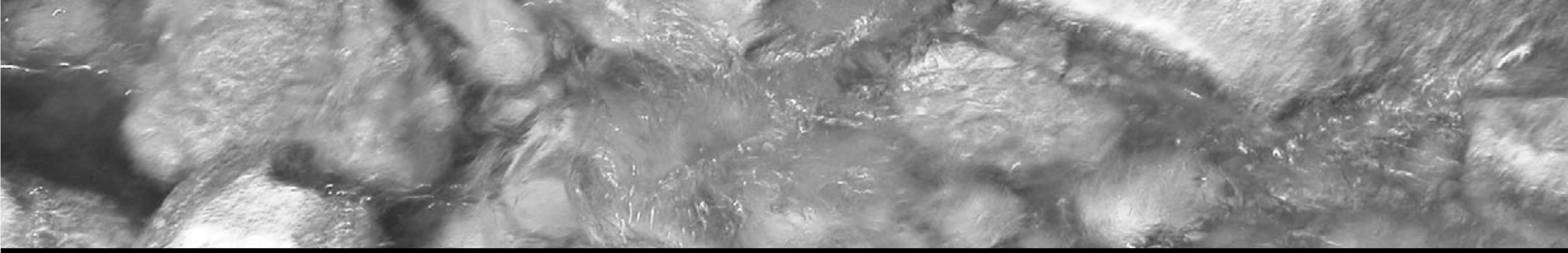

1. Introduction: Catchments and receiving waters

Every patch of land is part of a ’catchment’ that drains to a ‘receiving water’. In other words, water that falls on land (usually as precipitation), and that neither evaporates nor is taken up by plants, will find its way to a body of water. Depending on where the land is, its receiving water may be a small stream, a river, a wetland or lake, an estuary, a marine embayment, or the ocean (Fig. 1). In some places, an underground aquifer that has little or no connection to any surface water may be a receiving water. Although we consider the interaction between groundwaters and surface waters in this report, our focus is on surface waters, and streams in particular.

Any change in the way the land is used may cause changes in physical, chemical or biological processes in its receiving waters. Clearing forest cover, converting grassland to agriculture or mining, and urbanizing by covering land with surfaces that are impermeable to water (such as roads or roofs) are examples of land-uses that can degrade[a] receiving waters. All of these activities potentially change the way water runs from the land to the receiving water body and increase the amount of

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[a] Waters that are in less than natural condition are termed ‘degraded’.

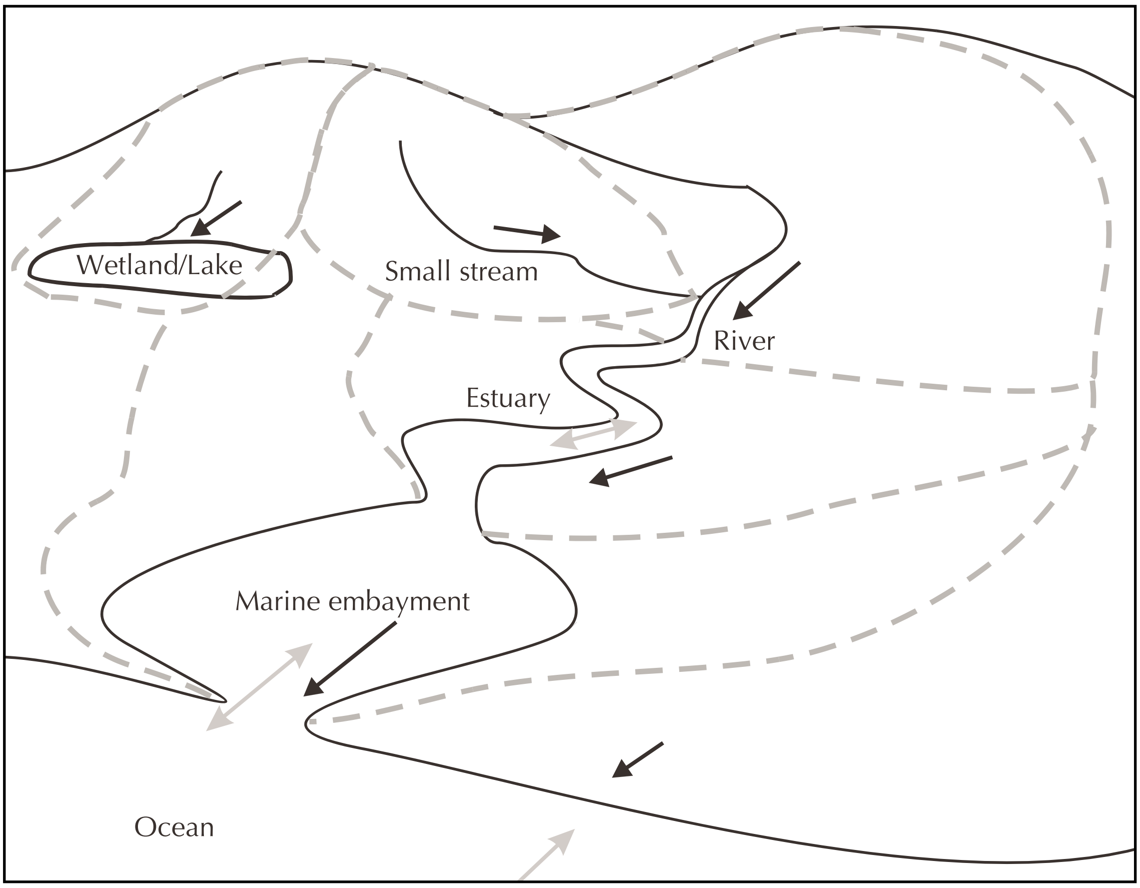

Figure 1. Types of receiving waters and their catchments (grey dashed boundaries). For each receiving water type, the direction of freshwater flow is indicated (black arrow), and for receiving waters with marine influence, the bi-directional nature of tidal flushing is portrayed (grey arrows).

Box 1. Urban stormwater drainage terminology

It is common practice to reduce the potential impacts of forestry, agriculture and mining by maintaining a buffer of vegetation between the activity and the receiving water. In contrast, urban developments around the world have almost always been constructed so that water that falls on roofs and roads is drained into a system of pipes or lined drains that lead directly to the nearest receiving water. We will refer to this type of drainage system as **'conventional stormwater drainage'** in this report. **Urban stormwater runoff** is the water that flows through the lined or piped drainage system to receiving waters.

The primary purpose of conventional stormwater drainage has usually been to prevent flooding of property and waterlogging of the foundation of constructions. However, in achieving these aims, conventional drainage also efficiently drains away water from frequent small rain events that poses no risk to property if intercepted appropriately.

In the 1990s, after it had become clear that there were downstream environmental costs to conventional drainage approaches, stormwater managers sought to mitigate impacts to receiving waters using detention basins and treatment wetlands. These **'end-of-pipe'** approaches, were misleadingly called 'Best Management Practice' (primarily in North America: Roesner *et al.* 2001), although the evidence that they resulted in any mitigation of stream impacts is at best equivocal (Horner *et al.* 1999; Maxted 1999; Horner *et al.* 2001).

New approaches to stormwater management use a suite of measures to intercept and treat water at a range of scales, ranging from **'at-source'** (measures that intercept water at the houseblock or roadside scale) to 'end-of-pipe' (e.g. Victorian Stormwater Committee 1999). We will refer to these new approaches collectively as **'water sensitive urban design'** or WSUD (although it should be noted that the term WSUD is increasingly being applied more broadly than just in stormwater management).

contaminants that the water carries. In this report, we focus on the product of one of these land-uses, namely urban stormwater, the water that drains from the impermeable surfaces that are part of urban land-use (Box 1).

The degree of impact to receiving waters from urban land-use (or indeed any other land-use) depends on the extent of the area it covers, on how much runoff from the land-use drains to the receiving water, and on whether runoff reaches the stream by sealed drains or by more natural flow paths.

Small streams and wetlands have smaller catchment areas than larger streams and wetlands. An area of altered land-use is likely to have a greater impact on a small stream than it would have on a large river, because it will cover a larger proportion of the small stream's catchment area. Estuaries and coastal embayments typically have larger catchments again: they, together with the ocean, differ from streams, rivers and lakes in that they are not just a product of the water draining their catchments, but are also influenced by tidal flushing of seawater (Fig. 1). Impacts of changed land-use on the ecology of these coastal waters are likely to be reduced with increased degrees of tidal flushing.

The primary focus of this report will be small streams, because these are the most abundant of receiving waters and because, with their small catchments, they are very sensitive to land-use change. The responses of small streams to land-use change can serve as a warning signal of potential damage to downstream waters. Equally, the protection of small stream ecosystems will assist (if not ensure) the protection of larger receiving waters downstream. The report describes the physical, chemical and biological processes of streams, how these processes are affected by urban development built using conventional stormwater drainage design (Box 1), and how these impacts may be minimized by new design approaches.

1.1 Pathways for water: catchment to stream

The stream is a product of the water falling on its catchment and the pathways that water subsequently takes. While the interactions of these hydrological pathways and processes in catchments are complex, a simplified conceptual model can illustrate the important processes. They can be altered by conventional stormwater drainage (Fig. 2), but they can also be mimicked or preserved by alternative approaches to drainage, such as water sensitive urban design (WSUD: Box 1).

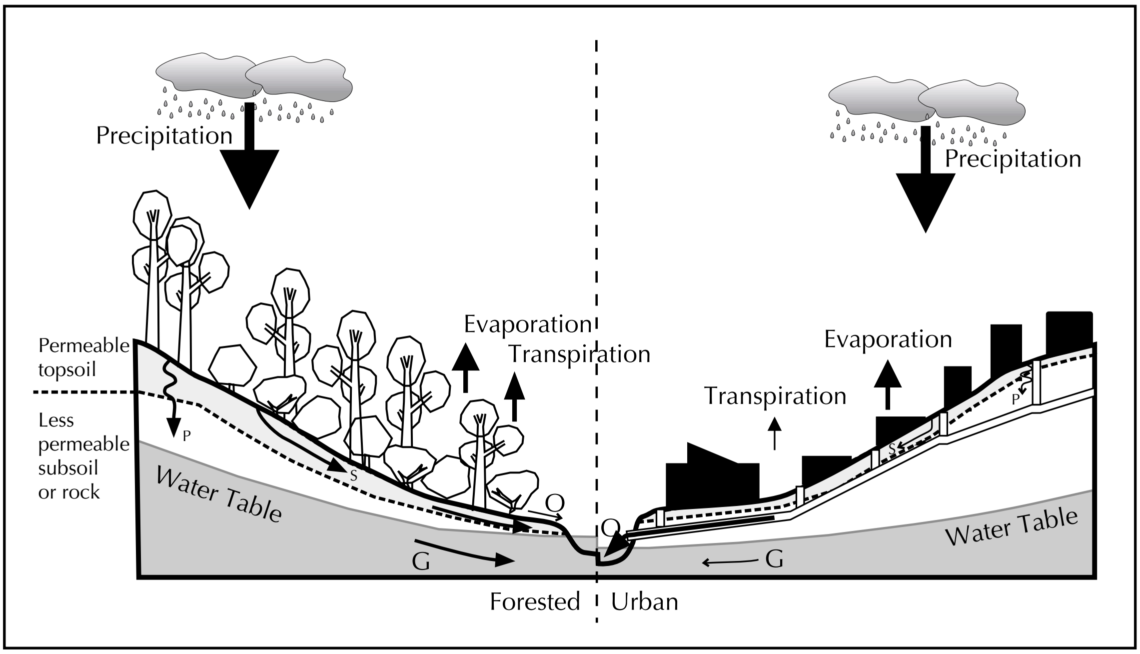

Figure 2. The water cycle in a forested catchment and in an urbanized catchment with a conventional stormwater drainage system (not considering imports of water supply or export of wastewater). The size of arrows indicates qualitative differences in the relative size of annual water volumes through each pathway in a typical south-eastern Australian coastal catchment. Water that falls on the catchment and is not evaporated or transpired may reach the stream by three possible paths: overland flow (O: almost all of which is transmitted to the stream by stormwater pipes in the urban catchment), subsurface flow through permeable topsoil (S), or percolation (P) into groundwater flow (G). (Partly adapted from Dunne & Leopold, 1978.)

Water that falls on a catchment as rainfall (or sleet, snow or hail) may then take several paths. In most parts of the world, a large proportion of rainfall returns to the atmosphere through evaporation (Fig. 2). In naturally vegetated catchments, a further large proportion is evaporated by being transpired through plants drawing water from the soil and releasing it through their leaves. If vegetation is replaced by bare earth or constructed surfaces, less water is lost from the catchment through transpiration (Fig. 2).

Water that does not return to the atmosphere by these pathways will drain to the stream by one of three other pathways. In a forested catchment, the primary pathways are sub-surface flows, either via shallow pathways in the permeable topsoil (S in Fig. 2) or via percolation into the less permeable deeper soils or rock and into the groundwater (P and G in Fig. 2). Baseflows in streams of forested catchments are primarily fed by groundwater flow. In south-eastern Australia, only a small proportion of water reaches streams of forested catchments via overland flow[b], and all of this overland flow will occur during infrequent large storms that are either large enough to saturate the topsoil of the catchment, or intense enough to exceed the infiltration capacity of the soil.

When urban impervious surfaces are constructed, overland flow becomes more frequent for several reasons. First, less area is available for infiltration into the soil; second, construction often involves the removal of permeable topsoil from the catchment, further reducing the capacity for infiltration. Conventional stormwater drainage reduces infiltration further again by ensuring that all water draining off impervious surfaces is transported directly to the stream. The result is much less water reaching the stream through shallow subsurface flows, and much less water percolating to groundwater. Therefore, the water table is not replenished and baseflow levels decline in the stream (Fig. 2). The water that would naturally have taken these pathways, and the water that would naturally have been transpired by forest plants, is instead delivered to the stream by an efficient network of pipes: essentially a very large increase in the frequency and size of ‘overland’ flow (albeit through pipes: Fig. 2).

The above description of the natural behaviour of forested catchments and their streams is, of course, a broad generalization and simplification. The relative importance of the various hydrological pathways will vary with climate, soil type, catchment geology, catchment topography and vegetation types. However, it is generally true in south-eastern Australia that overland flow occurs infrequently in natural catchments and makes up a small proportion of the flow in streams.

The changes to hydrological pathways resulting from conventional stormwater drainage are likely to be observed across all regions. The patterns described here are consistent with those derived for North America (Gordon *et al.* 1992; Arnold and Gibbons 1996; Basnyat *et al.* 1999). Lower water tables are the norm for urban areas of south-eastern Australia. However, the urban effect of lower water tables is not universal. In some older cities of the world, water tables have been reported to rise as a result of leaky water supply or sewerage infrastructure (Yang *et al.* 1999). In one affluent arid zone, heightened water tables have been attributed to garden irrigation (Osborne and Wiley 1988; Al-Rashed and Sherif 2001). In most urban areas of south-eastern Australia, infrastructure leaks or garden watering volumes are unlikely to be large or extensive enough to raise water tables. However, this may not be the case in some towns with dryland salinity problems, such as Wagga Wagga.

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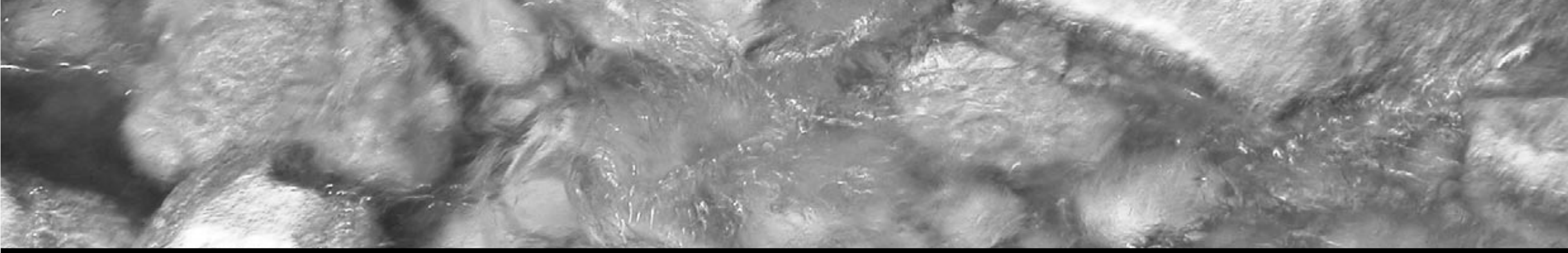
[b] Hydrologists working at large scales sometimes call the water flowing in streams ‘runoff’ or sometimes, ‘surface runoff’. This use of the term should not be confused with ‘overland flow’, which we use to describe one of the pathways that water falling on the catchment may take to the stream channel.



2. Physical, chemical and ecological processes in the stream

The changes to the catchment water balance caused by conventional drainage of urban areas lead to a range of changes in stream ecosystems. The changes are inter-related and difficult to separate. In this section, we outline the nature of changes typically observed in streams of urban catchments around the world, concentrating on the physical and chemical changes that are most relevant to ecological degradation.

2.1 Flow

Increased ‘overland’ flow (i.e. flow through stormwater pipes) resulting from conventional stormwater drainage changes the patterns of flow in the stream. In a perennial stream of a forested catchment, baseflow is fed by groundwater and most small rain events cause negligible change to the amount of water flowing down the stream. Larger rain events allow topsoils to wet enough for shallow subsurface flows to reach the stream, resulting in a delayed increase in stream flow followed by a gradual decline back to baseflow levels (solid line in Fig. 3). In an equivalent stream of an urbanized catchment with conventional stormwater drainage, baseflow levels are reduced, and every time there is sufficient rainfall to wet the impervious surfaces of the catchment the stream receives an immediate input of stormwater through the pipes. Stream flow is therefore much more variable (‘flashier’), and in larger storms, the peak flow is much increased and the decline back to baseflow is much quicker (dashed line in Fig. 3).

So, conventionally drained urban areas have three important effects on stream hydrology.

1. Baseflow usually becomes lower.
2. Small–moderate increases in flow become more frequent resulting from direct surface runoff in small rain events.
3. Peak flows resulting from larger rain events become larger, but the high flows do not last as long.

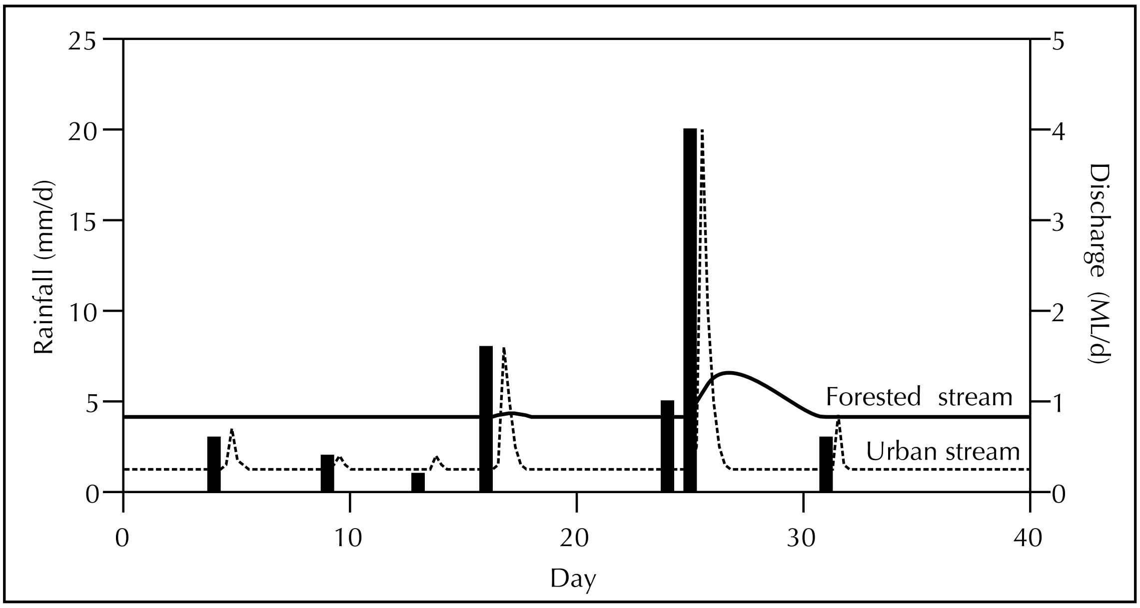


Figure 3. Schematic diagram showing flow response to rainfall (bars) in two hypothetical streams with a catchment of 1 km^2: one draining a forested catchment (solid line) and one draining an urbanized catchment with conventional stormwater drainage systems (dashed line).

2.2 Channel form

Streams are naturally dynamic systems, and channel form (the shape of channel meanders and cross-section, the composition of the sediment and rocks making up the stream bed) depends on catchment topography and geology and the position along the stream. Despite this variability in form, conventionally drained urbanization affects channel form in broadly predictable ways.

Stream channels adjust their width and depth in response to long-term changes in sediment supply and the size and frequency of high flow events, unless they are constrained by unerosive bedrock (Dunne and Leopold 1978). Stormwater management policies of the recent past aiming to control channel erosion have generally aimed to control runoff from a 1 in 1.5 or 1 in 2 year storm event, so that the maximum flow rate does not exceed pre-development conditions. However, such policies fail to consider the importance of the frequency or duration of these high flows to channel erosion. Frequent, smaller floods in conventionally drained urban catchments may be more important causes of channel incision than these large infrequent events (MacRae and Rowney 1992). The influence of these more frequent, smaller events may also explain the common observations of disproportionate increases in channel erosion compared to increases in discharge (Neller 1989; Booth 1990). Urban development with conventional drainage increases both the size of infrequent floods (such as the 1 in 2 year storm event), and the frequency of smaller high flow events that may contribute to channel erosion.

Wolman (1967) described a cycle of sedimentation and erosion of stream channels associated with catchment urban development. Land cleared and exposed during construction was observed to produce enormous sediment loads into streams. This input of sediment can lead to an ‘aggradation’ phase in which erosion resulting from increased runoff is countered by a filling of channels by the released sediments. The delivery of construction-related sediments to streams is likely to be worsened if conventional stormwater drainage infrastructure is in place prior to construction.

An erosional phase followed the construction-aggradation phase in Wolman’s cycle. When sediment loads from the catchment are reduced, following construction, increased frequency and magnitude of high flows gradually remove the sediments deposited in the channels, and the channel widens and deepens. During this phase, in densely developed catchments (with conventional drainage systems) most of the sediment being carried by the stream can come from channel erosion rather than from the catchment (Trimble 1997).

Although the nature and magnitude of channel response to catchment urbanization can vary with catchment slope, geology, sediment characteristics and land-use history (Gregory *et al.* 1992), the channel responses described by Wolman (1967) have been observed in streams around the world (e.g. Neller 1989; Roberts 1989; Booth 1990). All of the studies that have reported such a cycle of sedimentation and erosion have been in conventionally drained urban areas. Much attention has been paid to the importance of the increased size of the infrequent ‘bank-full’ discharge in determining channel form. In a natural stream, such floods occur, perhaps once each year or two. If such a flood increased in size but not frequency, its erosional power would not be greatly increased (at least in unconfined streams), because once floodwaters overtop their banks and spill into the floodplain, increases in depth (which determines water velocity in the channel) will not be great.

It is therefore likely that the most important effect of urban stormwater on channel form is the increased frequency of smaller floods that approach or exceed bank-full. (We discuss this class of floods and their ecological implications further in section 2.4.) Therefore, in highly developed catchments, while armouring of channels may provide short-term control of bed and bank erosion, dispersed management of runoff from impervious surfaces throughout the catchment (to reduce the frequency and intensity of frequent smaller floods) may be the most effective approach to controlling incision of stream channels. However, this proposition remains to be tested.

Box 2. Water quality terminology

A variety of substances that can occur in stream water may have deleterious consequences for the stream ecosystem. In this report we refer to such substances collectively as **contaminants** when they are present but not necessarily causing harm, and as **pollutants** when they are thought to be having a deleterious effect. **Nutrients** are contaminants that have a beneficial effect to plants, but in excess cause excessive plant growth that in turn has deleterious effects to the rest of the stream ecosystem. **Toxicants** are contaminants that have a directly deleterious effect on organisms.

Contaminant levels can be measured in two ways. **Concentrations** are measures of how much of a contaminant is in a fixed volume of water (units in mass/volume, e.g. mg/L). **Loads** are measures (always estimated) of how much contaminant is transported by a stream over a period of time (units in mass/time, e.g. kg/yr).

Concentrations of contaminants in stream water are often variable in time, particularly in high flow events, when concentrations of many contaminants can increase. Because of this, and because most water flows down streams in high flow events, loads are primarily determined by the amount of contaminants delivered during high flow events. To assist in estimating loads, hydrologists use a statistic called **event mean concentration (EMC)**, calculated from a series of samples taken during the rise and fall of a high flow event. EMC is not the simple mean of the sample concentrations, but the mean calculated by weighting the concentration of each sample by the rate of water discharge at the time of sampling. (So if 1,000,000 L were discharged during an event, then the EMC estimates the average concentration in each of those 1,000,000 litres)

2.3 Water quality

Poor water quality is a major cause of degradation to streams and aquatic ecosystems in general (ANZECC and ARMCANZ 2000). Urban stormwater delivers a range of contaminants to receiving waters, and is a major contributor to water quality degradation in urban areas. The impacts of stormwater-derived pollution are inextricably linked to hydrological impacts, so stormwater management should not be aimed solely at water quality improvement. This section briefly describes catchment processes that drive water quality in streams, the major classes of stormwater-derived contaminants and how these can affect stream ecosystems.

2.3.1 Catchment processes and stream water quality

In the absence of human impacts, natural concentrations of nutrients (see Box 2 for a definition), suspended particulate matter, salts and other substances in stream water vary from catchment to catchment, determined by the chemistry of the underlying bedrock and soils, the air from which rain falls, and the characteristics of the catchment vegetation. In forested catchments, almost all of the contaminants that fall from the air, that are eroded from rocks, or that derived from plants or animals, are taken up by processes in the forest or its soil. Many substances, such as metals and phosphorus, have a strong affinity for soil particles. So, if the dominant flow path for water is subsurface, then very little of these substances reaches streams.

In contrast, nitrate (an oxidized form of nitrogen) does not have a strong affinity for soil particles and can be transported efficiently by sub-surface flows. However, nitrogen is an important nutrient for many biological processes, and nitrogen retention and removal rates can be high in forest soils, particularly in riparian zones[c] (Peterjohn and Correll 1984; Addy *et al.* 1999).

In undeveloped catchments, substances that are potential contaminants for receiving streams are usually efficiently retained or removed by terrestrial processes in the catchment. Water flowing in the streams of these catchments is usually of high quality: very low levels of contaminants with high levels of dissolved oxygen.

Urban land-use increases the amounts of many contaminants in the catchment, and introduces a large number of potentially toxic contaminants that are not found at all in undeveloped catchments. The importation of food and other materials results in increased amounts of nutrients and carbon in urban catchments. Human activities produce new contaminants that may have been absent or present in trace amounts before the land was urbanized. For example, zinc drains off galvanized iron roofs; other metals, oils and rubber build up on roads from vehicles; fertilizers and pesticides are applied to gardens; herbicides are applied to paths and other surfaces.

So stormwater draining off impervious surfaces carries many types of contaminants, some of which are unique to urban land, and some of which are a product of natural catchment processes, such as fallout from the air, or leaf litter. A large proportion of some contaminants in stormwater can come from the air (see review by Duncan 1995). If impervious surfaces are conventionally drained, then the contaminants are delivered efficiently to receiving streams every time there is enough rainfall to produce runoff from an impervious surface.

Conventionally drained stormwater systems therefore deliver a wide variety of contaminants to streams frequently, as well as causing changes to temperature, dissolved oxygen concentrations (DO) and pH. The effects of altered water quality on stream ecosystems are complex and the impacts of different contaminants are interrelated. For instance, increased concentrations of suspended particulate matter can reduce the toxicity of some contaminants, while changes in pH or DO can result in the release of heavy metals or phosphorus from sediments. Furthermore, contaminants may alter the effects of flow disturbances and vice-versa: for instance, in a high-flow event a rock-clinging animal stressed by the presence of a toxicant may be more likely to be dislodged (thereby increasing the risk of death) than an unstressed animal.

2.3.2 Toxicants

Many toxic substances have been identified in urban stormwater runoff: metals are the most prevalent in North American urban runoff, with organic contaminants (such as pesticides, herbicides and hydrocarbons) also identified as concerns (Novotny and Olem 1994; Kimbrough and Litke 1996; Schroeter 1997). Metal concentrations in urban stormwater runoff are typically 100 times greater than in non-urban runoff (Welch 1992), but concentrations in receiving urban streams are usually much less than concentrations in undiluted stormwater. The toxic significance of metal concentrations is often difficult to interpret, because the fraction that is bio-available[d] is unknown (Davies 1986; Welch *et al.* 1998). Timperley (1999) suggested that bio-available concentrations in New Zealand urban streams may be very low (< 1% of total dissolved concentrations), and therefore argued the toxic effects of urban stormwater may be minor.

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[c] Riparian zone: along the stream's banks and floodplain.

[d] Bio-available: present in a form that can be taken up directly by microbes, plants or animals.

Box 3. Measuring the intensity of urban land-use

Until recently, the most common measure of urban density used to assess impacts on aquatic ecosystems has been **total imperviousness** (TI), the proportion of a catchment's area covered by **impervious surfaces** (surfaces such as roofs and pavements that are impermeable to water). The observation that the ecological condition of streams broadly declines with increasing TI has led some authors to argue that stream degradation is inevitable above a certain TI (most commonly 10%: Beach 2001; Center for Watershed Protection 2003). Other authors, unsatisfied by the noisiness of relationships based on TI, suggested that indicators more inclusive of the broad range of urban impacts, such as percentage of catchment in urban land-use (Morley and Karr 2002) or a complex metric based on many aspects of urban land (McMahon and Cuffney 2000), might be better predictors of stream degradation. However, these indicators have not proven much better predictors of stream degradation than TI.

Booth and Jackson (1997) suggested that **effective imperviousness** (EI, imperviousness calculated using only those impervious surfaces that are directly connected to streams by pipes or sealed drains) might be a better predictor of stream degradation as it only includes those impervious surfaces that are likely to be having the greatest direct impact on the stream. Recent research in the east of Melbourne has shown EI to be a stronger explanatory variable for a range of indicators of in-stream ecological condition (Hatt *et al.* 2004; Taylor *et al.* 2004; Walsh 2004b; Walsh *et al.* 2004; Newall and Walsh 2005; Walsh *et al.* in press). This finding suggests that replacing stormwater drainage pipes with alternative drainage systems that promote retention and infiltration of stormwater is likely to be an effective means of reducing the impact of urban stormwater on receiving waters.

The argument that toxic impacts of urban stormwater are minor is a common one. Horner *et al.* (1997) asserted that water quality was unlikely to be the cause of observed poor ecological health in streams of the Puget Sound region in the NW USA, because observed concentrations of contaminants were mostly below US EPA chronic exposure guidelines. They also dismissed the relationship between event mean concentration of zinc (a potentially toxic heavy metal) and total catchment imperviousness (see Box 3) as not substantial. Yet when appropriately transformed, the illustrated relationship was highly significant (Fig. 3 in Horner *et al.* 1997: $R > 0.9$).

Stormwater can contain many different contaminants, which may have additive effects (the total effect equals the sum of the individual effects) or even synergistic effects (the total effect exceeds the sum of the individual effects). Therefore the reliance on chronic exposure guidelines or trigger values (Table 1) of single contaminants to assess the toxicity of stormwater runoff is likely to result in an underestimation of ecosystem impacts.

Short-term toxicity tests on stream biota using urban stream water have produced mixed results, although longer-term in-situ toxicity tests have more consistently demonstrated the potential toxic effects of urban runoff (e.g. Pesacreta 1997; Crunkilton *et al.* 1999; Burton *et al.* 2000). These toxicity tests have been conducted in the absence of flow-related stresses. The toxic effects of urban stormwater on in-stream plants and animals are likely to be greater when associated with flow-related disturbances following storm events.

Table 1. Default trigger values for slightly disturbed rivers in NSW (ANZECC and ARMCANZ 2000). The ANZECC guidelines recommend the use of trigger values to assess risk of adverse effects resulting from nutrients, biodegradable organic matter and pH. The guidelines define upland streams as 150–1500 m altitude.

Variable	Unit	Upland river	Lowland inland river	Coastal river
Total phosphorus	mg P/L	0.02	0.05	0.025
Filterable reactive phosphorus	mg P/L	0.015	0.02	0.02
Total nitrogen	mg N/L	0.25	0.5	0.35
Nitrate/Nitrite	mg N/L	0.015	0.04	0.04
Ammonium	mg N/L	0.013	0.02	0.02
Dissolved oxygen: lower limit	% saturation	90	85	85
Dissolved oxygen: upper limit	% saturation	110	110	110
pH: lower limit		6.5	6.5	6.5
pH: upper limit		8.0	8.5	8.5

2.3.3 Nutrients and suspended particulate matter

Many of the substances present in stream water that are essential to the functioning of aquatic ecosystems under normal conditions, act as contaminants when they occur in excessive concentrations. Of primary importance are nutrients, which are required for the growth of algae and other aquatic plants. The two most important nutrients are nitrogen and phosphorus. Algal growth in streams is usually limited (if there is enough light) by a shortage of one of these nutrients (more usually phosphorus in small streams). High concentrations of one or both can lead to excessive plant growth with other ecological consequences, perhaps most importantly the tendency for decreases in dissolved oxygen at night resulting from plant respiration.

Suspended particulate matter (SPM) is another example of a contaminant that is required in small concentrations for ecosystem function in streams. SPM contains organic matter, which is an important source of energy for microbes and aquatic invertebrates. However, excessive SPM increases the turbidity of water, thereby reducing light for plant growth, and can result in smothering of habitat in zones of little flow, and scouring of habitat in zones of high flow (Metzeling *et al.* 1995; Wood and Armitage 1997). In streams receiving urban stormwater, impacts of increased SPM on stream plants and animals may be more severe than equivalent increases in SPM in non-urban streams, because of contamination of sediments by toxicants (Williamson 1985; Charbonneau and Kondolf 1993).

Organic matter associated with SPM is part of a class of contaminants termed ‘oxygen-depleting substances’. These substances are broken down either by chemical reactions or microbial processes that require oxygen. The effect of excessive presence of oxygen-depleting substances in stream water is to reduce dissolved oxygen available for in-stream plants and animals. ‘Biochemical oxygen demand’, a measure of the effect of oxygen-depleting substances, has been shown to be correlated with catchment urbanization (Walsh *et al.* 2001), probably as a result of efficient delivery of organic matter to streams by stormwater pipes (Walsh and Breen 1999).

In the past, the major focus of stormwater management aiming to reduce levels of nutrients (and other contaminants) has been on *loads* (e.g. Lawrence and Breen 1998; see Box 2 for the distinction between loads and concentrations). Contaminant loads are critical for the management of large downstream receiving waters such as lakes, estuaries or coastal embayments (see below). However, their relevance to the functioning of stream ecosystems is arguable. A large proportion of contaminant loads are transported during infrequent, large storm events, so loads may reflect conditions that are rarely experienced by the plants and animals of the stream.

Plants and animals in streams are likely to be more strongly affected by contaminant *concentrations* during dry weather and following small, frequent storms. The concentrations experienced during these times may not be indicated reliably by estimates of annual loads. As an example, consider stormwater treatment ponds, which have commonly been constructed in urban areas to reduce nutrient loads to streams and downstream waters. These ponds retain and treat water delivered in storm events, which usually has much higher contaminant concentrations than baseflow water. It is possible that the minimum concentration to which the pond treats this stormwater may be higher than the concentration of water that flows into the pond during dry weather (e.g. Fletcher and Poelsma 2003). So, although the pond may be efficiently reducing contaminant loads being transported down the stream over a year, the water released from the pond during dry weather may have higher contaminant concentrations than the water flowing in. Because of possible effects such as these, Helfield and Diamond (1997) argued that, in some circumstances, constructed wetlands can actually cause degradation of stream ecosystems.

SPM and nutrient concentrations can be strongly affected by agriculture, forestry and other non-stormwater-related impacts. So the effects of urban stormwater on these aspects of water quality may be masked by other catchment land-uses not associated with stormwater. For instance, while concentrations of several contaminants in streams on the eastern fringe of Melbourne were well explained by stormwater (see below), baseflow concentrations of nitrate were strongly explained by the density of septic tanks in the catchment, suggesting subsurface flows as the primary pathway for this contaminant (Hatt *et al.* 2004). Similarly, SPM in that study was not well correlated with urban density, probably because of the silty nature of the Dandenong Ranges sediments (Hatt *et al.* 2004).

2.3.4 Gross 'pollutants'

Conventional stormwater drainage systems tend to collect and concentrate large amounts of rubbish, leaf litter and other refuse (collectively called gross pollutants) into receiving waters, primarily because the first path for water to take once it falls on an impervious surface is 'down the drain'. Gross pollutants are the most visible symptom of the problem with conventional stormwater drainage, and as a result a large proportion of money spent on stormwater management goes towards trapping gross pollutants before or after they reach receiving waters. Ironically, these very visible and unsightly products of stormwater may be the least harmful of stormwater contaminants to the ecology of receiving waters (except, perhaps, for those gross pollutants that may contain oxygen-depleting or toxic substances).

There are many types of gross-pollutant traps, used in cities around Australia, which are effective at retaining these large contaminants. However, most of these traps do little to stem the flow of fine sediments, toxicants and nutrients to receiving waters, and these 'less-than-gross' pollutants continue to cause ecological damage to streams and waters downstream. In contrast, drainage systems that are primarily designed to minimize the transport of sediments, nutrients and toxicants by promoting infiltration near-source also happen to be extremely efficient at trapping gross pollutants (Lloyd *et al.* 2002).

2.3.5 Temperature

Streams that receive water from conventionally drained urban areas usually have elevated water temperatures (e.g. Walsh *et al.* 2001; Hatt *et al.* 2004), probably as a result of being heated by impervious surfaces and the dominant piped pathways for water to the streams. The wider and more open channels of incised urban streams probably contribute to an increase in the range of temperature variation between day and night. Warmer water is likely to stimulate physiological processes in streams and worsen the problems of nuisance algal growth. Many stream species are adapted to cool waters and are likely to suffer thermal stress in such streams. Thermal pollution downstream of small farm dams in rural streams has been reported to affect macroinvertebrate and fish communities (Lessard and Hayes 2003; Maxted *et al.* in press), and a similar effect is likely downstream of constructed stormwater treatment ponds (Fig. 4, Walsh 2004a).

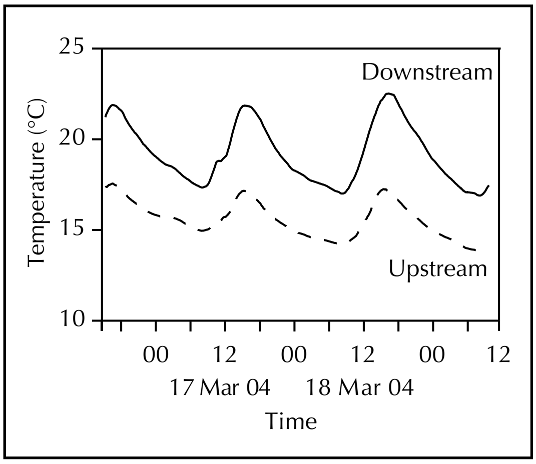


Figure 4. Temperature in Olinda Creek, 100 m upstream and immediately downstream of the outlet of the Hull Road constructed stormwater treatment wetland in Melbourne, measured every 5 min over three days in March 2004. The creek downstream of the wetland was 3–4°C warmer and the variation from day to night was ~1°C greater than the creek upstream (Source: Walsh 2004a)

2.3.6 Predicting stream water quality in urban catchments

Conventionally drained urban land has repeatedly been shown to increase the concentrations and loads of nutrients, suspended solids and other contaminants in urban streams (e.g. Osborne and Wiley 1988; Corbett *et al.* 1997; Basnyat *et al.* 1999). Concentrations in particular have been shown to be correlated with total catchment imperviousness (TI: Arnold and Gibbons 1996; Horner *et al.* 1997; Center for Watershed Protection 2003). Hatt *et al.* (2004) demonstrated that effective imperviousness (EI: see Box 3) was a better variable than TI

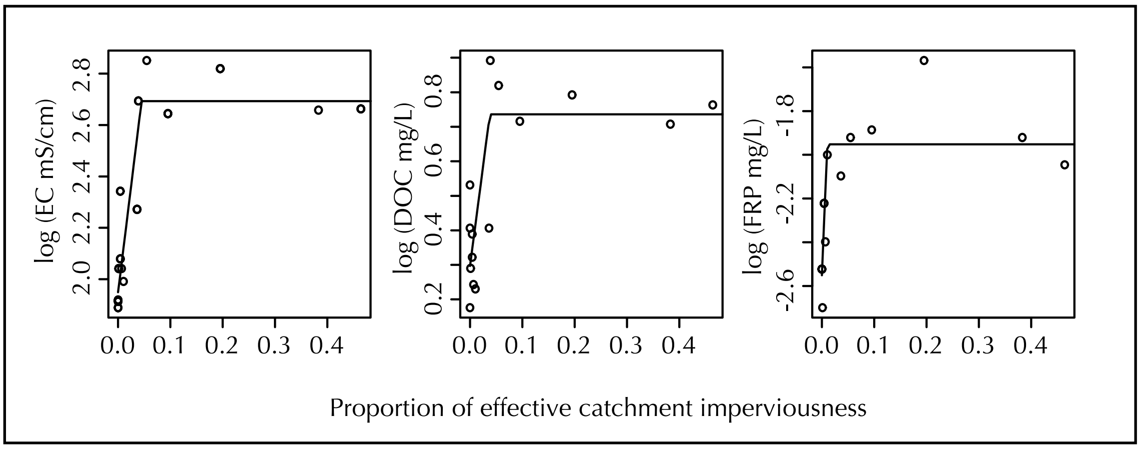


Figure 5. Median baseflow measurements of electrical conductivity (EC), dissolved organic carbon (DOC) and filterable reactive phosphorus (FRP) in 15 small streams in the east of Melbourne, Victoria, plotted against effective imperviousness. The trend lines show the best fit model as determined by Walsh *et al.* (in press): piecewise linear regressions to a threshold effective imperviousness beyond which there is no change.

to explain median baseflow concentrations of dissolved organic carbon (DOC), filterable reactive phosphorus (FRP) and salinity (as estimated by electrical conductivity, EC) in small streams of eastern Melbourne. Using the same data, Walsh *et al.* (in press) modelled the relationships of these variables as linear increases with EI up to a threshold after which there was no further increase (Fig. 5). For all three variables, the threshold was reached at 1–5% EI.

This work suggests that EC and the concentrations of DOC and FRP during baseflow can be strongly determined by a small proportion of the catchment covered by impervious surfaces that are connected to the stream by pipes. So, the models suggest that when a very small amount of land in a catchment is developed and drained using conventional stormwater management techniques, the receiving stream's baseflow water quality is likely to be typical of degraded streams in metropolitan areas. The most hopeful approach for developing urban land while maintaining good stream water quality (at levels close to pre-development levels) is the dispersed, catchment-wide application of WSUD, so that very little or none of the catchment's impervious surfaces drain directly to streams.

2.4 Ecological change

The changes to flow patterns, channel form and water quality that result from conventional stormwater drainage have severe and predictable

Table 2. Typical symptoms of the 'urban stream syndrome' (from Cottingham *et al*. 2004)

Affected feature	Response
Hydrology	• Decreased low flow volume (Rose and Peters 2001) (but see Nilsson *et al*. 2003) • Increased frequency and magnitude of peak flow (Leopold 1968; Wong *et al*. 2000) • Decreased groundwater recharge and lower water table (Groffman *et al*. 2003; but see Nilsson *et al*. 2003)
Geomorphology	• Increased channel erosion, incision (and sediment transport depending on the age of catchment development) (Wolman 1967; Roberts 1989; Booth 1991)
Water quality	• Increased contaminant loads and concentrations (Osborne and Wiley 1988; Corbett *et al*. 1997; Basnyat *et al*. 1999; Hatt *et al*. 2004)
Ecology	• Reduced frequency of connection between the stream channel and associated floodplain and wetland systems (Center for Watershed Protection 2003) • Habitat simplification • Less diverse biotic communities (Paul and Meyer 2001) • Decreased nutrient retention and altered patterns of nutrient and energy cycling (few published studies: see Paul and Meyer 2001)
Biodiversity	• Decreased biodiversity values (genetic, species and community levels) (Richter *et al*. 1997; Chessman and Williams 1999; Walsh *et al*. 2004)

Table 3. Conceptual framework of stormwater impacts to stream ecosystems, comparing two urban scenarios and the pre-urban condition. The scenarios are based on a hypothetical stream in the Dandenong Ranges (rainfall frequencies based on 1965–1975 data for Croydon, Victoria: Australian Bureau of Meteorology), with the two urban scenarios assuming a total imperviousness >10%. From Walsh *et al*. (in press).

Storm size and frequency	Conventional urban design[1]	Low-impact design[2]	Pre-urban land
No effective rainfall (<1 mm/d: ~67% of days)	Low water table, low baseflow; High P, N concentrations; Variable, mostly low, turbidity; High pollutant spill risk; High algal biomass, variable O_2; Low invertebrate and fish diversity	Plentiful baseflow of high quality water fed by subsurface flows; Good quality habitat supporting diverse biota	Plentiful baseflow of high quality water fed by subsurface flows; Good quality habitat supporting diverse biota
Small–moderate rain events (1–15 mm/d:~29% of days)	Moderate to large discharge increase; Possible substratum movement and bank erosion; Inflow with high N, P, TSS and toxicant concentrations; Loss of sensitive biota (Flow disturbance–toxicant interactions); Filamentous algal and eutrophic diatom growth stimulated	No surface runoff; Replenished subsurface-fed baseflow; Negligible physical disturbance from slightly higher flows	No surface runoff; Replenished subsurface-fed baseflow; Negligible physical disturbance from slightly higher flows
Large rain events (>15 mm per day: ~4% of days, mostly in wet season)	Large flood; Major incision and bank erosion; Large inflow of N, P, TSS and toxicants; Loss of all sensitive biota; Smothering/scouring of algae	Large flood; Substratum movement and bank erosion; Inflow with high N, P, TSS and toxicant concentrations; Loss of sensitive biota, but species adapted to annual flooding likely to re-colonize	High discharge; Substratum movement; Increased N,P, TSS concentrations; Temporary loss of some species, but those adapted to annual flooding will re-colonize

[1] All impervious surfaces drained by pipes or sealed drains directly to stream

[2] Runoff from impervious surfaces retained up to a 15 mm rain event

consequences for stream ecosystems. Indeed, the term ‘urban stream syndrome’ has been coined to describe the sick state of streams of urban areas around the world (Cottingham *et al.* 2004; Meyer *et al.* in press). Compared with streams of undeveloped catchments, streams of conventionally drained urban catchments typically retain or process less of the nutrients in stream water, have greater in-stream plant growth, and have fewer animal species — and those species present tend to be adapted to high levels of disturbance (Table 2).

In streams draining catchments with little or no human land-use impacts, the primary disturbance that animals and plants experience is a flood disturbance that may occur on average once in one or two years with variable intensity. Urban stormwater impacts alter that disturbance regime drastically. To describe the

Box 4. Defining 'small-to-moderate' and 'large' storms

Walsh *et al.* (in press) defined a **'small-to-moderate' storm** as one that is large enough to produce runoff from impervious surfaces, but not so large that it would have produced overland flow from a block of land in the catchment before the land was developed. The lower size limit for such a small storm is sometimes called 'effective rainfall', and is typically assumed to be 1 mm/day. The upper limit (i.e. the rain required to produce overland flow) will depend on the climate of the region, the topography, geology, soils and vegetation of the catchment, and the size of the block of interest. We are most interested in blocks of a size at which stormwater management can be primarily applied: the housing allotment or the streetscape. Walsh *et al.* (in press) estimated that rainfall of 15 mm/day was required to produce overland flow from a 600 m^2 allotment in a naturally forested catchment in the Dandenong Ranges, east of Melbourne. (To make this estimate, they used a local rainfall record and a simple rainfall–runoff model: Chiew and McMahon 1999; Cooperative Research Centre for Catchment Hydrology 2003.)

In the pre-urban, forested condition of the Dandenong Ranges, daily rainfall of >15 mm, defined as a **large storm**, generates runoff on approximately 4% of days (15 days per year on average, most of these occurring during the wettest months of September–November). Frequency of runoff from impervious surfaces (daily rainfall > 1 mm) would be 33% (121 days per year on average). So in summary for the Dandenong Ranges, in an average year:

- Dry weather occurs on 67% of days (244 days per year)
- Small–moderate storms occur on 29% of days (106 days spread throughout the year)
- Large storms occur on 4% of days (15 days per year, rarely outside the three wettest months of the year).

As noted above, the values of these statistics (size range of small-to-moderate storms, their frequency and distribution throughout the year) will differ between regions and catchments, and perhaps within catchments depending on soil and topographic characteristics. However, the general pattern of smaller rain events being more frequent and more widely spread throughout the year than larger rain events will apply in most coastal regions of south-eastern Australia.

changes in the disturbance regime, we follow the conceptual framework of Walsh *et al.* (in press) that compared a stream in a forested catchment with a stream draining a conventionally drained, moderately urbanized catchment (Table 3). This framework distinguishes three primary states to illustrate the differences in disturbance regime:

a) dry weather, which is the norm for most of the year in all of New South Wales;

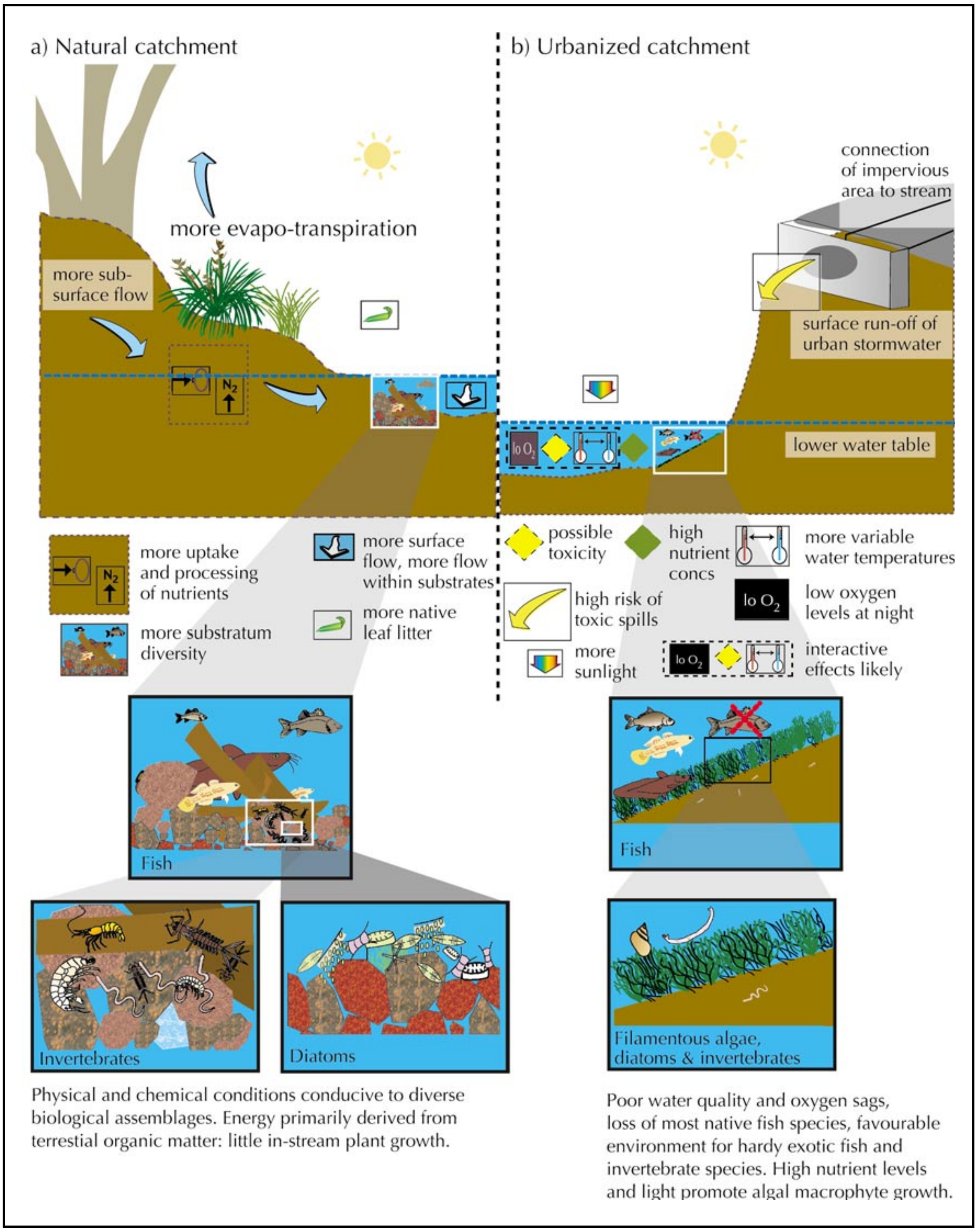
b) frequent, small–moderate storms; and

c) infrequent, large storms (we define these categories of storm in Box 4).

2.4.1 Dry weather

During dry weather (Fig. 6), the stream degraded by urbanization is a product of channel form changes that have occurred during past high-flow events. The loss of large particles (e.g. cobbles) from erosional zones and infilling by

Figure 6. Dry weather. Conceptual model of structure and function of a stream draining a) a forested catchment and b) a conventionally drained urbanized catchment in periods of no rain.



Physical and chemical conditions conducive to diverse biological assemblages. Energy primarily derived from terrestial organic matter: little in-stream plant growth.

Poor water quality and oxygen sags, loss of most native fish species, favourable environment for hardy exotic fish and invertebrate species. High nutrient levels and light promote algal macrophyte growth.

fine sediments in depositional zones, together with reduced baseflow[e] result in much reduced flow of water through the streambed. In streams draining relatively undisturbed catchments, this 'hyporheic' flow is responsible for a major part of in-stream processing of nutrients in many undisturbed streams (e.g. Mulholland *et al.* 1997), as well as being habitat for a poorly-studied but diverse fauna (called hyporheos: Boulton *et al.* 1998).

Erosion and incision of channels result in wider channels, so that even where riparian vegetation has been protected, the capacity for the riparian zone to shade the stream is reduced. The increased light to the surface of the stream together with the increased baseflow concentrations of nutrients results in excessive growth of algae and perhaps flowering aquatic plants (called macrophytes) on the bottom of the stream. The algae growing in well lit, nutrient-enriched streams are often dominated by filamentous green and blue-green algae, as well as diatoms (single-celled algae with shells made of silica), which grow on the algal filaments, rocks and sand of the stream.

In contrast, the well-shaded, low-nutrient conditions that are more typical of streams in undisturbed, forested catchments result in much less obvious algal growth, dominated by sparse covering of rocks by diatoms more adapted to these conditions.

Most of the carbon and nutrients that make up and are used by the microbes, plants and algae in streams of undisturbed, forested catchments come from the riparian zone; from leaf litter, wood and forest insects falling into the stream (Minshall *et al.* 1983). In streams of urban catchments, carbon that is fixed by plants in the stream (algae and macrophytes) by photosynthesis becomes more important (Grace and Walsh unpublished).

Streams in undisturbed catchments generally support diverse assemblages of invertebrates (insects, crustaceans, worms, etc.), with many species of sensitive groups such as mayflies, stoneflies and caddisflies. Streams of many parts of south-eastern Australia, including areas that are vulnerable to future urban development are home to many invertebrate species that are only found over a very limited area, and are therefore of conservation significance (Chessman and Williams 1999; Walsh *et al.* 2004). In contrast, streams of conventionally drained urban catchments have a much less diverse assemblage of invertebrates, usually dominated by a few types of worms, midge larvae and snails, all tolerant of pollution and hydraulic disturbance, and many originating overseas (e.g. Chessman and Williams 1999; Paul and Meyer 2001; Walsh *et al.* 2001; Wang and Lyons 2003). Such assemblages are subject to a range of interacting disturbances during dry weather flows, resulting in the loss of many of the more sensitive species (Fig. 6).

Native fish species and other aquatic vertebrates, such as platypus (Serena and Pettigrove in press), frogs and turtles, are also likely to be stressed by baseflow conditions in streams of conventionally drained urban areas, as well as being limited by the reduced habitat complexity of the incised channels.

So, stream ecosystems continue to suffer the impacts of urban stormwater runoff during periods of dry weather. Low flows, more light, and high nutrient concentrations combine to promote increased growth of plants, particularly filamentous algae and macrophytes. The resulting large fluctuations in dissolved oxygen concentrations combine with reduced habitat complexity and the increased risk of dry weather toxic spills from conventional stormwater drains to stress in-stream animals and exclude many sensitive species. The areas of eroded substrate and other areas filled in with sediment combine with the low flow to result in very little processing of nutrients within the streambed sediments.

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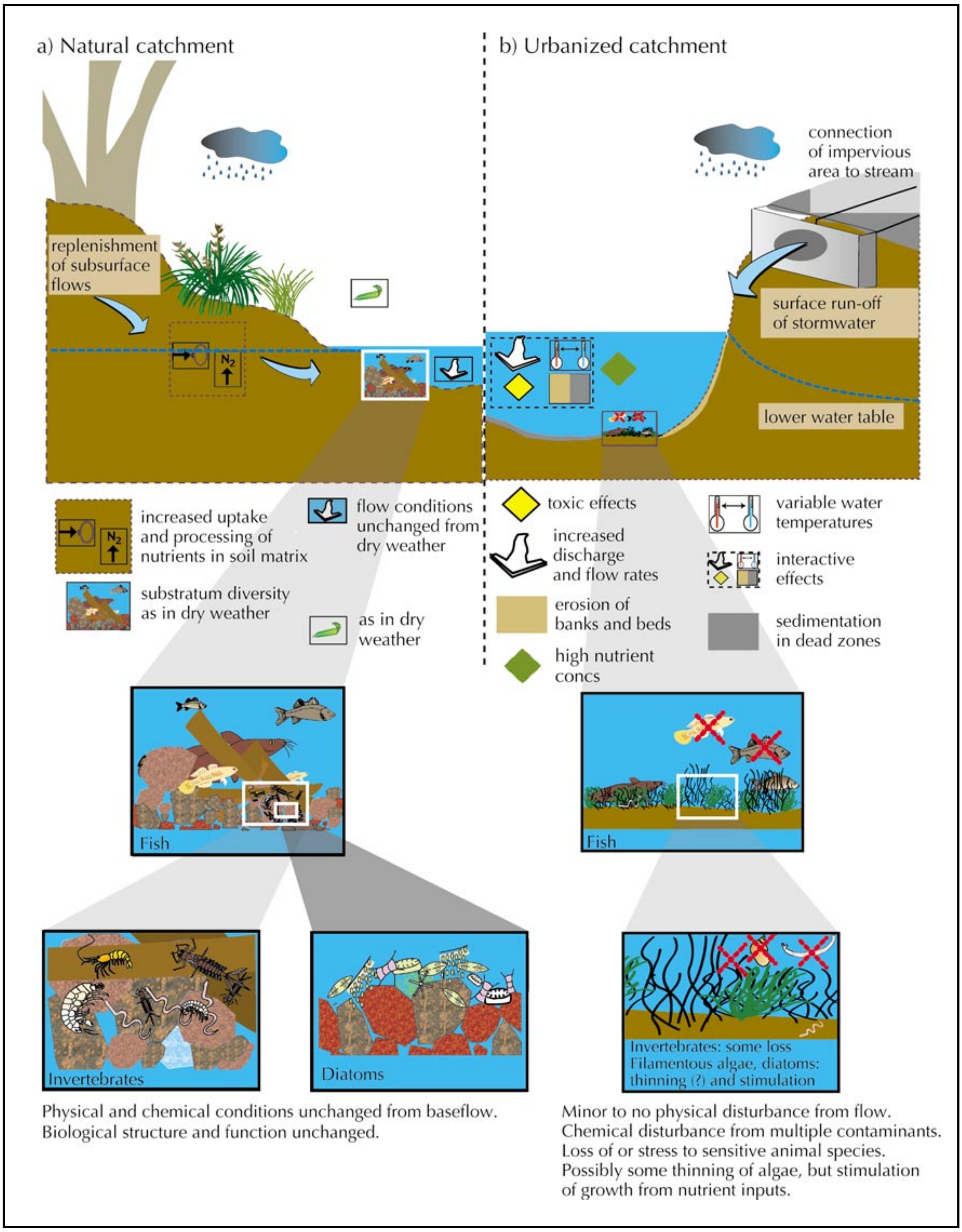
[e] While we acknowledge that a reduction in baseflow is not a universal trend in streams of urban catchments, we argue that effective impervious areas must reduce baseflow. Other factors associated with urban land (such as leakages from water supply or sewerage infrastructure) may counter this effect. As the focus of this report is stormwater, we will assume that these other factors are not significant in our conceptual framework.

Figure 7. Streams following small–moderate rain events. Conceptual model of structure and function of a stream draining a) a forested catchment and b) a conventionally drained urbanized catchment following a small–moderate rain event (>1mm and less than large enough to produce surface runoff in an undeveloped catchment).



2.4.2 Following a small-to-moderate storm

Small-to-moderate storms (Box 4; Fig 7) serve to replenish subsurface flows in catchments unaffected by urban land-use, thereby maintaining baseflow. In streams of such catchments, these storms generally cause negligible or very little increase to the flow rate of receiving streams (Fig. 3). So the stream in an undeveloped catchment experiences no change from baseflow conditions following small storms (Fig. 7a). To use the statistics for the Dandenong Ranges (Table 3, Box 4), animals and plants living in the stream of the undeveloped catchment experience no disturbance from high flow for 350 days each year (246 dry weather days and 106 days of small–moderate storms).

In contrast, the stream of the conventionally drained urban catchment experiences flow-related disturbances of varying intensity 130 days each year (combined average frequencies of small-to-moderate and large storms). Stormwater runoff delivered by conventional drains following small-to-moderate storms increases flow rates in receiving streams. For small storms, the hydraulic disturbance to animals and plants is likely to be minor, but in moderate storms, it will be more significant and can cause erosion of stream channels (Fig. 7b).

Conventionally drained stormwater runoff from all small-to-moderate storms delivers high concentrations of nutrients and at least some toxicants to the stream. Taylor *et al.* (2004) suggested that these frequent pulses of high nutrient water with moderate increases in flow were the primary driver behind increases in the biomass of algae on the bottom of streams in urban catchments. The increased flow, increased concentrations of nutrients and toxicants and the increased erosion and associated sedimentation of the channel are likely to interact in complex ways to stress or kill animals that may have colonized the stream during dry weather.

The greatly increased frequency of this class of disturbance events is the most striking difference between streams of undeveloped catchments and streams of conventionally drained urban catchments. The impacts of these events are the primary drivers behind the degraded condition of the urban stream during dry weather (see previous section). It is therefore likely that the greatest benefit to the ecological condition of streams can be achieved by controlling runoff (i.e. preventing overland flow from the catchment) resulting from these small-to-moderate storms. Fortunately, from an engineering perspective, controlling small-to-moderate storms is not difficult (if this aim is applied at small scales, near source). Unfortunately, the conventional approach to stormwater drainage that has been applied widely in all Australian cities has primarily been concerned with rapidly draining runoff from large storms, and in the process doing the same for the small and moderate storms.

2.4.3 Following a large storm

When a storm is large enough to produce overland flow from parts of undeveloped, forested catchments, streams rise (Fig. 8). If the increased flow is large enough, the sediments, rocks and wood in the stream can be moved around, physically disturbing the animals and plants of the stream. Suspended sediments can scour substrates and reduce light availability to plants in the bottom of the stream. Nutrients and other contaminants can also be mobilized in these high flow events and all these effects interact to stress and kill some animals and plants (Fig. 8a).

However, streams of undeveloped catchments have plentiful refugia[f], and many animals are able to use these areas in times of disturbance to allow recolonization after the flood. Because such floods usually occur during late winter or spring, many species have life cycles that are adapted to this disturbance cycle.

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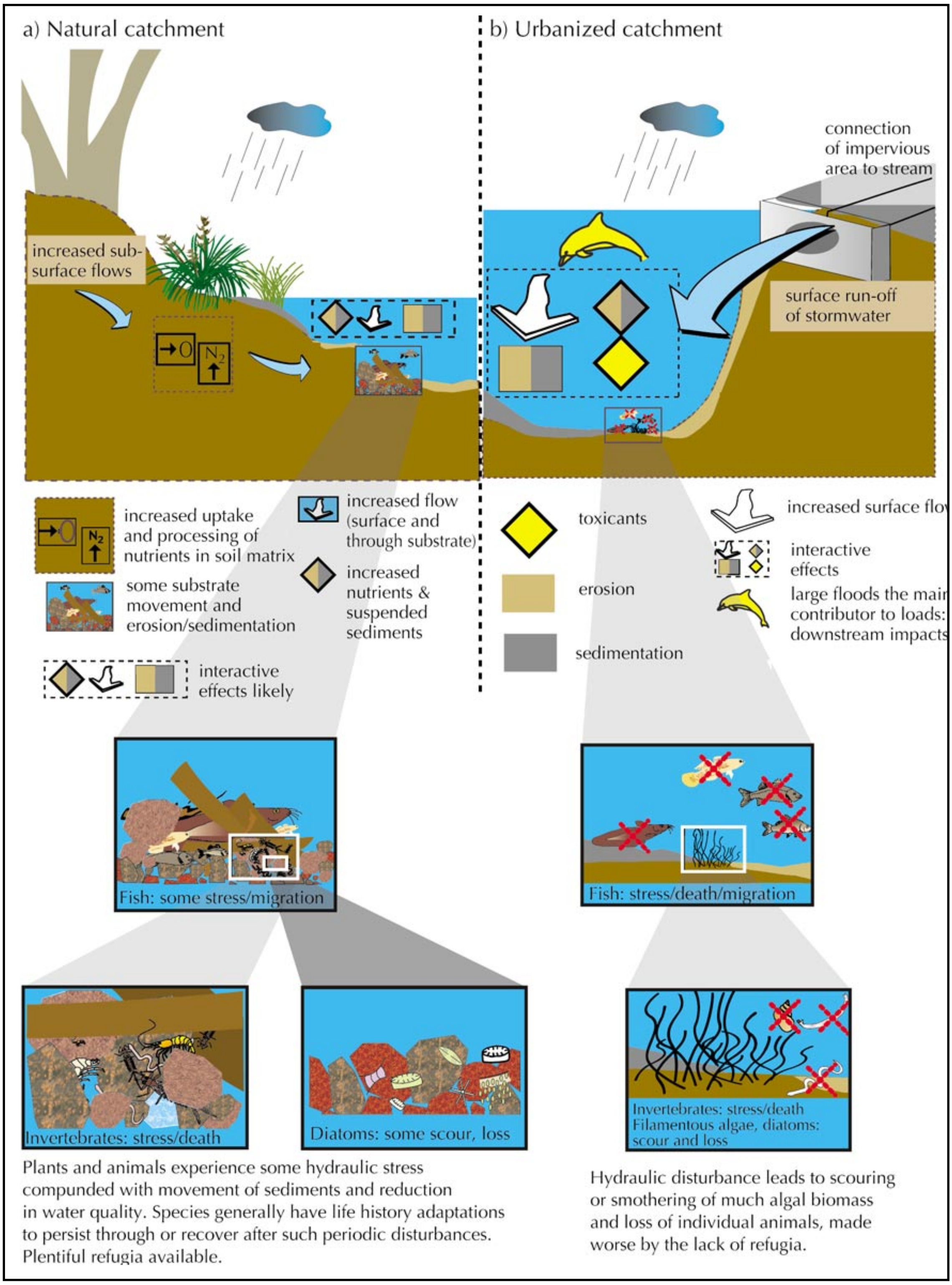
[f] Refugium (refugia): A place (places) to hide from the disturbance, such as within the deeper sediments, or in dead-flow zones that may be caused by large objects or backwaters in the complex stream channel, or perhaps in temporary waters formed on the floodplain.

Figure 8. Streams following large rain events. Conceptual model of structure and function of a stream draining a) a forested catchment and b) a conventionally drained urbanized catchment following a large rain event (a storm large enough to produce surface runoff in an undeveloped catchment).



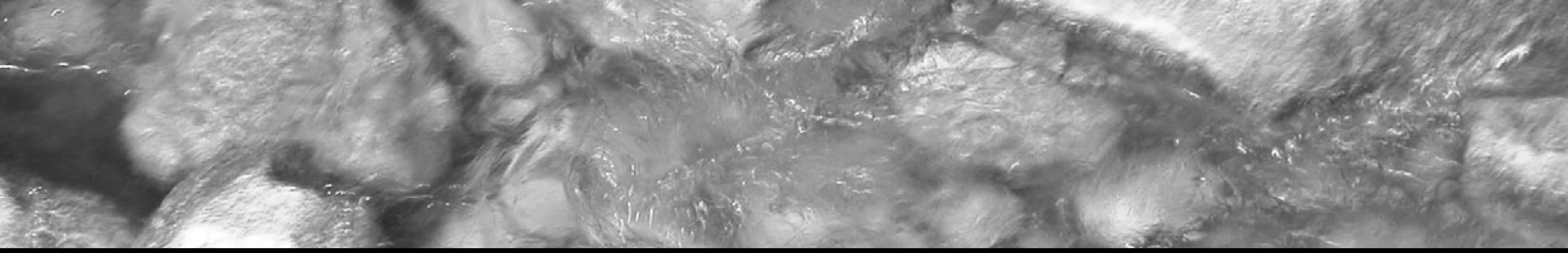
Plants and animals experience some hydraulic stress compunded with movement of sediments and reduction in water quality. Species generally have life history adaptations to persist through or recover after such periodic disturbances. Plentiful refugia available.

Hydraulic disturbance leads to scouring or smothering of much algal biomass and loss of individual animals, made worse by the lack of refugia.

In degraded streams of conventionally drained urban catchments, the floods following large storms are likely to produce more severe disturbances than equivalent floods in streams of undisturbed catchments because they will be associated with larger inputs of contaminants, including many toxicants not found in undisturbed catchments. Furthermore there are likely to be few refugia for animals to hide from the disturbance in the degraded stream (Fig 8b).

However, the disturbance following a large storm in the degraded stream may not be more damaging to the stream's plants and animals than the disturbances resulting from more frequent moderate-size storms, particularly if moderate storms produce a large enough rise in water level to reach the bank-top. Some parts of the channel may experience more severe physical disturbance than in smaller floods, causing greater scour of algae and loss of animals. However, once the bank is breached, large increases in discharge are likely to produce only small increases in water velocity in the channel, as water spills into the floodplain.

The loss of refugia in degraded urban streams is most likely driven by the increased frequency of small floods rather than an increase in the severity of annual floods. It is therefore possible that, if small more frequent floods can be controlled, then the impacts of larger floods may be ameliorated: partly because more refugia should persist and partly because dispersed control of smaller floods by retaining the first x mm of rain should reduce the size of the resulting large flood. Even if these larger floods are associated with greater toxicity, the capacity of many stream taxa to recolonize after periodic disturbances suggests that their ecological impact may not be as great as that of more frequent smaller floods.



3. Priorities for protection of small streams from stormwater impacts

The first priority for stormwater management—if designed to protect stream ecosystems—should be the retention of water from small-to-moderate rain events. Ideally this water should be allowed to infiltrate into the soil, or evaporate or be transpired back into the atmosphere. This aim is most easily achieved at small-scales, close to the impervious surfaces that the water runs off. If, on the other hand, water throughout the catchment is collected and transported to a point some distance downstream for retention and treatment, often impractically large areas would be required to allow sufficient infiltration or evaporation.

The dispersed, catchment-wide application of water sensitive urban design (WSUD), if aimed at retaining, or allowing the infiltration of all overland flow from small rain events, will greatly reduce the risk of dry weather toxic spills. Through its effects on water pathways following rain events, such WSUD should result in baseflow conditions similar to those in streams in undeveloped catchments, both during dry weather and following small–moderate rain events. Furthermore, this strategy should ameliorate the impacts of larger, less frequent floods.

This aim is consistent with the stormwater management guidelines for British Columbia in Canada (Stephens *et al.* 2002), which include the prevention of overland flow from small, frequent rain events as a primary objective: primarily to maintain a natural water balance. However, the British Columbia guidelines take a seemingly unrelated approach to protecting stream ecosystems: the primary objective for 'biophysical protection' is to limit impervious area to less than 10% of total catchment area. The argument that a limit of catchment imperviousness to 10% is required to protect the integrity of stream ecosystems is common in the United States (sometimes termed the 10% rule, Schueler and Claytor 2000; Beach 2001; Center for Watershed Protection 2003). However, the logic behind this argument is flawed and its utility in guiding the development of urban areas is severely limited and usually impractical (Walsh 2004b).

Effective imperviousness (EI; Box 3) provides a conceptual link between the objective of minimizing overland flow and the objective of minimizing impervious area — objectives that have, to date, not been adequately reconciled. Next, we show that EI is a potentially strong predictor of the ecological condition of streams, and propose a method for determining it which links it to objectives for reducing the frequency of overland flow.

3.1 Effective imperviousness

Catchment EI has been shown to be a strong explanatory variable, not only for some stream water quality variables (Fig. 3), but also for a range of in-stream ecological indicators (Fig. 9). In streams of the Dandenong Ranges, east of Melbourne, the composition of macroinvertebrate assemblages and diatom assemblages and the biomass of algae growing on stream bottoms were all strongly explained by EI (Fig. 9a–c, Taylor et al. 2004; Walsh 2004b; Newall and Walsh 2005; Walsh *et al.* in press). There is evidence that other aspects of stream ecosystem condition show similar patterns. For instance, the ratio of production to respiration[g] within a stream reach showed a similar relationship (Fig 9d, Grace and Walsh unpublished).

Algal biomass and diatom assemblage composition reached a threshold of degradation at a low level of EI (1–5%), as did the water quality variables (section 2.3.6).

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[g] Production : respiration ratio — a measure of the relative importance of in-stream algal production compared to energy sources from outside the stream to the functioning of the stream ecosystem

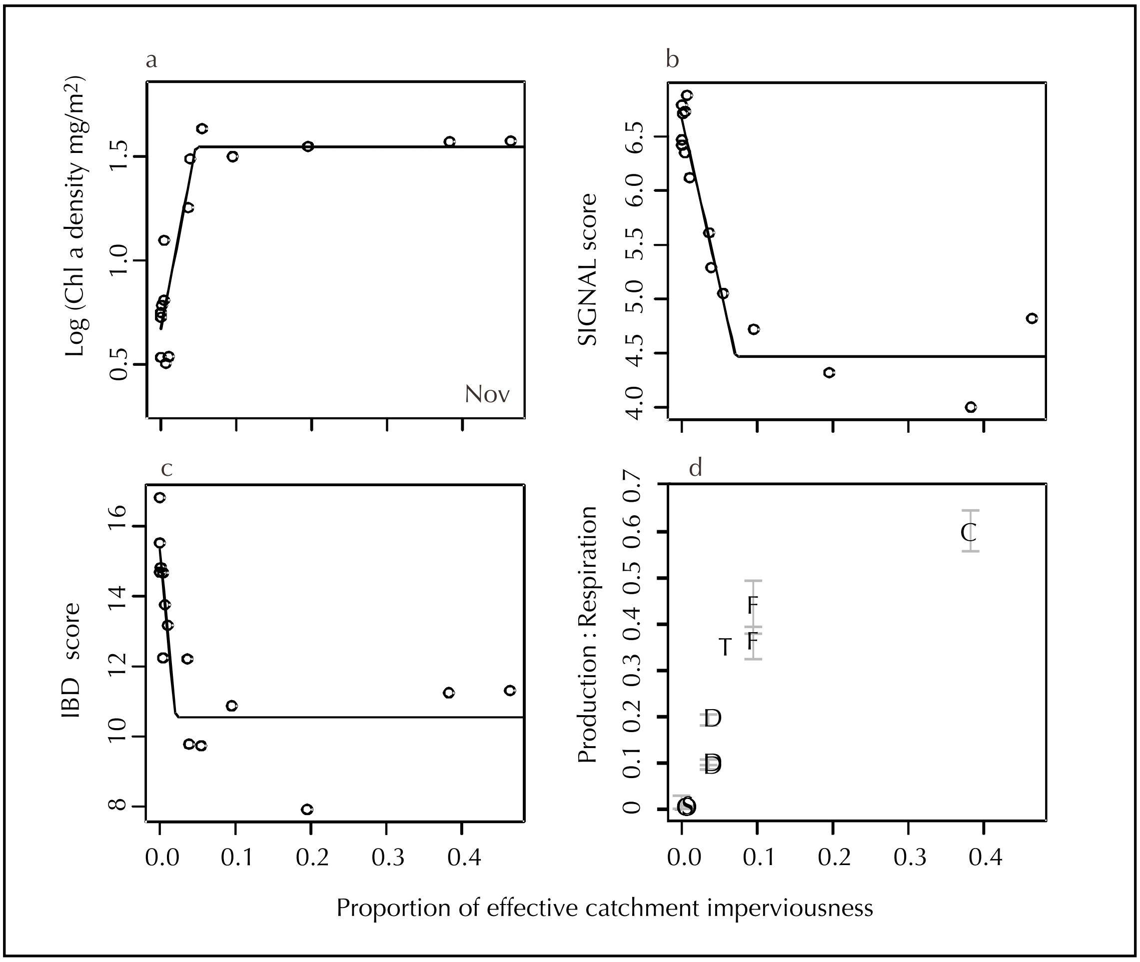


Figure 9. Representative relationships between ecological indicators and effective imperviousness in streams of the Dandenong Ranges. a) Median benthic algal biomass in Nov 2002; b) SIGNAL scores based on macroinvertebrate families collected from riffles in spring 2001 and autumn 2002; c) Indice Biologique Diatomées (IBD) based on diatom species collected in autumn and spring 2002; d) whole reach estimates of the production:respiration ratio measured on multiple occasions in most streams Dec 2002 to Feb 2003. a–c from Walsh *et al.* (in press), d from Grace and Walsh (unpublished). In a–c, points represent the mean value for each stream, and the trend lines show the best fit model determined by Walsh *et al.* (in press). In d, letters represent a mean estimate for each stream on one sampling occasion (sCotchmans, Ferny, Little sTringybark, Dobsons, Sassafrass, Lyrebird), with error bars showing the range of measurements on that occasion.

Macroinvertebrate assemblage composition appeared less sensitive to degradation, reaching a threshold at a higher level of EI (6–15%).

Based on these findings from the east of Melbourne, only a very small part of a catchment needs to be developed and conventionally drained before the biological community of its receiving stream is severely degraded. If these patterns are indicative of patterns in other regions, then the appropriate catchment objective to protect small stream ecosystems is to limit EI to less than 5%.

The nature of this objective is very different from the 10% impervious rule espoused by Beach and others (Schueler and Claytor 2000; Beach 2001; Center for Watershed Protection 2003), in which no clear distinction between TI and EI is made. Beach (2001), in particular, expressed pessimism that stormwater treatment measures could ‘break’ the rule and allow for good stream health in catchments with >10%

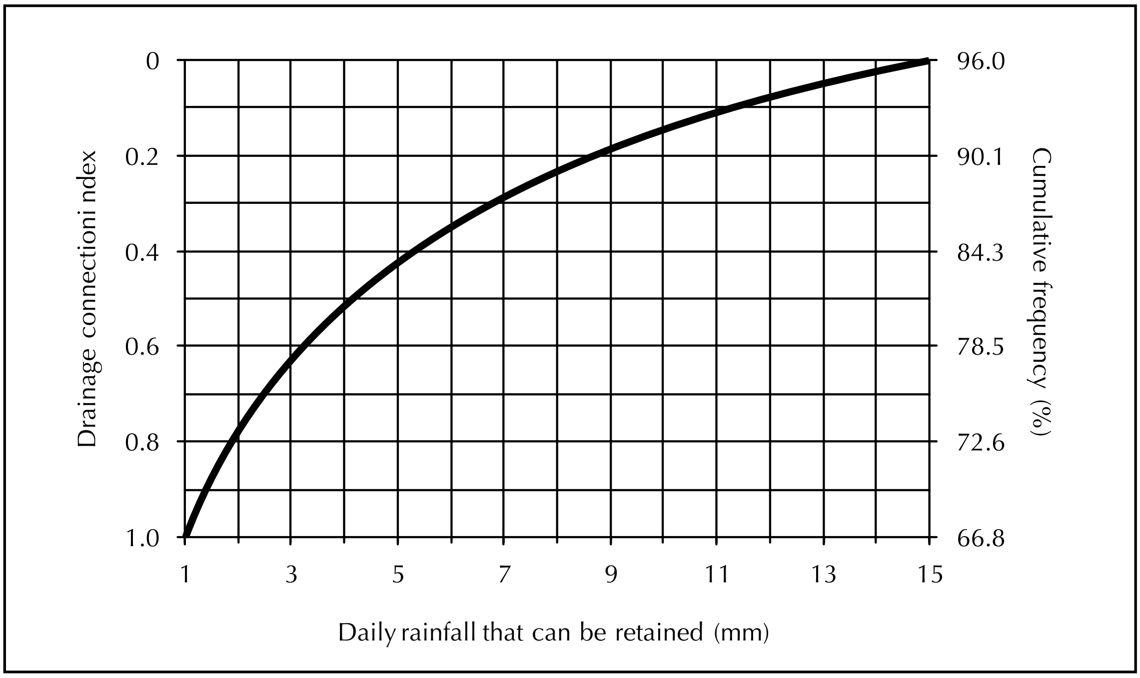


Figure 10. Cumulative rainfall frequency curve for calculating the connection index for stormwater treatment on a 600 m^2 block in the Dandenong Ranges. The x-axis is the daily rainfall that can be retained by the treatment measure from 1 mm (effective rainfall required to produce runoff from an impervious surface) to 15 mm (the average daily rain event required to produce overland flow from the block). The connection index is scaled on the cumulative frequency of the rainfall event.

imperviousness. On the contrary, we argue that the importance of EI in explaining ecological condition in streams points to dispersed stormwater treatment measures (which reduce EI) as a very practical way of achieving good stream health in urbanized catchments.

Are the patterns observed in eastern Melbourne likely to be indicative of patterns elsewhere? We cannot be certain until similar studies are conducted elsewhere. However, while no other similar studies have explicitly calculated EI, the consistent pattern of a noisy negative relationship between a range of ecological indicators and TI in cities across the USA (see review by Center for Watershed Protection 2003) suggests that similar relationships are likely, although the threshold EI is likely to vary with different climates and catchment characteristics. Ongoing research at the CRCs for Freshwater Ecology and Catchment Hydrology and the NSW Department of Environment and Conservation is testing the consistency of these relationships in several eastern Australian cities.

3.1.1 Linking effective imperviousness and frequency of overland flow

All of the Dandenong Ranges studies used a statistic termed ‘drainage connection’ to more easily separate the effects of EI and TI:

Effective imperviousness (EI) = Total imperviousness (TI) × Drainage connection

If an impervious surface was connected to a stream by a stormwater pipe or a sealed drain, we said its ‘connection’ equalled 1 — that is, its effective impervious area equalled its total impervious area. There were no formal stormwater treatment measures in any of the catchments studied: impervious surfaces that were defined as unconnected (i.e. connection = 0, EI = 0) drained either to surrounding pervious surfaces, or to vegetated or earthen swales and then to streams. The primary hydrological effect of this type of indirect drainage is interception and infiltration of water only following small rain events. For large events interception efficiency would decrease. Yet, in

Box 5. Calculating drainage connection, effective impervious area, effective imperviousness

1. Calculate the total impervious area (TIA) and the total area of the land parcel.
2. For the entire parcel, use MUSIC ('Model for Urban Stormwater Improvement Conceptualisation'; CRC for Catchment Hydrology 2003) to model the size of rain event (in mm/d) that would have been required to produce overland flow from the land when it was in its pre-developed state (Rainfall_{max}).
3. Use a local record of daily rainfall data (at least 10 y if possible) to produce a cumulative frequency curve of rainfall events, and scale the drainage connection index from 1 at frequency of 1mm/d to 0 at frequency of Rainfall_{max} (e.g. Fig. 10). (Alternatively, an existing default relationship appropriate for the catchment of interest could be used instead of steps 2 and 3.)
4. Estimate the size of the rain event that can be retained completely (i.e. no overland or piped flow) by the treatment measure. Use the connection-index v. rainfall-event-size relationship to determine connection. Effective impervious area (EIA) = (TIA x Connection)

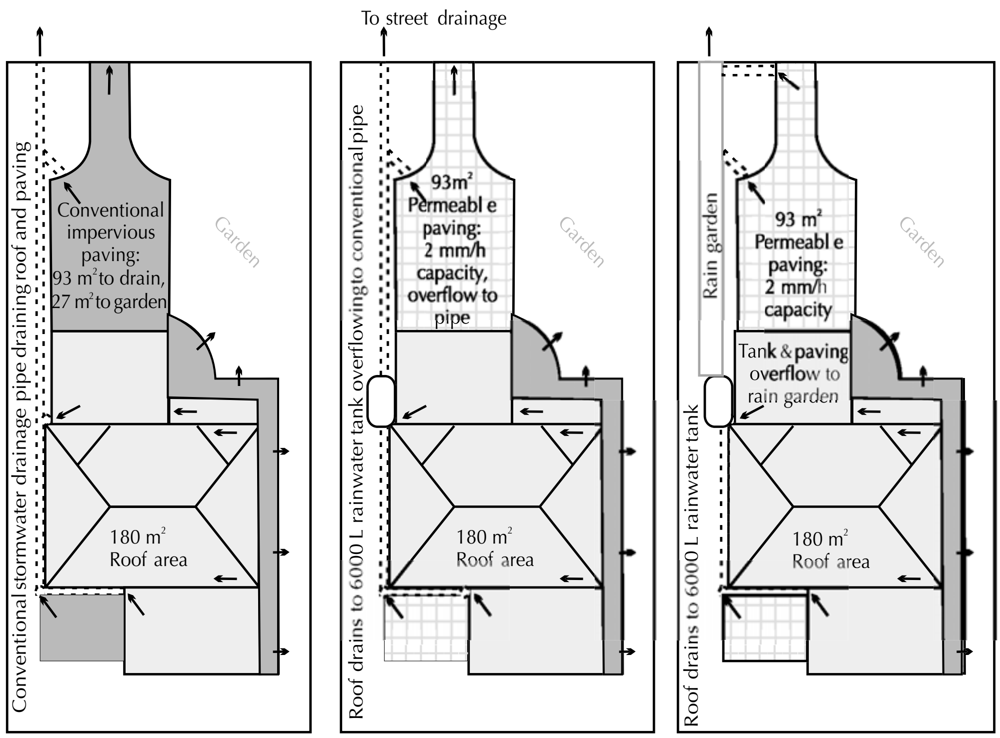
   Effective imperviousness (EI) = EIA/Total Area (e.g. Fig 11a, b).

If treatments are applied in a 'train', calculate EIA for each primary treatment. Then, for each step in the treatment train, repeat step 4, so that the EIA following step i (EIA_i) is used to calculate the resultant EIA following step i +1 (EIA_{i+1}).

$\text{EIA}_{i+1} = \text{EIA}_i$ x Connection (e.g. Fig 11c for a housing allotment and Fig 12 for a streetscape).

all studies, drainage connection was the single most important variable explaining variation in a range of ecological indicators. This suggests that these informal interceptions may have a strong influence on the receiving stream ecosystem.

However, the binary classification of impervious surfaces as connected or not, while a useful indicator in the Dandenong Ranges, is an over-simplification. The efficiency of drainage pathways is actually a continuum, from hydraulically efficient pipes to a hypothetical large retention basin that allows no overland flow in even the largest conceivable storm. We therefore propose drainage connection as a continuous variable ranging from 0 to 1. Its value is determined by the maximum size of a rainfall event that is retained by the drain or the stormwater treatment measures between the impervious surface and the stream (see Box 5). Because the major impact of conventional stormwater drainage is to increase the frequency of direct stormwater runoff to the stream, we have scaled the drainage connection index to the frequency of rainfall occurrence rather than the size of the rainfall event (Fig. 10). This means that preventing runoff from the first 5 mm of rainfall has a larger effect on the index than preventing runoff from the next 5 mm of rainfall (i.e. in Fig. 10, if a piped system is replaced with a system that retains events up to 5 mm, connection decreases from 1.0 to 0.42, but retaining 10 mm only further reduces connection to 0.15). This is consistent with the finding that swales with limited hydraulic capacity in the Dandenong Ranges appeared to be effective at disconnecting impervious areas from streams (Walsh *et al.* 2004).



(a) Conventially drained block
Property area = 600 m^2
TIA = 300 m^2
TI = 300/600 = 0.50

27 m^2 paving draining to garden
(connection = 0)

EA = 180 + 93 + (27x0) = 273 m^2

EI = 273/600 = 0.45

(b) Some stormwater treatment
As for (a) but with tank which
receives 180 m^2 roof runoff,
on avg retains 8 mm/d event
(connection = 0.23);
93 m^2 of permeable pavement
on avg retains 5 mm/d event
(connection = 0.42)

EIA = (180 x 0.23) + (93 x 0.42) + (27 x 0)
= 80.5 m^2
EI = 80.5/600 = 0.13

(c) Stormwater treatment train
As for (b) but now all runoff from
tank and permeable paving
(EIA = 80.5 m^2)
drains to a rain garden which
on avg retains 15 mm/d event
(connection = 0)

EIA = 80.5 x 0 = 0 m^2

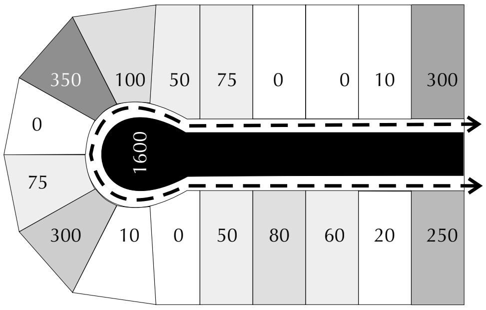
EI = 0/600 = 0

Figure 11. Three drainage scenarios for a typical housing allotment in the Dandenong Ranges, illustrating the calculation of effective impervious area (EIA) and effective imperviousness (EI) in each case. a) a conventionally drained block; b) the same allotment with a rainwater tank draining the roof, and permeable paving installed instead of conventional paving; c) as for b) but with a rain garden taking overflow drainage from the tank and pavement. Connection estimates use the curve in Fig. 10. Arrows indicate the direction of flow.

This approach to calculating drainage connection is only one possibility, but at the time of writing it is our favoured approach because it has been developed from our conceptual framework of how storms of various sizes affect stream ecosystems. Ongoing research at the CRCs for Freshwater Ecology and Catchment Hydrology is assessing how well a range of indices describing connection and EI predict stream condition in several Australian cities.

3.2 At-source treatment: control of small-to-moderate floods

Minimizing EI requires the prevention of overland flow from small-to-moderate floods. The most efficient scale at which to achieve this aim is as near the source of runoff as possible. The examples in Figs. 11 and 12 illustrate conceptually that it is feasible to achieve frequency of overland flow close to



EIA houseblocks 1630 m^2
EIA road = TI road = 1600 m^2
Total EIA pre-treatment = 3230 m^2

Biofiltration system along road
retains 10 mm event from this EIA:
connection of street = 0.15

EIA street = 3230 x 0.15 = 485 m^2
Total area of street & houseblocks = 12800 m^2
EI street = 485/12800 = 0.04

Figure 12. A streetscape of housing allotments with variable stormwater treatment at the allotment scale (numbers in each block = effective impervious area, EIA). A biofiltration system along the road verge retains and infiltrates water draining from the allotments and the road. Calculation of EIA and effective imperviousness (EI) of the entire streetscape is illustrated

the pre-urban condition at the scale of the houseblock or the streetscape in a typical suburban development, particularly if treatment measures are installed as a treatment train. There are many different treatment measures available that can form part of a treatment train (Victorian Stormwater Committee 1999; Ecological Engineering *et al.* 2004).

While the overall objective for EI to protect stream ecosystems needs to be set at the scale of the catchment, the methods for reducing connection need to be determined and applied at the scale of the development. The default aim for new developments should be EI of 0, preferably through a treatment train of small-scale treatments. The immediate aim for existing developments should be no increase in EI, and the long-term aim should be the maximum possible reduction in EI, given available space, through retrofitting of existing stormwater drainage systems as they reach the end of their life.

If existing developments have high levels of TI (say >50%), then the potential for dispersed small-scale treatment will become more limited, as pervious spaces are required for many stormwater treatment measures (although tanks for re-use, sub-pavement filtration systems and green roofs[h] are possibilities in such areas). The restoration of small streams draining highly developed catchments may be unattainable: an assessment of the stream's position on ecological-condition graphs such as Figs. 5 and 9 can assist in making this decision. If it is decided that a stream is beyond restoration, then the focus of stormwater management should turn to the next downstream receiving water: which may change the priorities for management techniques. For example, if the downstream receiving water is a lake or estuary, the primary focus may then be on load reduction.

3.3 Protection or restoration of riparian zones and catchment forest cover

Many US researchers, seeking factors other than imperviousness to explain degradation of streams in urban areas, have looked beyond drainage infrastructure for a possible cause. Some have argued that retention of watershed forest and wetland cover, and wide continuous riparian buffers with mature native vegetation are important catchment features to mitigate the impacts of urbanization (e.g. Horner *et al.* 2001). Stephens *et al.* (2002) proposed the retention of 65% forest cover across the catchment and a 30-m-wide intact riparian corridor along all streamside areas, as primary objectives for stormwater management in British Columbia.

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[h] Green roofs are covered with a permeable layer of soil and planted with vegetation. They are a more common feature of cities in Europe than Australia.

While the nature of catchment vegetation, and particularly riparian vegetation, can be an important determinant of the nature and condition of stream ecosystems, these recommendations in the context of stormwater management are flawed because they divert attention away from the problem (stormwater drainage infrastructure). For instance, the catchments of the Dandenong Ranges studied by Walsh and colleagues (Hatt *et al.* 2004; Taylor *et al.* 2004; Walsh 2004b; Walsh *et al.* 2004; Newall and Walsh 2005; Walsh *et al.* in press) were chosen so that forest and urban land-use combined to form all or almost all of catchment land coverage. Yet catchments with forested reserves as the dominant land-use but with as little as 5–10% EI drained to streams in poor ecological condition. So, although there may be good reasons for aiming to maximize forested land in urbanized catchments, any beneficial effects they may have on streams are likely to be substantially reduced or annulled by impacts of conventional drainage design.

The conservation and restoration of riparian vegetation, more than catchment vegetation, has been a common focus of waterway management in urban and rural areas. Generally, riparian vegetation has a strong influence on stream ecology (e.g. Groffman *et al.* 2003; Pusey and Arthington 2003). Beneficial riparian effects on streams include:

- moderation of water temperature;
- shading, which reduces in-stream plant production;
- supply of organic matter, such as leaves and terrestrial insects to provide energy to the stream food web;
- supply of woody debris to create stream habitat;
- interception of sediments and other contaminants from the adjacent catchment;
- the uptake and transformation of nitrate from shallow groundwater.

However, almost all of these effects of riparian vegetation are substantially reduced by the impacts of conventional stormwater drainage described in section 2. Stormwater-induced incision and widening of stream channels reduces riparian effects on temperature and shading. Increased flashiness of flows reduces the retention of woody debris and other organic matter. The bypassing of riparian zones by stormwater drainage pipes removes or greatly reduces their capacity to intercept contaminants from the catchment. Incision, in combination with reduced infiltration in the catchment, can reduce riparian groundwater levels, which can have dramatic effects on soil, plants, and microbial processes. Groffman *et al.* (2003) found drier more aerobic riparian soils in more urbanized streams than in rural streams. The drier urban riparian soils had comparatively high nitrification rates (producing nitrate) and low denitrification rates (converting nitrate into other compounds including nitrogen gas). Groffman *et al.* (2003) suggested that, in highly urbanized catchments, riparian zones might in fact become sources of nitrate to the stream rather than the sinks that they are usually considered.

Riparian management in urban catchments is therefore not a simple issue. However, the beneficial effects of riparian vegetation on stream condition are likely to be enhanced if stormwater is managed by dispersed treatments in the catchment. Dispersed stormwater management can maintain groundwater levels and avoid bypassing the riparian zone by direct piping to the stream.

Conventional stormwater drainage can potentially threaten riparian zones of high conservation value. Stormwater draining from upland suburbs above Lane Cove bushland in Sydney resulted in contamination of the naturally low-nutrient floodplain soils with heavy metals and nutrients, resulting in uncontrollable weed invasion (Riley and Banks 1996). Dispersed upland treatment of stormwater draining from these suburbs may alleviate this problem.

So, conservation and restoration of riparian vegetation should not be considered a primary objective for stormwater management, as suggested by Stephens *et al.* (2002). On the contrary, sound management of stormwater drainage systems is likely to be required to make the conservation and restoration of riparian vegetation possible.

3.4 End-of-pipe treatment: the final carriage of the treatment train

By recommending the primary use of dispersed, retention and infiltration treatments, we have emphasized the importance of mimicking terrestrial processes in managing stormwater. We have de-emphasized the use of stormwater treatment wetlands and ponds, which have been the cornerstone of so-called ‘Best Management Practice’ in 1990s USA (Roesner *et al.* 2001), and continue to be important elements of stormwater management in Australia (Lawrence and Breen 1998).

Wetlands and ponds can be effective means for reducing contaminant loads downstream, but their effectiveness will be limited unless they are appropriately designed and placed at the end of the treatment train. It is possible that, in some circumstances, wetlands may have deleterious effects on stream ecosystems by increasing baseflow concentrations of some contaminants and increasing stream temperature (Walsh 2004a, and see section 2.3.5).

If the primary aim of stormwater management is the protection of a receiving small stream, then we recommend that off-stream wetlands or ponds be used only as part of a more dispersed treatment train. Large wetlands and ponds are more appropriate stormwater treatment techniques when the principal aim is loads reduction to protect larger downstream receiving waters.

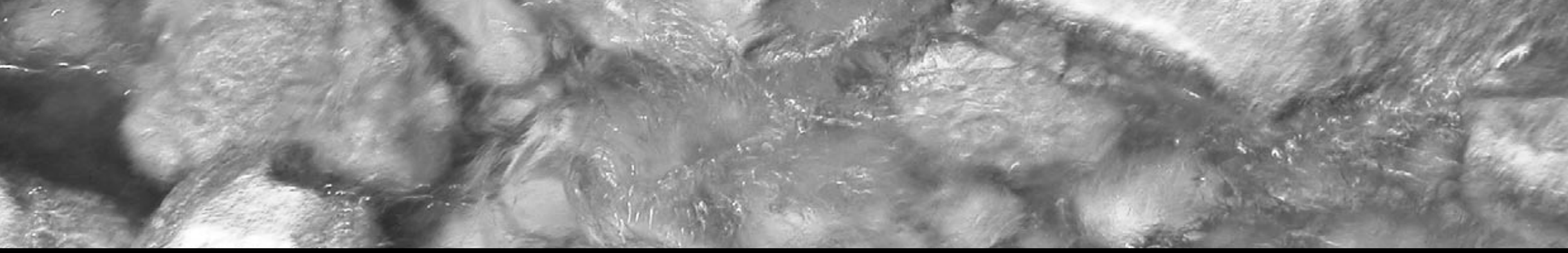
3.5 Summary of stormwater management objectives to protect stream ecosystems

The protection of stream ecosystems from urban land-use can only be achieved through a catchment-wide application of appropriate stormwater treatment.

The first step is to determine the catchment characteristics of the stream: most importantly its current EI. For good stream condition, the aim is a catchment EI of very much less than 5%.

To achieve this aim, stormwater drainage in all developments in the catchment must retain water for infiltration, evapotranspiration or re-use from all rain events up to the size of event that would have produced overland flow from the development in its pre-urban state.

If the physical (and social and economic) constraints of existing catchment development preclude reduction of EI to low enough levels to produce a predicted improvement in condition of the receiving small stream, then stormwater management should be aimed at the next receiving water downstream.



4. A few words on other receiving waters

4.1 Rivers

The national water quality guidelines make a distinction between upland streams (which are mostly small) and lowland streams (Table 1, ANZECC and ARMCANZ 2000). In this report, because our emphasis is on catchment effects, we have chosen to distinguish between streams on the basis of catchment size: fewer large rivers are severely degraded by urbanization because of their large catchments. Only large rivers whose catchments contain large cities are likely to be severely degraded by urban land-use. Most large rivers, however, would be considered lowland.

It is likely that large rivers respond to catchment EI in the same way as small streams. Degradation of the Yarra River, which flows into Melbourne, Victoria, appears to follow a trajectory very similar to that seen in small streams. A longitudinal study of macroinvertebrate assemblages in the Yarra showed detectable degradation in assemblage composition in reaches with >3.4% TI, with severe degradation typical of degraded metropolitan small streams observed in reaches with >7% TI (C. J. Walsh unpublished data, Gippel and Walsh 1999). The mechanisms behind these impacts are likely to be very similar to those described for small streams.

The ecology of large rivers has much in common with the ecology of small streams, but a few differences are noteworthy. Because they are generally wider, they usually receive more sunlight. Particularly in lowland rivers, plankton communities (i.e. weak-swimming microscopic plants and animals that float in the water column) are more important components of large riverine communities. If the river is deep and turbid, most of the biological activity is likely to be concentrated around the shallow edges of the channel (Thorp and Delong 1994).

The floodplains of lowland rivers are particularly important to their functioning (e.g. Junk *et al.* 1989), with transfer of materials and energy between the floodplain and the channel being a critical element of lowland river function. This feature of lowland rivers is often disrupted by urbanization if floodplains are built upon and the rivers are engineered to prevent floodplain inundation.

4.2 Lakes and wetlands

In contrast to streams in which disruption to flow is a critical element of stormwater impacts, the ecological effects of urban stormwater on lakes and wetlands are primarily associated with reduced water quality. In particular, increased loads of nutrients may accelerate the process of eutrophication. More localized impacts may occur from other contaminants, particularly toxicants.

The nutrient most commonly causing eutrophication in freshwater lakes is phosphorus, and, like other contaminants, in general it increases with levels of EI. In lakes, as in streams, it is important to link management planning and actions within a catchment to ecological responses by using predictive models. Several models exist for linking changes in nutrients (particularly phosphorus) to changes in phytoplankton (algae) to changes in zooplankton (animals) (Lathrop *et al.* 1998; Hipsey *et al.* 2003). Sustainable nutrient loads will most likely need to be estimated for each lake or wetland individually. This load target can be assessed against estimates of contaminant loads resulting from potential development or stormwater management scenarios using MUSIC (Model for Urban Stormwater Improvement Conceptualisation; Cooperative Research Centre for Catchment Hydrology 2003).

Stormwater inputs to lakes may cause pulses of contaminants other than nutrients in the water column, and may cause more persistent contamination of bottom sediments, possibly leading to toxicity. As for nutrients, modelling is required to determine the effects of possible development or management scenarios on toxicity in the lake. One possible approach to assessing the ecological impacts of toxic inputs is to use a fate and transport model to predict the likely contaminant exposures in the water column and bottom sediments and compare these exposures to toxicological information. The effects of a mixture of multiple contaminants together with physical effects such as changes to the light climate could be modelled (Warne 2003). This approach will give a reasonably precautionary and practical approach to determining if toxicity is likely to occur in a given management scenario.

Thus for lakes, stormwater management for contaminant loads is appropriate. While it has been common to model lake responses to land-use by assuming a standard load from urban land-use (e.g. Soranno *et al.* 1996), it is critical for determining appropriate stormwater management options that loads estimates be made for urban land using realistic estimates of effective imperviousness.

4.3 Estuaries and coastal embayments

Perhaps more commonly than any other aquatic ecosystem, estuaries[i] are subject to urban impacts, because they provide ideal locations for human settlements. Surprisingly, despite this, the relationship between urban land-use and the ecology of estuaries has been poorly studied. It is likely that the impact of urban stormwater on estuaries will decrease with increasing degrees of tidal flushing.

There are a variety of estuarine forms, varying in degrees of tidal flushing (Morrisey 1995). All estuaries are dominated by soft sediments that settle in their sheltered waters. The accumulation of contaminants from stormwater (and other catchment activities) in estuarine sediments is likely to be a long-term impact.

Two studies have demonstrated ecological impacts of urban land-use on well-flushed estuaries. Morrisey *et al.* (2003), studying several large estuaries in the Auckland region, showed that the composition of invertebrate assemblages living in estuarine sediments (benthic invertebrates) was correlated with concentrations of sediment contaminants. Furthermore, assemblages of more urbanized estuaries were more alike to each other than they were to rural estuaries. If the major mechanism for degradation in estuaries is through contamination of sediments, then it is likely that attempting to control contaminant loads will be the most appropriate approach to stormwater management.

However, a study of small tidal creeks in the USA found that one of the impacts of catchment urbanization was increased variability in salinity, as stormwater flowed into the tidal creeks following each rain event (Lerberg *et al.* 2000). This suggests that stormwater management approaches that control the frequency of runoff (as proposed for the protection of small streams), rather than load reduction, would be more appropriate at least for small estuaries. Lerberg *et al.* (2000) also found benthic invertebrate assemblage composition in the tidal creeks was correlated with catchment imperviousness, as found in freshwater systems.

Coastal embayments (for example Botany Bay, Sydney, or Port Phillip Bay, Melbourne) are regarded separately from estuaries, as they are generally not detectably diluted by freshwater inputs. These embayments and the ocean are perhaps the most resilient to urban stormwater impacts, primarily because they

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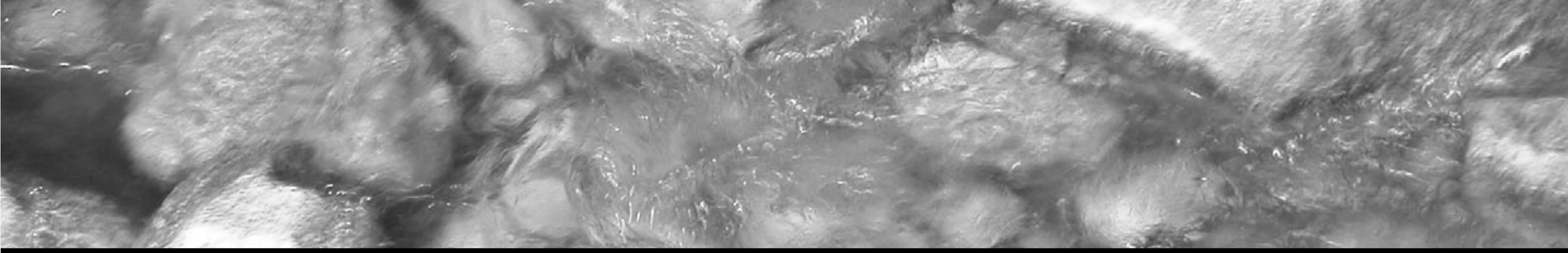
[i] Estuary: a semi-enclosed coastal body of water, which has a free connection with the open sea, and which is measurably diluted by freshwater draining from the land (Morrisey 1995).

have a very large capacity for dilution of stormwater effects from tidal flushing.

Impacts from stormwater in marine ecosystems are possible. In the ocean off Cairns, impacts to the Great Barrier Reef occur from both agricultural and urban stormwater (Williams 2001). However, impacts are most likely in sheltered environments with limited flushing, such as urbanized embayments, harbours and marinas.

Loads-based management is most appropriate for marine waters.



5. Concluding comments

Current research suggests that it is possible to develop an urban catchment at least up to a density typical of Australian suburbs, and have an ecologically healthy stream flowing out of it. That target has yet to be achieved anywhere in the world.

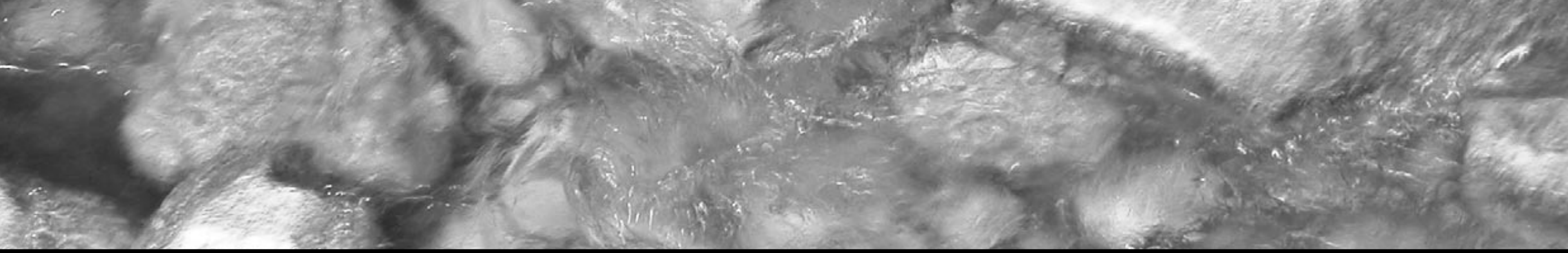
Achieving this aim will require a radical and universal change in practices and attitudes to planning and building stormwater drainage, catchment-wide. It will require that all stormwater drainage be constructed to retain all water from small-to-moderate storms.

This is a departure from stormwater management of the recent past, which has focused on reduction of contaminant loads. The new, recommended approach is compatible with objectives for reducing loads, but it introduces a new and important dimension that is critical to the ecology of streams and tidal creeks, if not larger estuaries as well: that is, reducing the frequency of disturbance.

For lakes, wetlands, some relatively enclosed estuaries and the ocean, objectives for reducing contaminant loads are appropriate.

The management of stormwater impacts to any waterbody is ultimately acted out on each parcel of land that is being or has been developed somewhere up in the catchment. One question, critical to the health of the waterbody, needs to be asked in each land parcel: namely,

> *What pathways will rain take once it has fallen on this land?*



6. Acknowledgements

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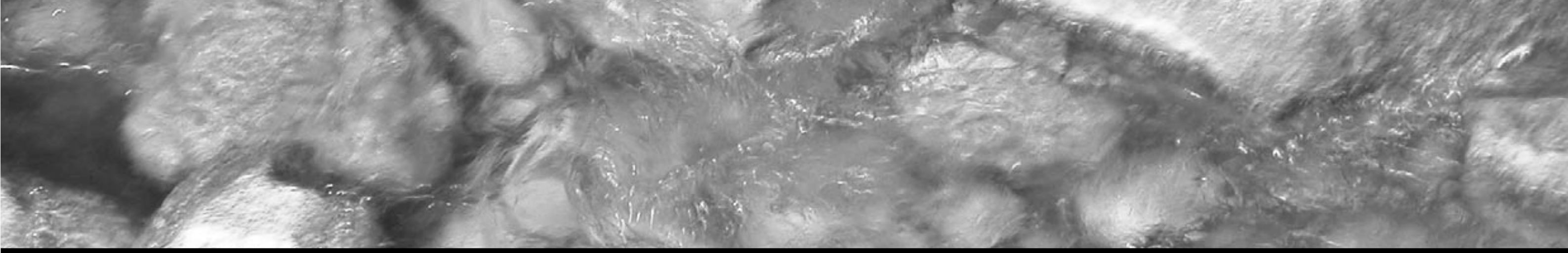

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