Melbourne Waterway Research-Practice Partnership

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# The feasibility of maintaining ecologically and geomorphically important elements of the natural flow regime in the context of a superabundance of flow: Stage 1 – Kororoit Creek study

Hugh P Duncan, Tim D Fletcher, Geoff Vietz & Marion Urrutiaguer

THE UNIVERSITY OF MELBOURNE

WATERWAY ECOSYSTEM RESEARCH GROUP

Melbourne Water

## Technical Report

14.5

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## *The feasibility of maintaining ecologically and geomorphically important elements of the natural flow regime in the context of a superabundance of flow – Stage 1: Kororoit Creek Study*

**Report to:** **Melbourne Water**

**Published:** September 2014

**Cite as:** *Duncan, HP, Fletcher, TD, Vietz, G & Urrutiaguer, M (2014) The feasibility of maintaining ecologically and geomorphically important elements of the natural flow regime in the context of a superabundance of flow. September 2014. Melbourne Waterway Research-Practice Partnership Technical Report. 14.5.*

**Contact authors:** **Hugh Duncan** (hugh.duncan@unimelb.edu.au), **Tim Fletcher** (tim.fletcher@unimelb.edu.au), **Geoff Vietz** (g.vietz@unimelb.edu.au) or **Marion Urrutiaguer** (marion.urrutiaguer@melbournewater.com.au)

**Reviewed by:** Darren Bos and Chris Walsh (The University of Melbourne)

Cover photo: Photograph of Kororoit Creek at gauging site at Holden Road, Diggers Rest

# Summary

This project is testing the extent to which ecologically and geomorphically important flow metrics can be maintained at their pre-development level in the context of an increase in flow volume due to urbanisation. In this first stage of the project, we tested this question for the ephemeral Kororoit Creek catchment, using seven flow metrics:

- Tqmean
- Fraction of time > $Q_{1.5yrARI}/2$
- Fraction of time > $Q_{2yrARI}/2$
- R-B Index
- Days per year of zero flow
- Mean duration of zero flow periods
- Month of minimum monthly flow

The results demonstrated that each of the flow metrics is drastically changed by the level of urbanisation proposed for the catchment. The testing undertaken demonstrates that it is not possible to return these flow metrics to near their pre-development state without achieving total runoff volume reductions in the range of 70-90% below the fully urbanised state. It should also be noted that only a limited number of stormwater management strategies within that volume reduction range maintain flow metrics close to their natural values. A summary of the results and their implications is given below

- For this catchment, it seems that closely approaching pre-urban metrics will require significant reductions in total runoff volume (70-90%).

- The ephemeral nature of the upper Kororoit Creek catchment means that meeting the metrics relating to low flows is challenging.

- Important variations in performance against the adopted flow metrics can be observed for the same volume reduction with changes in stormwater management strategies. However the volume reduction objective adopted has overall a much larger influence on the performance against the flow metrics adopted (than changes in management strategies).

- Performance against the adopted metrics for a given runoff reduction is improved when all impervious runoff is intercepted. Runoff from impervious areas is very destructive to the flow regime, even when contributed by only a small fraction of the total catchment area.

- It is important to note that stormwater needs to be harvested at a point upstream of the smallest tributaries within the catchment for all these receiving waters to be protected. This way flows are intercepted before they enter the natural drainage network, rather that harvesting downstream, where damage to upstream waterways will have already been done.

***The results of the Kororoit Creek catchment modelling indicate that, at least for ephemeral streams, unless a water balance close to natural is achieved, hydrologic and geomorphic characteristics key to ecological processes and functions will not be retained and the waterway will thus be significantly altered. In any case, the stream's ephemerality and the particular ecological values that are unique to ephemeral stream in Melbourne will be lost.***

The next stages of the project will test the degree to which these results apply to wetter catchments, and will attempt to derive predictions of the ecological consequences of the modelled hydrologic outcomes.

# Introduction

This report outlines the results of the first stage of the Melbourne Waterway Research & Practice Partnership project 2.1: Optimizing flow regimes in the context of a superabundance of water.

## Project overview

This project aims to assess to what extent stream flow regime can be maintained at levels likely to sustain healthy ecosystems if a catchment's total runoff volume remains significantly greater than natural with the stormwater management measures adopted as part of urbanisation. This question is currently very relevant as a number of studies done across the Melbourne region indicate that retaining enough stormwater to match natural total runoff volume can be challenging for a range of reasons including cost and lack of demand (see for example Wettenhall, 2013), and may thus not be achieved everywhere. In this context, it would be very useful to understand whether stormwater measures could be designed so that the resulting flow regime can support a healthy ecosystem despite total runoff volume exceeding its natural level.

The approach adopted in this project is to examine this question for 2-3 case study catchments with the aim to generalise findings where possible in order to provide practical guidance for developments in the Melbourne region. The steps in the methods are presented in Figure 1.

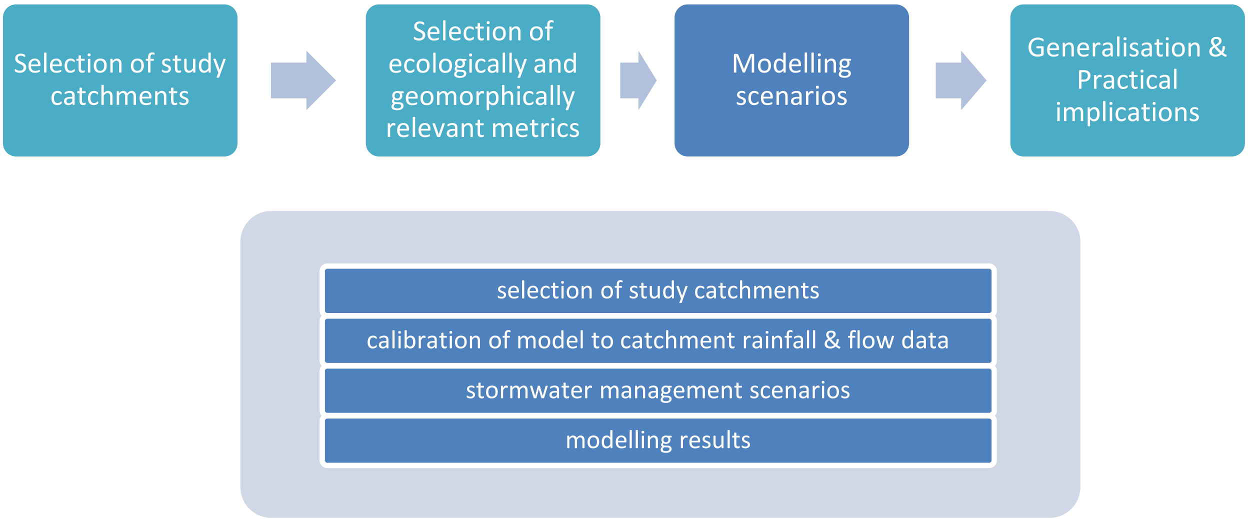

**Figure 1. Conceptual diagram of steps involved in project.**

This report presents the work undertaken in the first stage of the project, the selection of flow metrics and the results of the first catchment analysed in the project: Kororoit Creek.

Future reports from this project will report on the outcomes from other catchments, and draw together implications for setting stormwater management objectives.

## Project context, drivers and research questions

Melbourne is the fastest growing city in Australia and recent projections indicate that it could require an additional 1.6 million dwellings by 2051 to accommodate a potential growth by 3.4 million people, (State of Victoria, 2014).

Melbourne's urban growth is both a challenge and an opportunity to implement integrated water management (IWM) solutions, delivering multiple outcomes that includes management of stormwater to achieve waterway protection and liveability.

We know that when urbanisation occur current stormwater and drainage management practices result in significant degradation of waterways, and thus the loss of the values and services provided by health waterways (Wenger et al., 2009). We also have strong evidence, however, to indicate that urbanisation can occur without degrading waterways when natural water-quality and flow regimes are maintained, and stormwater standards suited to achieve the protection of waterway condition in urban development have been defined (Walsh et al., 2012).

Whilst progress has been made in adopting stormwater management practices to improve water quality, the management of urban hydrology for waterway condition outcomes (rather than flooding) has until relatively recently received less attention (Burns et al., 2012) and remains a challenge in practice. Returning pre-development runoff volumes requires preventing 80-95% of runoff (with the exact amount depending on rainfall and catchment physiography) from entering the stream (Burns et al., 2013). In typical urban areas, investigations have shown that under current policies and industry practice this can be difficult (Poelsma et al., 2013).

Water demand is a key factor in the feasibility and cost of maintaining a pre-development stormwater flow balance. When the stormwater volume to be detained in the catchment far exceeds water demand, it may not be feasible or at least very costly to maintain a pre-development flow regime. Based on this realisation, practitioners involved in the IWM planning of urban growth areas posed the following questions:

- Can we protect waterways without reducing total runoff volume to its natural level?
- Is it possible for example to protect waterways while only reducing total runoff volume by 60%? rather than maintaining the pre-development natural water balance with a 90% runoff volume reduction?

This project aims to provide some practical answers to these questions by examining case study catchments across the Melbourne region.

## Selection of study catchments

This project aims to provide generalise findings for the Melbourne region. As such, the analysis needs to include a representative sample of catchments, taking into account:

- both greenfield and retrofit contexts (acknowledging that analysis of the retrofit context will be limited by a lack of available pre-development flow data)
- a range of climatic conditions (from east to west of Melbourne) and thus a range of natural flow regimes (from perennial to ephemeral).

In addition, priority was given to catchments which are of strategic interest for urban planning, such as being the subject of a Regional Plan or a Precinct Structure Plan (i.e. marked for development). Finally, as the analysis is only possible for catchments that have good data, catchments were assessed for the availability of flow, rainfall, geomorphic and ecological data.

Based on the above criteria, the first catchment chosen for the superabundant flows study was Kororoit Creek above the gauging station at Holden Road near Diggers Rest (231106A). Kororoit Creek is located close to the western fringe of suburban Melbourne and is proposed for development in the near future (several current Precinct Structure Plans – such as Plumpton and Kororoit Creek – are located within the Kororoit Creek catchment). As with most streams in areas to the west and northern fringes, Kororoit Creek has an ephemeral[1] flow regime.

The proposed next study catchment will be McMahons Creek in the Yarra catchment. It provides a clear contrast to the present catchment (Kororoit Creek), due to its high rainfall and perennial flow regime.

## Kororoit Creek

### *Catchment characteristics*

The Kororoit Creek catchment rises in low hills to the northwest of Sunbury at an elevation of about 500 metres, and flows southwards in two parallel branches which join just upstream of the gauging station, west of Diggers Rest (Figure 1). Total catchment area above the gauge at Holden Road, Diggers Rest, is 74.91 km$^2$.

The geology of the area is dominated by the basalt flows of the newer volcanics. Flows occurred from many small vents, some of which are still present as low hills on the catchment boundary. Unlike the deeper valleys of Toolern Creek to the west and Jacksons Creek to the east, Kororoit Creek remains almost entirely upon the newer volcanics layer. Only in small patches in the north of the catchment are the underlying Ordovician sediments exposed.

Land use is rural throughout the catchment, except for a small area of residential development on the eastern boundary near Sunbury and the passage of the Calder Freeway through the catchment. Vegetation is mostly grassland, with a little open woodland (dominated by *Eucalyptus camaldulensis*) along watercourses, and rows of eucalypts and conifers along some roads and fence lines. Topography and vegetation in the vicinity of the gauging site are shown in Figure 2 and Figure 3. Total impervious area and directly connected impervious area are estimated to be 1.95% and 0.2% respectively.

Vegetation in the catchment in 1858 can be seen in Figure 4, which shows Mount Blackwood (left), old Mount Aitken station (centre), and Mount Aitken (right). It also shows the East Branch of Kororoit Creek (foreground) and the surrounding area. The proportion of tree cover has arguably changed less over the last 150 years at this location than at many other sites in the Melbourne area.

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[1] We distinguish between perennial, intermittent and ephemeral flow regimes. Perennial means that the stream flows all the time (perhaps with rare exceptions), while an intermittent stream may cease flowing for some weeks or perhaps months per year. An ephemeral stream is one which is not normally flowing, but will flow during large rainfall events, or perhaps for limited periods during the wet season. The Kororoit Creek study catchment is considered ephemeral (it becomes intermittent and perennial further downstream of the defined study area).

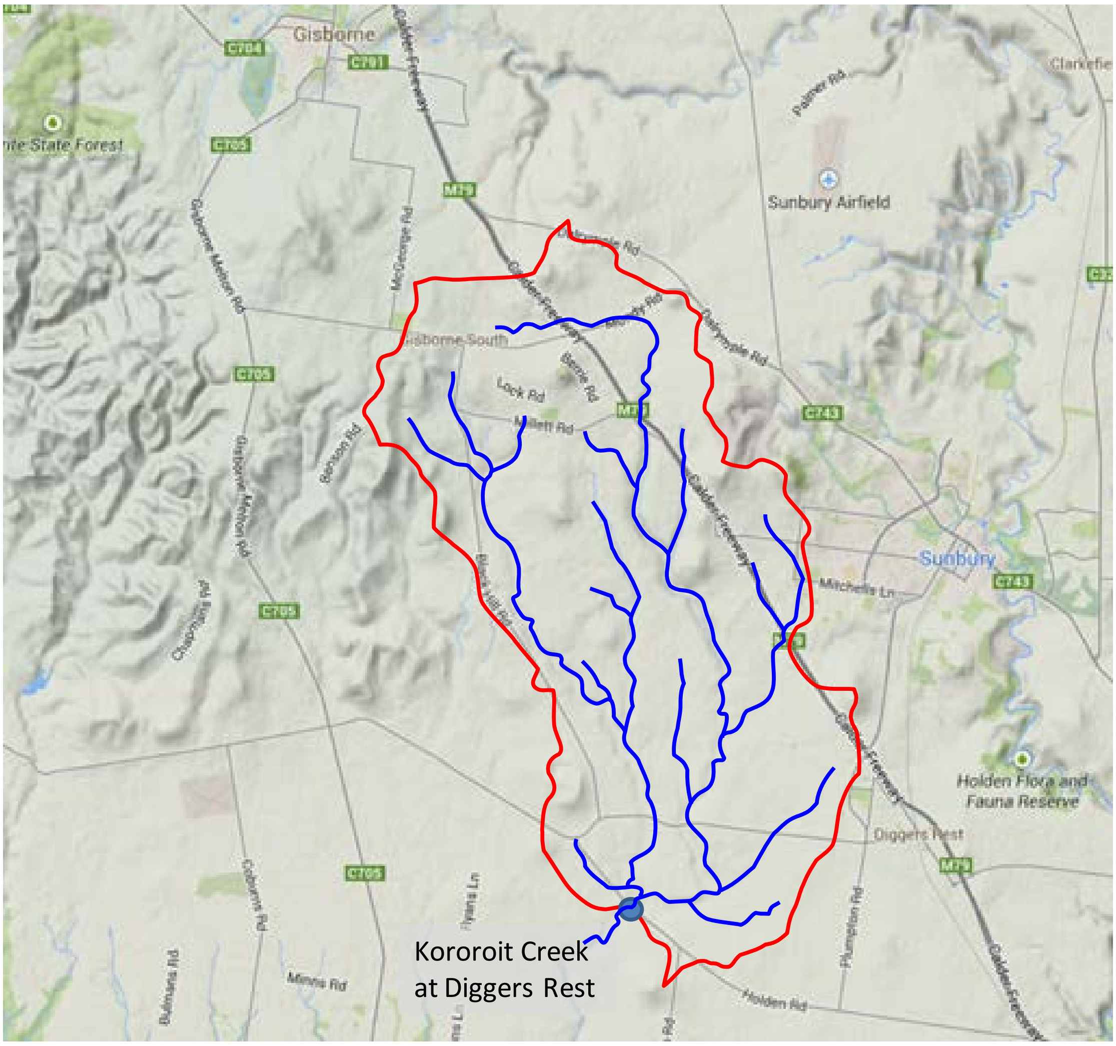

Figure 2. Kororoit Creek catchment.

Figure 3. Kororoit Creek catchment near Holden Road gauging site (at concrete bridge in distance).

Figure 4. Kororoit Creek at the gauging site.

Figure 5. Detail from 'View from Mount Topheli[?] on the Koroite Creek' by George Gilbert, 1858.

### *Rainfall and streamflow*

Rainfall and runoff are both low compared with surrounding areas, which is a distinctive feature of the catchment. Long term mean annual rainfall ranges from about 700 millimetres over the headwaters to the north to a little over 500 millimetres at the gauging station downstream. Runoff is about 4% of rainfall, on average, and is characterised by long periods of zero flow.

There are three rain gauges with good quality data that are relevant to the catchment:

- Kororoit Creek at Diggers Rest (231106A) which is also the stream gauging site,
- Toolern Vale (587019) to the west, and

- Jacksons Creek at Sunbury (230104A) to the east.

All three gauges have satisfactory data from early in 2006 until late in 2013, so this study uses the seven July-June water years from July 2006 to June 2013. The rain gauge sites are shown on Figure 5 with their associated Thiessen polygons. A composite rainfall file has been produced by weighting each rainfall record according to the catchment area which it best represents.

It is unfortunate that all three rain gauges are located towards the south end of the catchment, and so do not sample the rainfall on the higher ground to the north. The next comparable gauge to the north (at Rosslynne Reservoir) is too far away to have a significant effect on the Thiessen polygons, and in any case is not on the higher ground but in the valley of Jacksons Creek. The result is that the composite Thiessen rainfall is likely to underestimate the total catchment rainfall. To partly compensate for this, the composite rainfall has been scaled up by a factor of 1.10, so that the mean composite rainfall equals the mean rainfall at the wettest of the three gauges (Toolern Vale).

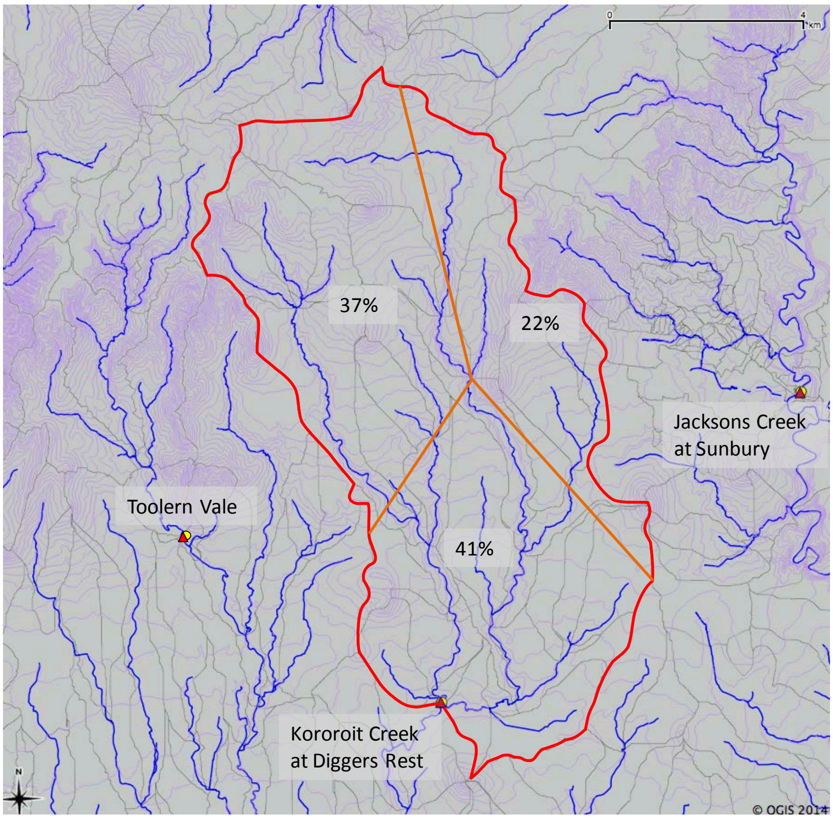

Figure 6. Kororoit Creek catchment showing rain gauges and Thiessen polygons

The Kororoit Creek at Diggers Rest stream gauging station (231106A) defines the catchment for this study. Data quality has been consistently flagged as good from 2002 to the present, so good quality flow records are available for the full period of composite rainfall data.

Figure 6 shows the daily streamflow record for the seven water years from July 2006 to June 2013. The ephemeral nature of this catchment can be clearly seen, with occasional large flows separated by long periods of zero or near zero flow.

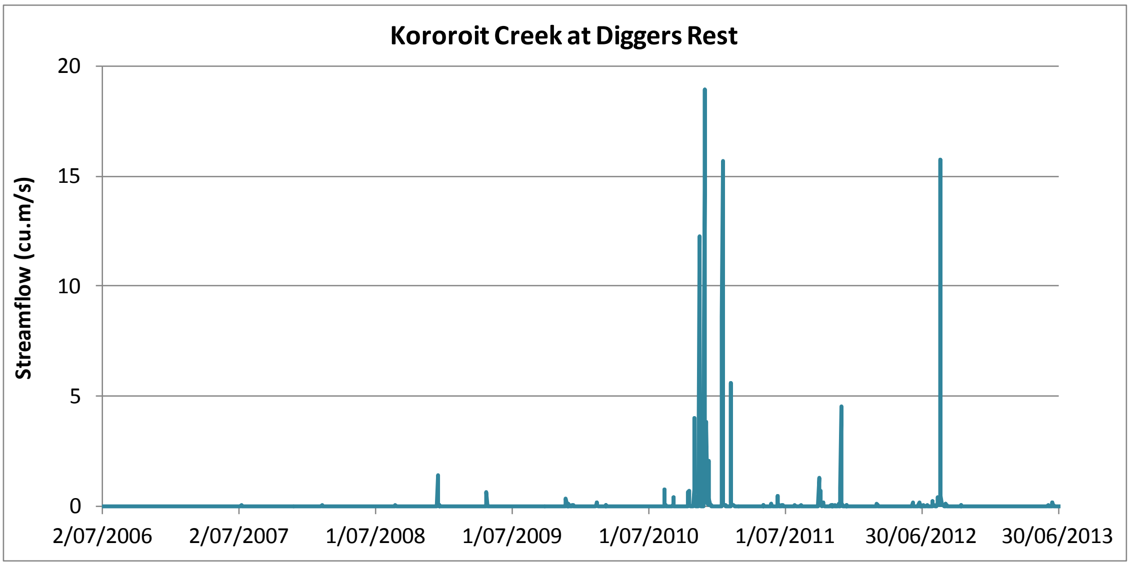

Figure 7. Daily streamflow data.

# Selection of flow metrics

Flow regimes have both direct and indirect impacts on stream ecosystems. The magnitude of flow will affect the wetted cross-sectional area in a stream, and thus affect habitat. It will also affect the level of hydraulic stress placed on both biota (flora and fauna) and on the channel itself. The frequency of particular flow events is also important. For example, the frequency of flows above a given threshold will affect the disturbance frequency, which in turn will influence the ability of species to recolonise after a disturbance event. Similarly, the frequency of low-flows or zero flows will affect the ability of certain species to survive (depending on the species adapted to the particular environment). The duration of such events will also be important; for example, pools may be sustained during low-flow periods, depending on the length of the period. The variability of rate of change will influence the ability of species to, for example, seek refuge. Finally, the timing of flow events (be they high flows or low flows) is important, as it may influence reproductive cycles in plants and animals, among other things.

At the core of this project is the establishment of a range of stormwater management scenarios that meet the specified total runoff volume reduction and the comparison of their impact on the receiving waterway flow regime. The first step of this project consequently consisted of establishing a metric that would allow this comparison. Flow metrics are hydrological statistics or indices intended to quantitatively describe a particular aspect of streamflow behaviour for descriptive or comparative purposes. Many flow metrics have been proposed, directed at various aspects of the overall flow regime. Olden & Poff (2003) review no less than 171 flow metrics described in the literature. To simplify the modelling process, and allow a practical analysis of the modelling results, we needed to retain a manageable number of metrics.

The overall objective of the comparison of various stormwater management scenarios is to help define the waterway outcomes that could be reasonably expected. As such, an important selection criterion for the flow metrics examined is the evidence of causal link with stream health. The flow metric selection thus consisted of finding the smallest set of flow metrics that adequately describe a waterway flow regime. Flow metrics hypothesised to be of ecological or geomorphic importance were reviewed separately as presented in the next two sub-sections before being combined in a short-list of metrics for the next step of the project.

Flow regimes can be assessed according to a number of distinct hydrologic aspects. Several studies (Burns et al., 2010; Kennard et al., 2010; Olden & Poff, 2003; Richter et al., 1996 and others) identify the five separate aspects summarised above – flow magnitude, frequency, duration, rate of change, and timing. In some cases further characterisation is useful, such as for separate consideration of high and low flows. These categories are, of course, not completely exclusive since some metrics may be relevant to more than one aspect, but they nevertheless provide a convenient framework for the metric review and assessment presented in this report.

The great majority of metrics reviewed are derived from daily flow data, rather than from hourly or shorter time steps. This may be in part a pragmatic response to data availability, but it also reflects the relatively large size of catchments most often assessed. We have also adopted daily flow metrics for this study.

## Flow metrics

### ***Literature review of ecologically relevant hydrological metrics***

Flow metrics that have been shown to be significant explanatory variables for ecological or biological stream condition are summarised in Table 1. All of these metrics are potentially suitable for our purposes, since they have all been shown to be significant explanatory variables for ecological condition in at least one location. There is, however, clearly much correlation between them, and the list can be reduced further. We used the following considerations in short-listing metric for this project:

- Metrics based on comparing with pre-development flows require an additional step, and introduce an additional source of error, through the need to establish pre-development flows.
- Metrics based on extreme flows (such as 9 × median) will be less stable and have wider confidence bands than those based on less extreme flows (such as 3 × median).
- Metrics which incorporate many or all daily flows in their calculation (such as the R-B Index) will be more stable than those that use only a few (such as the maximum change in flow).
- Some measures of extreme events tend to become more extreme as record length increases.
- Some metrics derived in wetter climates may be less suitable in our generally drier catchments.
- Finally, some metrics may need to be refined to apply correctly in a Southern Hemisphere location.

*Importantly, we take the view that the list of metrics chosen needs to be short enough to be implementable in practice. We therefore do not attempt to include metrics from all sub-categories (e.g. magnitude of both low flows and high flows), but choose a selection which covers the ecologically important aspects of the flow regime, without undue redundancy.*

Table 1. Ecologically important flow metrics. The reference provided describes the original source for each metric. Refer to the original reference for details on how to calculate each metric.

| Metric | Metric Number | Comments | Ecological significance | Reference |
|---|---|---|---|---|
| **Magnitude** | | | | |
| *Magnitude of high flow events:* | | | | |
| Mean of all April flows | M1 | April is spring at the study site | As Spring is an important period for a number of biological processes (e.g. breeding, migration), the magnitude of flow during this period is important. | Kennen et al (2010) |
| Ratio of 25% to 75% exceedence flows | M2 | | Describes long-term variability. | Kennen et al (2008) |
| *Magnitude of low flow events:* | | | | |
| Mean of minimum April flows | M3 | April is spring at the study site | As Spring is an important period for a number of biological processes (e.g. breeding, migration), the magnitude of flow during this period is important. | Kennen et al (2010) |
| 7-day minimum flow / water year mean daily flow, calculated each year then averaged | M4 | Often called Baseflow Index<br>We prefer Low-flow Index | As many ecological processes are impacted (positively or negatively) by low flows, the magnitude of low flow spells is important. | Olden & Poff (2003)<br>Burns et al. (2010) |
| **Frequency** | | | | |
| *Frequency of high flow events:* | | | | |
| Events per year > twice the mean flow | F1 | | Measure of flashiness, which impacts stream ecology through, for example, washout of both habitats and organisms themselves | DeGasperi et al (2009) |
| Events per year > twice the mean flow under forested conditions | F2 | Need to simulate pre-development flows | As above | Cassin et al (2005) |
| Events per year > three times the median flow | F3 | Less relevant if median flow is zero | As above (varying definitions of what makes a "peak") | Clausen & Biggs (1997)<br>Burns et al (2010) |
| Events per year > 5, 7, or 9 times the median flow | F4 | Less relevant if median flow is zero | As above | Helms et al (2009) |

| **Metric** | **Metric Number** | **Comments** | **Ecological significance** | **Reference** |
|---|---|---|---|---|
| Events per month with total rise ≥ 9 times the median total rise | F5 | | As above | Steuer et al (2010) |
| Events per year > 75th percentile flow for the entire flow record | F6 | | As above | Kennen et al (2010) |
| Events per year producing quick flow | F7 | | As above | Kennen et al (2008) |
| *<u>Frequency of low flow events:</u>* | | | | |
| Low flow events per year < 25th percentile flow for the entire flow record | F8 | | The frequency of low flow events will affect ecological processes (positive or negative) that depend on low-flows. For example, the frequency of low flows may reduce the diversity of fish species. | Kennen et al (2010) |
| Events per year > half the mean flow under forested conditions | F9 | Need to simulate pre-development flows | As above | Cassin et al (2005) |
| **Duration** | | | | |
| *<u>Duration of high flow events:</u>* | | | | |
| Median duration of events > 95th percentile flow | D1 | *Total* duration of target events known by definition | Duration of flood flow events, which can explain impacts on flow-sensitive taxa | Steuer et al (2010) |
| Mean duration of events > 75th percentile flow for the entire flow record | D2 | *Total* duration of target events known by definition | As above | Kennen et al (2010) |
| Percent of time > 2-year mean flow under forested conditions | D3 | Need to simulate pre-development flows | As above | Cassin et al (2005) |
| Fraction of time that daily mean flow > annual mean flow | D4 | Often called Tqmean, short for 'time (above) flow mean' | As above (this is a commonly-used measure of flow flashiness and is widely used to assess impacts of urbanisation on hydrographs) | Booth et al (2004),<br>Cassin et al (2005),<br>Burns et al (2010) |
| Fraction of time that daily mean flow > 0.5-year high flow | D5 | | As above | Booth et al (2004a) |
| *<u>Duration of high flow season:</u>* | | | | |
| Time between first and last events > twice the mean flow under forested conditions, in a water year | D6 | Need to simulate pre-development flows | Describes the length of the high-flow season, which can impact important ecological outcomes such as flow-dependent breeding cycles | Cassin et al (2005) |

| **Metric** | **Metric Number** | **Comments** | **Ecological significance** | **Reference** |
|---|---|---|---|---|
| Time between first and last events > twice the mean flow, in a water year | D7 | | As above | DeGasperi et al (2009) |
| *Duration of low flow events:* | | | | |
| Mean duration of events < half the mean flow under forested conditions | D8 | | Describes the length of low-flow season, which can impact important ecological outcomes such as flow-dependant breeding cycles (for example fish migration) | Cassin et al (2005) |
| **Rate of change:** | | | | |
| Sum of the absolute value of the relative change in daily flows | C1 | Increases as record length increases | Measure of variability in flows, which can affect organisms who may be unable to cope with flashy conditions. Conversely, rapid rates of change may have positive influence on some ecosystem processes. | Steuer et al (2010) |
| Sum of the absolute values of change in mean daily flows / sum of the mean daily flows | C2 | This is the R-B Index, or 'Richards-Baker flashiness index' | As above | Baker et al (2004) |
| Maximum change of flow in one falling period | C3 | | Measure of rate of change due to drying conditions (particularly relevant where extractions lead to unnaturally rapid loss of wetted habitat) | Steuer et al (2010) |
| Skewness | C4 | | General measure of flashiness. | Steuer et al (2010)<br>Burns et al (2010) |
| **Timing:** | | | | |
| Julian date (continuous count of days since a set reference date) of the day after the 7-day minimum flow period for the year | T1 | Not unique if zero flows are common | Measure of seasonality of flows, which will have ecological consequences in terms of artificial misalignment with time-specific | Cassin et al (2005) |

### ***Selection of a subset of ecologically relevant flow metrics***

For low-flow magnitude we adopt the principle of what is commonly called the Baseflow Index (Metric M4 in Table 1): the seven-day minimum flow divided by the mean daily flow.  We however choose to rename it following the advice of authors such as Hamel et al. (2013) who suggest that baseflow refers to *flows which reach a waterway through subsurface means (i.e. thus describes the flow pathway)*, while *low-flow is more appropriately used to talk about the portion of the hydrograph below a specified 'low-flow threshold'.* We have therefore renamed this metric the Low-flow Index. The specified calculation method, deriving one value each year then averaging them, prevents the index becoming more extreme as the record length increases.

Although we adopt this metric in theory, it is not practical for Kororoit Creek since the stream is highly ephemeral. There are typically over 200 days of zero flow per year, so the observed low-flow index is always zero, and so is the modelled low-flow index even from otherwise poor models. The logical extension of low-flow magnitude after it has decreased to zero is how long it stays at zero. A long run of zero flow is a drier event than a short run, just as a low seven-day minimum flow is drier than a high seven-day minimum flow. Therefore at Kororoit Creek we have replaced the low-flow index with the number of days per year of zero flow, and the mean duration of zero flow periods. These metrics can also be regarded as measures of low-flow duration.

For high-flow frequency we adopt in principle the number of events per year greater than three times the median flow (F1 in Table 1). Again, this metric is not entirely suitable at Kororoit Creek where the median daily flow is zero. The metric may still be calculated and compared, but it has become a count of all events, not just high events. Since there is a broad similarity between the intent of this metric and the geomorphic metrics adopted below (which count time above a threshold, rather than events above a threshold), this metric is not used in the assessment of Kororoit Creek.

For high-flow duration we use the fraction of days that daily mean flow is greater than annual mean flow, or Tqmean (D4 in Table 1). This metric also carries information about the skewness of the distribution. A higher value indicates a more symmetric, less skewed distribution.

For rate of change we use the R-B Index (C2 in Table 2), which is the sum of the absolute values of change in mean daily flows divided by the sum of the mean daily flows.

For timing we modify the tabulated metric (T1 in Table 1) to make it more stable under low or ephemeral flows. Instead of locating the minimum seven-day period in a year, we specify just the minimum month. A calendar month is less likely to be continuously zero than a seven-day period, making multiple equally low solutions less likely.

### ***Geomorphically relevant flow metrics***

Geomorphic metrics aim to characterise the erosion of a stream. As such they are most commonly focused on high flows (as flows more likely to cause erosion) and time for which erosion of the channel occurs (ie. the erosion potential). In particular, this means examining what is referred to as the 'dominant discharge' or the 'effective discharge'. We have adopted the term *effective discharge* here, which is defined as the flow that is sufficient to cause erosion (specifically greater than the threshold for erosion or sediment transport) and is frequent enough that it can do the most work over time.

The most accurate determination of effective discharge commonly requires empirical determination using bedload sediment transport equations for pre- and post-development flow scenarios, but this can be onerous. Therefore, simpler hydraulic, or hydrologic approaches are more commonly employed.

### *Stream Erosion Index*

In eastern-seaboard cities of Australia the Stream Erosion Index (SEI) is most commonly used to identify an appropriate level of change in erosion from pre to post development (Brookes & Wong, 2009). The threshold for the SEI is based hydrologically on the 2-year Average Reccurrence Interval (ARI) event ($Q_2$) divided by 2. The SEI is then integrated over the flow regime and requires an acceptable level of SEI to be identified (Equation 1). Brookes & Wong (2009) suggested that an SEI of 3-5 (i.e. 3 to 5 times the 'effectiveness') was an acceptable level.

Equation 1 $$SEI = \frac{\sum(Q_{post} - \frac{Q_2}{2})}{\sum(Q_{pre} - \frac{Q_2}{2})}$$ with $Q_2$ being the 2-year ARI event

The basis for the hydrologically based SEI threshold (i.e. $Q_2/2$) is not described by the literature. There appears to be no relationship between the SEI threshold and the sediment that might comprise a channel. This approach assumes all streams are of a similar sensitivity, which is not the case (Bledsoe et al., 2012). It may mean that a more sensitive stream may be highly degraded under what would otherwise be considered an appropriate SEI. For example, for two catchments with similar hydrology, but different geology, a gravel/cobble bed stream may be adequately protected by the SEI metric, whereas, a sand bed stream could be highly degraded. It raises the question of whether the SEI threshold is appropriate for generic application to all stream types, and whether a hydrologic metric should be based on, for example, the bed sediments that are most readily mobilised as the catchment is urbanised.

### *Erosion thresholds*

The determination of thresholds for sediment movement is a long running challenge. Most commonly thresholds are based on hydrologic metrics not necessarily relevant to the sediment in the channel, even though the variability in thresholds for movement of different sediment sizes varies greatly. For example, the $Q_2$ (Metric G4 and G5 in Table 2) has been used as an important threshold for channel change (McCuen & Moglen, 1988). Pickup & Warner (1976) found the most effective discharge to be the 1.5-yr ARI, or for the bedload sediment to be in the range 1.15–1.4-yr ARI. Booth et al. (2004b) suggested that the half-year flood (G2 in Table 2) occurs often enough to transport streambed sediment in most alluvial channels. Wolman & Miller (1960) suggested that the flow threshold for the dominant discharge can be quite small, from the mean daily flow (G1 in Table 2) to a flow exceeded eight to ten times a year. This variation points to the importance of considering sediment size and type in calculations, and is a point that has long been raised (Sidle, 1988).

Some streams are more sensitive to flows of a given magnitude than other streams (Bledsoe, et al., 2012). For example, a streambed of fine-grained sand will be mobilised by a much smaller flow than a bed containing cobbles, and a bank of cohesive silt and clay may require a larger flow again. Incorporating stream sensitivity into the geomorphic metrics may reduce the risks of a generic threshold imposed on more sensitive streams, and may improve the applicability of a metric across a broad range of stream types.

Since the sediment on the channel bed often differs from that on the channel bank it may be important, in particular, to distinguish between thresholds of sediment movement for both separately. There has long been recognition that the threshold for sediment movement is different for the bed and the banks, with the latter often requiring larger events due to the more commonly cohesive, often vegetated sediments (Pickup & Warner, 1976).

Given the paucity of geomorphic metrics, differences between bed and bank thresholds, and the differing sensitivity of streams, we have developed two metrics for this project:

1. **Bed mobilisation** threshold based on the critical shear stress that would mobilise bedload sediments of concern.
2. **Bank mobilisation** threshold based on the hydrologic thresholds identified in Table 2.

The bed mobilisation and bank mobilisation are assessed against the duration of time for which the flow is greater than the threshold. This is similar to the approaches used within New South Wales (McAuley et al., 2010), but differs from the SEI approach that uses volume of flow above the threshold (Brookes & Wong, 2009).

Table 2. Metrics relevant to geomorphology and thresholds of sediment mobilisation

| Hydrologic metrics considered for bank mobilisation | Metric number | Comments | Reference |
|---|---|---|---|
| Fraction of time that daily mean flow > annual mean flow | G1 | Often called Tqmean, short for 'time (above) flow mean' | Booth et al (2004), Cassin et al (2005), Burns et al (2010) |
| Fraction of time that daily mean flow > 0.5-year high flow | G2 | | Booth et al (2004) |
| Stream Erosion Index (SEI) of between 3 and 5, based on Q2/2 pre/post development | G3 | Requires pre-post hydrology, does not take into account sediment type or threshold of movement | (Brookes & Wong, 2009) |
| Q2/2 as threshold for erosion of stiff clays | G4 | Basis for threshold is uncertain | (Earth Tech, 2005; McAuley, et al., 2010) |
| Q2 bedload transport should not exceed pre-development Q2 | G5 | | (McCuen & Moglen, 1988) |

### *Erosion thresholds for the study catchment (Kororoit Creek catchment)*

The approach adopted to determine bed and bank sediment mobilisation thresholds for the Kororoit Creek study catchment is presented below:

1. **Bed mobilisation**
    a. Bed sediment sizes were assessed (Figure 1a), with fine-grained gravels found to make up the majority of bed sediments, and overlying armoured sediments of fine to coarse-grained gravels. The intention was to retain all gravels, considering their importance ecologically and ability to armour the underlying sand, while accepting some loss of surficial sand-sized sediments based on this threshold.
    b. Determination of critical shear stress at the lower limit of mobilisation for gravel-sized sediments (approximately 2 $N/m^2$).
    c. Development of 1-dimensional hydraulic model (HEC RAS) from LiDAR (Figure 1b) to determine discharge at which critical shear stress is achieved (in this case 1.9 $m^3/s$).
    d. Relating discharge to a return period flow to enable comparison across stream systems (in this case approximately $Q_{1.5}/2$).

2. **Bank mobilisation**
   In the absence of data on erosion thresholds for cohesive sediments for Kororoit Creek, the commonly used $Q_2/2$ was adopted as the threshold.

The duration approach used here recognises that for larger flow events, commonly reaching high level benches or the floodplain, increases in discharge will have diminishing effectiveness in mobilising sediments (i.e. relatively small increases in flow depth and stream energy will be expended on benches and the floodplain rather than on the bed or banks). The duration of flows below bankfull stage have been identified as more important than larger flood events, particularly in terms of erosion of the bank toe (Bledsoe, 2002). We suggest, however, that this assumption requires further testing.

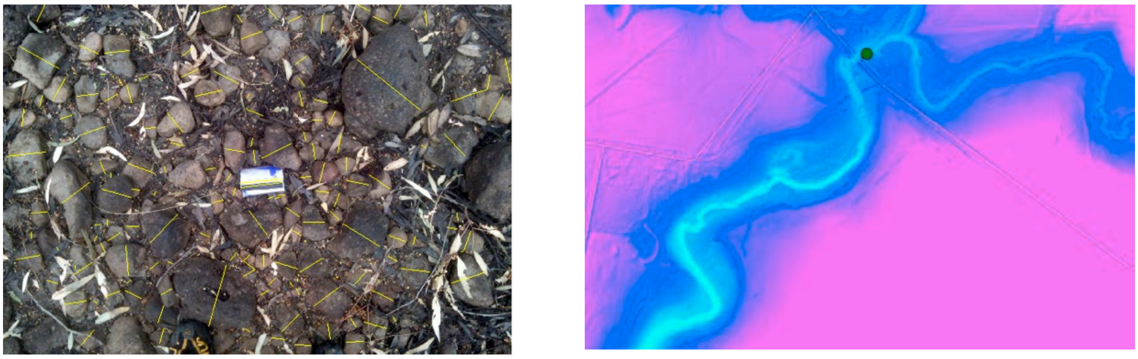

Figure 8. Kororoit Creek at Holden Rd (stream gauge site) showing a) bed sediment (wallet in photo for scale), and b) LiDAR (green dot shows location of stream gauge).

The approach adopted for determining these thresholds (particularly for bed sediment) for Kororoit Creek made it a time-consuming and data-heavy task. This limits the adoption of the geomorphologic metrics in other studies. However, identifying these thresholds for a range of systems, and for a range of sediment sizes, may enable a more generic relationship to be developed. The intention in this project is that development of a relationship between sediment classes and hydrologic thresholds may enable thresholds to be developed for other streams of interest based on cursory assessments of sediment class sizes.

Whilst geomorphic change is driven by hydrology it is worth noting that changes in sediment supply also play a significant role in the response of a channel, and physical habitat, to urbanisation of a catchment (Bledsoe, 2002; Vietz, 2013). For example, Vietz et al. (2014) found that the channel of Dobsons Creek, Melbourne, was considerably less incised, and more physically diverse, than nearby Bungalook Creek, even the two had similar levels of EI. They attributed this to the coarse-grained sediments (gravels and cobbles) liberated from the banks of Dobsons Creek and reworked by the channel. Bedload sediments also enable a stream to maintain a steeper gradient, and greater stability, for the same discharge (Bledsoe, 2002).

## Final list of metrics chosen for the Kororoit Creek study catchment

The final selection of both the ecologically and geomorphically relevant flow metrics for the study catchment (Kororoit Creek) is summarised in Table 3.

Table 3. Summary of final metrics chosen for the Kororoit Creek catchment

| Flow aspect | Metric selected | Definition and comments on calculation | Ecological or geomorphic significance |
|---|---|---|---|
| Low flow duration | Days per year of zero flow.<br>Mean duration of zero flow periods | Zero flow days in full record divided by number of years.<br>Zero flow days in full record divided by zero flow periods in full record. | Low flow periods affect habitat availability, as well as facilitating presence of species adapted to ephemeral conditions. |
| Low flow frequency | *Not used for Kororoit Ck, due to ephemeral nature* | Published metrics are unsuitable for highly ephemeral stream. Geomorphic metrics (see below) cover this aspect better. | - |
| Duration | Tqmean | Fraction of days with daily mean flow greater than annual mean flow. | Duration of peak flows is an indicator of the duration of 'disturbance events' (both water quality and hydraulic) |
| Rate of change | R-B Index | Sum of the absolute values of change in mean daily flows divided by the sum of the mean daily flows. | Variability of flows is an indicator of the duration of 'disturbance events' |
| Timing | Month of minimum monthly flow | Take mean of all flows in period of record in Jan, Feb, etc., and find minimum of these mean monthly flows. | Seasonality of minimum flows important for alignment with seasonal biological events. |
| Bed mobilisation | Fraction of time > $Q_{1.5yrARI}/2$ | Empirically derived based on analysis of sediments in study catchment and critical shear stress needed to mobilise them, combined with 1D hydraulic model. | Bed erosion influences habitat availability |
| Bank mobilisation | Fraction of time > $Q_{2yrARI}/2$ | Based on commonly-used threshold for bank mobilisation | Bank mobilisation affects sediment transport, habitat availability, riparian vegetation, etc. |

# Modelling

The seven selected metrics in Table 3 (Days per year of zero flow, Mean duration of zero flow periods, Tqmean, R-B Index, Month of minimum monthly flow, Q1.5/2, Q2/2) are treated equally in the calibration phase, using a composite goodness of fit measure. We do not apply an a-priori hierarchy or weighting to the metrics in their role as objective function components. The objective function is the sum of the squares of the error in each metric divided by its observed value. In the case of the month of minimum monthly flow, the square of the error is divided by 12 rather than the number of the month.

Catchment behaviour under a range of future scenarios was assessed by modelling in MUSIC. The key steps of the modelling were to:

- calibrate the model to observed data under current conditions (importantly, this involves fitting the model to the selected metrics),
- adjust model parameters to simulate fully urbanised land use on the same topography and soil type, and finally
- explore a wide range of possible stormwater management interventions (in every case the adopted flow metrics are calculated, and their behaviour is assessed).

## Calibration to current conditions

The calibration to current observed behaviour was carried out using the simplest possible catchment model (Figure 8), since the later addition of urbanisation and flow management features will necessarily add to the model complexity. It is important to remember that complexity added in this pre-development phase will be propagated through the model, where land uses will be represented by many nodes (e.g. residential areas will be broken up into roofs, roads, pervious, impervious, etc). Although the creek has two branches that join at the gauging site, they are very similar in area, land use, and topography. Combining them into a single source node has little effect on the model's goodness of fit. The pond node is intended to model the combined effect of existing farm dams and bed and bank storage along the channel.

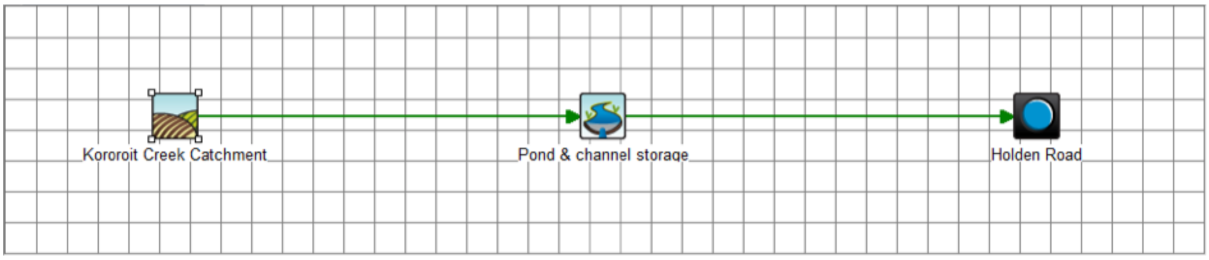

Figure 9. MUSIC model of current conditions.

The model was optimised manually, using a composite goodness of fit measure based on the selected daily flow metrics. While automated model fitting can be used, such approaches can be counter-productive, limiting the degree to which understanding of the catchment hydrology can both be derived and applied by the modeller (see a full treatment of this topic in Hamel & Fletcher, 2013). The Nash Sutcliffe E (coefficient of efficiency) has also been calculated for comparison (E=0.69) with the goodness-of-fit measures for each metric. Modified parameters of the optimised model are tabulated in Table 4. Parameters not listed retain their MUSIC default values.

Table 4. MUSIC parameters for Kororoit Creek under current conditions.

| **Parameter** | **Value** | **Parameter** | **Value** |
|---|---|---|---|
| *Catchment:* | | Daily deep seepage rate | 12% |
| Catchment area | 7491 ha | *Link:* | |
| Impervious fraction | 2% | Lag without routing | 240 min |
| Rainfall threshold | 2 mm/d | *Pond:* | |
| Soil storage capacity | 114 mm | Surface area | 220000 $m^2$ |
| Field capacity | 96 mm | Extended detention | 0.1 m |
| Infiltration coefficient | 58 mm/d | Permanent pool volume | 220000 $m^3$ |
| Infiltration exponent | 1.3 | Exfiltration rate | 0.1 mm/hr |
| Daily recharge rate | 20% | Pipe diameter | 140 mm |
| Daily baseflow rate | 20% | Overflow weir width | 6 m |

Observed and modelled daily streamflows are shown in Figure 9 for the wet 2010-2011 water year. Optimising using our adopted metrics places emphasis on total runoff volume, event timing, and duration of zero flow periods, but is less concerned with peak magnitude, as can be seen in Figure 9. Optimising using

Nash Sutcliffe E or Pearson $R^2$ places more emphasis on matching peak magnitudes at the expense of the other factors.

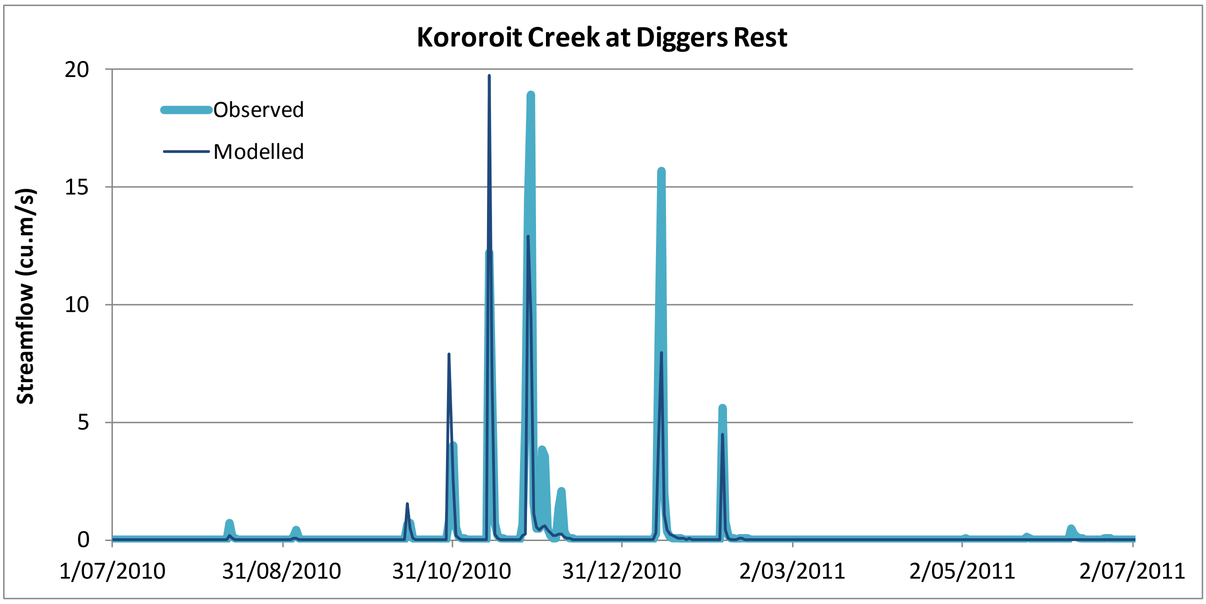

Figure 10. Observed and modelled daily streamflow for 2010-2011 water year.

## Urbanisation base case parameterisation

Having calibrated a MUSIC model to the pre-development state, the next step was to develop an urbanisation 'base-case' that represents urbanisation of the catchment without stormwater mitigation measures. Stormwater management scenarios were then applied to this base case.

### *Land use assumptions for the urbanisation base case*

The Kororoit Creek catchment at Holden Road is quite large (7491 ha) and has several Precinct Structure Plan (PCP) areas located within it, including Plumpton, Diggers Rest and Kororoit. The availability of detailed data on land uses (and thus impervious areas, etc) was limited at the time of developing the model. Furthermore, as the aim of this exercise was to model a typical western-regional ephemeral catchment, the task is to model a land use breakup which is representative of the region, rather than based on a specific combination of PSP areas. Based on advice from Melbourne Water[2] and Sara Lloyd[3], the Plumpton PSP was selected, as good data were available, and the precinct structure is considered relatively typical of the area. The land-use breakdown for the Plumpton PSP is presented in Table 5, along with the resulting MUSIC node areas applied to the study catchment (Table 6). The road corridor properties were derived from the report of Walsh et al. (2014).

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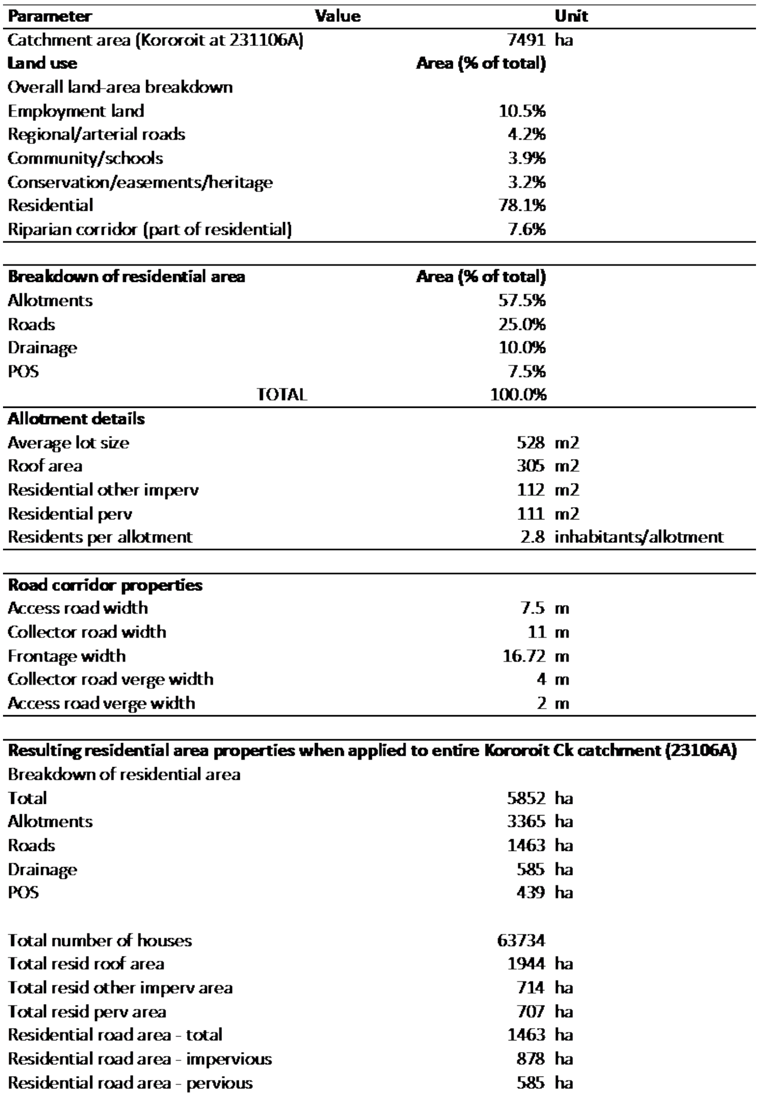
[2] Lauren Mittiga (personal communication): Melbourne Water

[3] Sara Lloyd (personal communication): e2 DesignLab

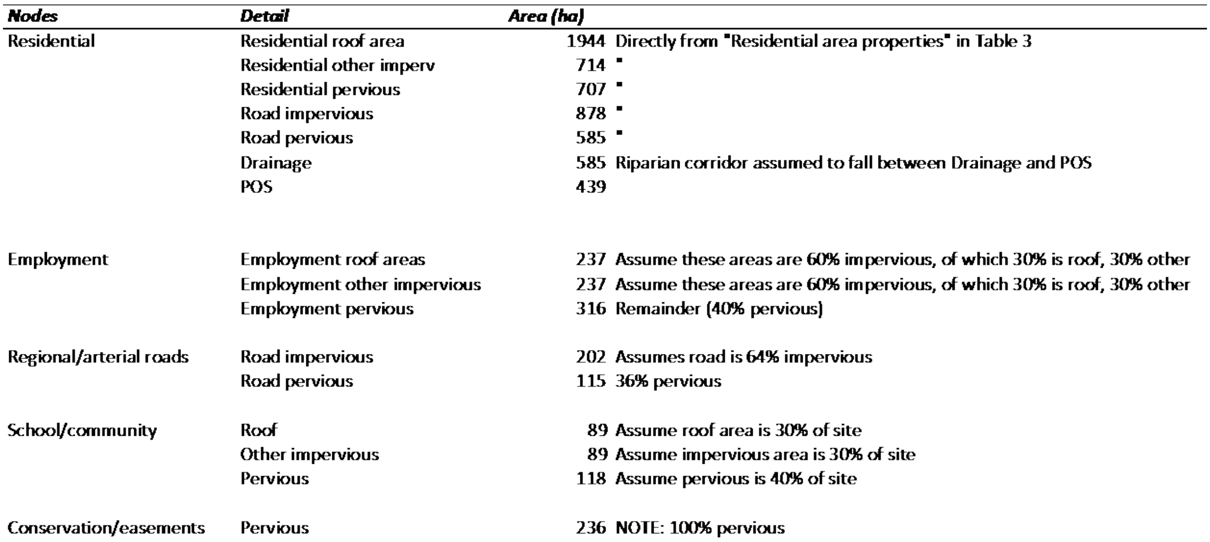
Table 5. Land-use breakdown and properties derived from Plumpton PSP. The catchment area (7491 ha) for the entire Kororoit Creek catchment (at gauge 231106A) is used to calculate resulting properties for the study catchment.



| Parameter | Value | Unit |
|---|---|---|
| Catchment area (Kororoit at 231106A) | 7491 | ha |
| **Land use** | **Area (% of total)** | |
| Overall land-area breakdown | | |
| Employment land | 10.5% | |
| Regional/arterial roads | 4.2% | |
| Community/schools | 3.9% | |
| Conservation/easements/heritage | 3.2% | |
| Residential | 78.1% | |
| Riparian corridor (part of residential) | 7.6% | |
| **Breakdown of residential area** | **Area (% of total)** | |
| Allotments | 57.5% | |
| Roads | 25.0% | |
| Drainage | 10.0% | |
| POS | 7.5% | |
| TOTAL | 100.0% | |
| **Allotment details** | | |
| Average lot size | 528 | m2 |
| Roof area | 305 | m2 |
| Residential other imperv | 112 | m2 |
| Residential perv | 111 | m2 |
| Residents per allotment | 2.8 | inhabitants/allotment |
| **Road corridor properties** | | |
| Access road width | 7.5 | m |
| Collector road width | 11 | m |
| Frontage width | 16.72 | m |
| Collector road verge width | 4 | m |
| Access road verge width | 2 | m |
| **Resulting residential area properties when applied to entire Kororoit Ck catchment (23106A)** | | |
| Breakdown of residential area | | |
| Total | 5852 | ha |
| Allotments | 3365 | ha |
| Roads | 1463 | ha |
| Drainage | 585 | ha |
| POS | 439 | ha |
| | | |
| Total number of houses | 63734 | |
| Total resid roof area | 1944 | ha |
| Total resid other imperv area | 714 | ha |
| Total resid perv area | 707 | ha |
| Residential road area - total | 1463 | ha |
| Residential road area - impervious | 878 | ha |
| Residential road area - pervious | 585 | ha |

The specifications in Table 5 were then used to inform the parameterisation of the base case urban MUSIC model (see also Figure 10), with the land use breakdown used to specify the area and imperviousness percentage of the various nodes. For example, residential areas were created in MUSIC using separate nodes for roofs, other impervious areas, pervious areas on properties, road areas (impervious and pervious), drainage corridors and public open space (POS).

Table 6. Specification of land-use properties into separate nodes for parameterising MUSIC.



| *Nodes* | *Detail* | *Area (ha)* | |
|---|---|---|---|
| Residential | Residential roof area | 1944 | Directly from "Residential area properties" in Table 3 |
| | Residential other imperv | 714 | " |
| | Residential pervious | 707 | " |
| | Road impervious | 878 | " |
| | Road pervious | 585 | " |
| | Drainage | 585 | Riparian corridor assumed to fall between Drainage and POS |
| | POS | 439 | |
| Employment | Employment roof areas | 237 | Assume these areas are 60% impervious, of which 30% is roof, 30% other |
| | Employment other impervious | 237 | Assume these areas are 60% impervious, of which 30% is roof, 30% other |
| | Employment pervious | 316 | Remainder (40% pervious) |
| Regional/arterial roads | Road impervious | 202 | Assumes road is 64% impervious |
| | Road pervious | 115 | 36% pervious |
| School/community | Roof | 89 | Assume roof area is 30% of site |
| | Other impervious | 89 | Assume impervious area is 30% of site |
| | Pervious | 118 | Assume pervious is 40% of site |
| Conservation/easements | Pervious | 236 | NOTE: 100% pervious |

### *MUSIC model set-up for the urbanisation base case*

The MUSIC model used to simulate the fully urban base case is shown in Figure 10. The major urban land uses have been separated out so that different levels of treatment can be modelled in the next stage. The complexity of the model is due to the need to model each surface type separately, so that individual treatments, such as tanks receiving roofwater, can be put in place within the model. The only other significant change from the current conditions model is a large increase in directly connected impervious area. The hydrological behaviour of directly connected impervious area is relatively predictable, and the pervious areas retain their calibrated values, so the fully urban model can be constructed with reasonable confidence.

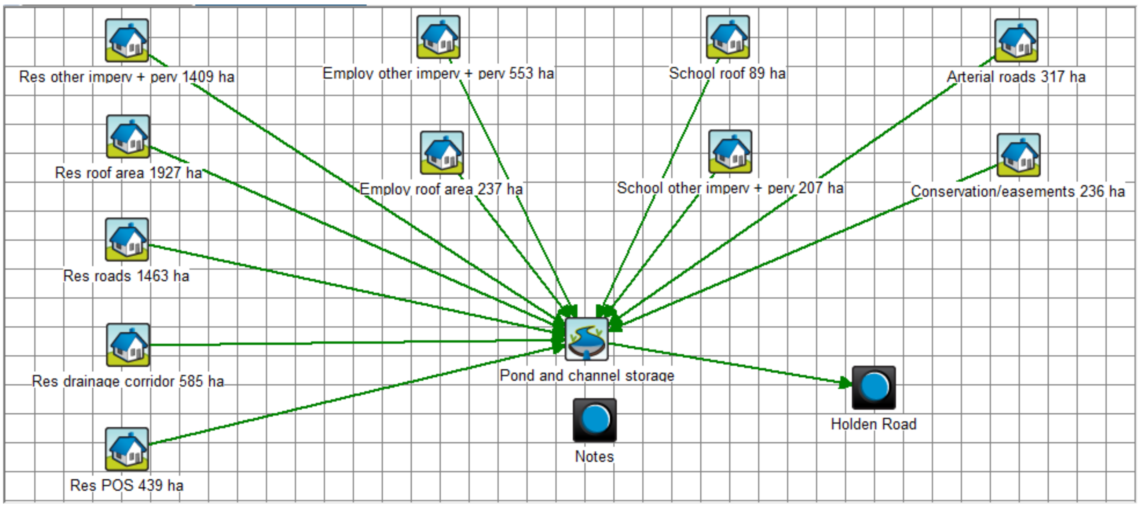


Figure 11. MUSIC model of fully urbanised catchment.

### *Modelled stream flows for the urbanisation base case*

Modelled streamflows from the urban catchment are very different from current observed flows (Figure 11), and this is reflected in the flow metrics (Table 7). The runoff coefficient has increased from 0.043 to 0.446, a factor of more than 10. The flow threshold metrics are many times larger than before, and the zero flow metrics are many times smaller. The hydrology of the modelled urban stream has changed almost beyond recognition.

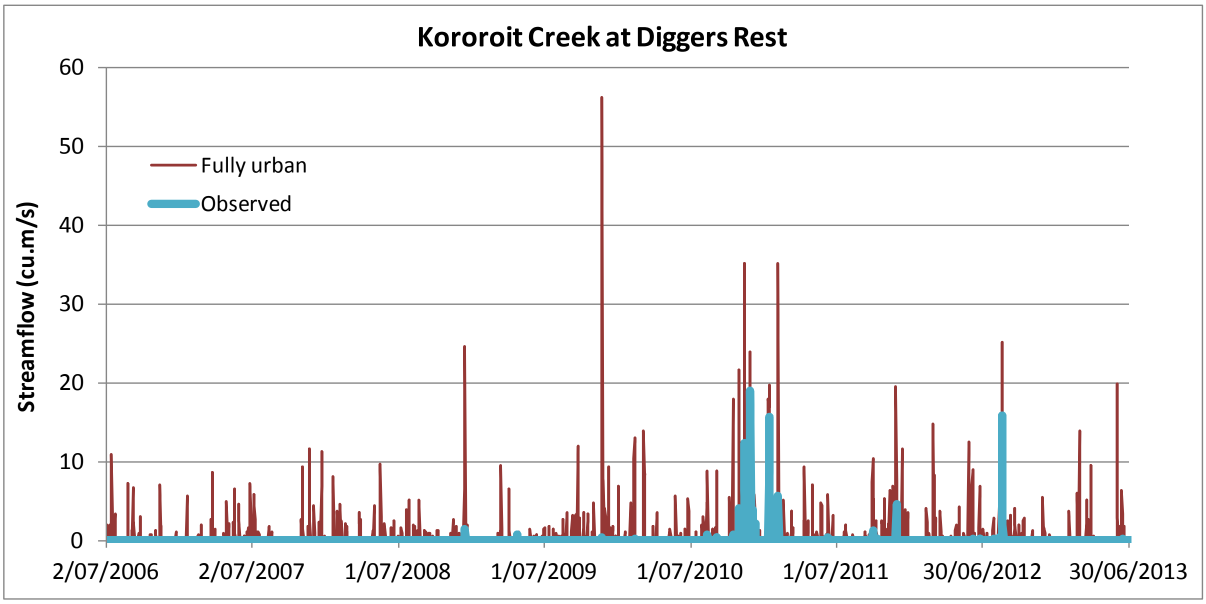


**Figure 12. Modelled daily streamflow from fully urbanised catchment.**

**Table 7. Flow metrics for observed, calibrated, and fully urban conditions.**

| Metric | Observed behaviour | Calibrated model | Fully urban model |
|---|---|---|---|
| Runoff coefficient | 0.0426 | 0.0415 | 0.446 |
| Tqmean | 0.0387 | 0.0348 | 0.155 |
| Fraction of time > $Q_{1.5yrARI}/2$ (1.9m3/s) | 0.0063 | 0.0051 | 0.0774 |
| Fraction of time > $Q_{2yrARI}/2$ (3.8m3/s) | 0.0047 | 0.0047 | 0.0418 |
| Days/year of zero flow | 245 | 260 | 33 |
| Mean duration of zero flow periods (days) | 90 | 87 | 9 |
| Month of minimum monthly flow | May | April | April |

## Development of stormwater management scenarios

The next step was to develop a range of stormwater management interventions that may help to return flow metrics towards their pre-urban condition, and model them in various combinations. To manage the large number of possible combinations, the simulations centre around a few specific volume reductions below the fully urban case, as shown in Table 8. Between them they cover the range from fully urban with no management to preservation of the current rural runoff volume.

In this report, we have adopted the following definition of total volume reduction:

For total flow volume[4] we use the mean of all flows over the adopted period of record (which can also be expressed as the runoff coefficient).

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[4] In this project, total flow volume is calculated from all surfaces (pervious and impervious). Therefore, percentage reduction in runoff volume is calculated from the change in the mean of all flows (pervious and impervious) over the period of record.

This metric has not been included explicitly in the model calibration and scenarios, rather it defines the extent to which the flow in a given scenario is excessive or superabundant, compared with predevelopment conditions.

Table 8. Volume reduction levels.

| Volume reduction below urban runoff | Rationale | Target runoff coefficient |
|---|---|---|
| 0% | Fully urban baseline | 0.446 |
| 30% | Proposed BPEM guidelines (for this rainfall region) | 0.313 |
| 65% | Proposed BPEM guidelines (for this rainfall region) | 0.156 |
| 80% | Approach current observed behaviour | 0.089 |
| 90% | Return to current observed behaviour | 0.043 |

### *Stormwater treatment measures considered*

There are several individual management interventions that can reduce total runoff volume and hence are likely to improve the selected flow metrics. They include:

- rainwater tanks, tanks capturing roof runoff for alternative water supply,
- bioretention capturing ground level impervious runoff,
- leaky tanks which are tanks that in addition to providing alternative water supply, slowly ‘leak’ part of the tank volume to a garden or open space green area (modelled as bioretention), and
- stormwater harvesting systems at the precinct scale represented in the model as either on-stream or off-stream storages in the catchment.

Losses from these systems include water lost to the atmosphere through evapotranspiration, as well as water that is ultimately directed to the sewerage system, after use in toilets, laundries, etc. Infiltration from bioretention systems is simulated at a very low rate, due to the heavy clay soils in the catchment, and is assumed to be subsequently lost to evapotranspiration from the surrounding soil. The individual stormwater control measures can be combined into a range of management scenarios. Interactions between the individual actions can be complex, so simulation provides the ideal way to assess the combined effects.

The scenarios that used tanks drew on assumed demands reported by Walsh et al. (2014). Residential demands were modelled in the present study at two levels – low or high:

- Low residential demands comprised garden watering of 12.97 KL/100 $m^2$ pervious area/year, toilet flushing of 52.9 L/allotment/day, and laundry use of 77.7 L/allotment/day.
- High residential demands included in addition hot water demand of 131.3 L/allotment/day.

Employment and school/community demands were modelled at just one level, based on residential garden and toilet demands: a seasonal demand of 12.97 KL/100 $m^2$ pervious area/year, and a uniform demand of 52.9 L/305 $m^2$ roof area/year. The 305 $m^2$ is the assumed average roof area per residential allotment.

### *Stormwater treatment design to achieve a set reduction in flow volume*

There are many ways to simulate a 30% reduction in flow volume, since only relatively small interventions are needed. Conversely, there are very few ways to simulate a 90% reduction, since every possible process must be scaled up to a high level to reach this demanding target. The range of combinations trialled here is summarised in Table 9. For every simulation run, the model parameters, the daily outflow record, and the selected metrics have been recorded for further analysis. A sample of the models used to simulate these scenarios is shown in Figure 12.

The nature of this project, whereby the volume reduction for a scenario is set, leads to some interesting results. Starting from a simulation that yields a particular volume reduction, changing just one factor – tank volume, reuse demand, bioretention area, etc – almost always changes the simulated volume reduction. To retain the *same* volume reduction, factors must be changed in pairs (or possibly in larger groups). For example, increasing the area of bioretention treating ground level runoff will remove more water from the catchment, while decreasing the tank volume on roof runoff will allow less reuse and so will remove less water from the catchment. Simulating both at once can yield another scenario with the same overall volume reduction. The pairs used in this study are indicated in Table 9. Although this process seems in some ways counter-intuitive, it accords with the objectives of the study – to assess the flow metrics *when complete volume reduction cannot be achieved*.

Table 9. Volume reduction scenarios, showing pairs of factors adjusted to retain the specified volume reduction

| Volume reduction below urban runoff | Scenarios | Pair of factors applied to derive scenarios meeting the specified volume reduction |
|---|---|---|
| 30% | Tanks only | lower uptake <=> larger tanks |
| | Tanks and bioretention | larger bio <=> smaller tanks |
| | Tanks and bioretention | higher demand <=> smaller tanks or bio |
| | Leaky tanks and bioretention | Leak to larger bio <=> smaller tank<br>Leak and spill to larger bio <=> smaller tank |
| 65% | Tanks and bioretention | larger bio <=> smaller tanks |
| | Leaky tanks and bioretention | Leak to larger bio <=> smaller tank |
| | Leaky tanks, bioretention, and reuse from half of all streams | Larger reuse from streams <=> smaller bio |
| 80% | Leaky tanks, bioretention, and reuse from half of all streams | Larger reuse from streams <=> smaller bio |
| | Leaky tanks, bioretention, and reuse from all streams | Larger reuse from streams <=> smaller bio |
| 90% | Leaky tanks, bioretention, and high reuse from all streams | N/A (one scenario) |

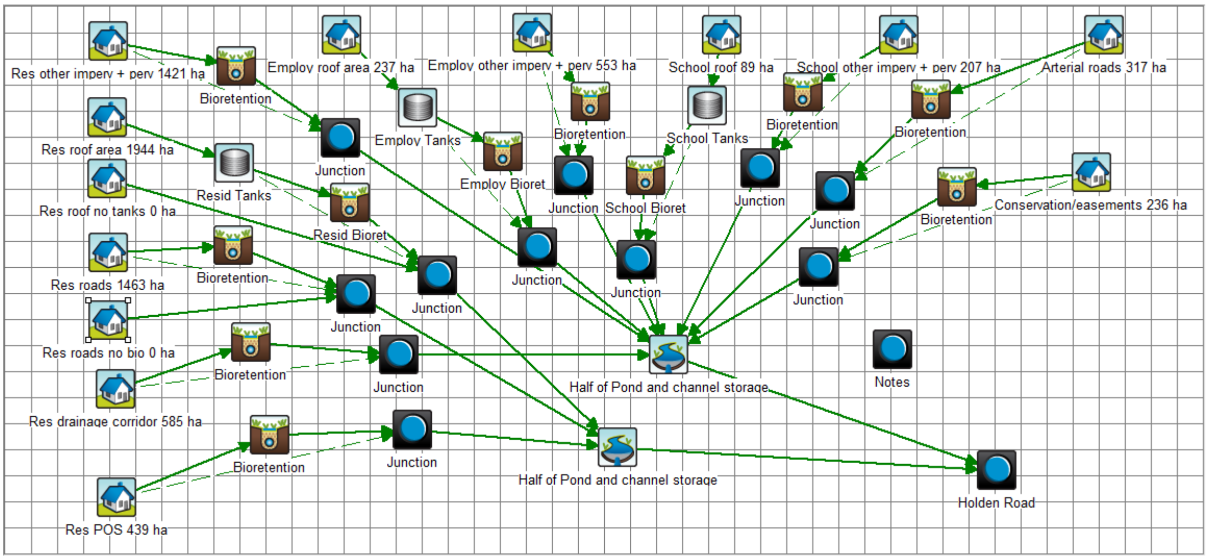


Figure 13. Sample MUSIC model of modified urban catchment.

# Results

## Summary

- For this catchment, it seems that closely approaching pre-urban metrics will require significant reductions in total runoff volume (70-90%).
- The ephemeral nature of the Kororoit Creek catchment means that meeting the metrics relating to low flows is particularly challenging. The binary nature of the ephemeral state precludes the possibility of allowing small proportional changes in low flow magnitude for example, since the flow regime would not then be ephemeral.
- The number of management strategies available diminishes as the volume reduction target adopted increases. A large number of treatment options can meet a 30% volume reduction, but options meeting 90% volume reduction are very limited.
- Important variations in performance against the adopted flow metrics can be observed for the same volume reduction with changes in stormwater management strategies.
- However the volume reduction objective adopted has overall a much larger influence on the performance against the flow metrics adopted (than changes in management strategies).
- Performance against the adopted metric for a given runoff reduction is improved when all impervious runoff is intercepted. Runoff from impervious areas is very destructive to the flow regime, even when contributed by only a small fraction of the total catchment area.
- It is important to note that stormwater needs to be harvested at a point upstream of the smallest tributaries within the catchment for all these receiving waters to be protected. This way flows are intercepted before they enter the natural drainage network, rather that harvesting downstream, where damage to upstream waterways will have already been done.

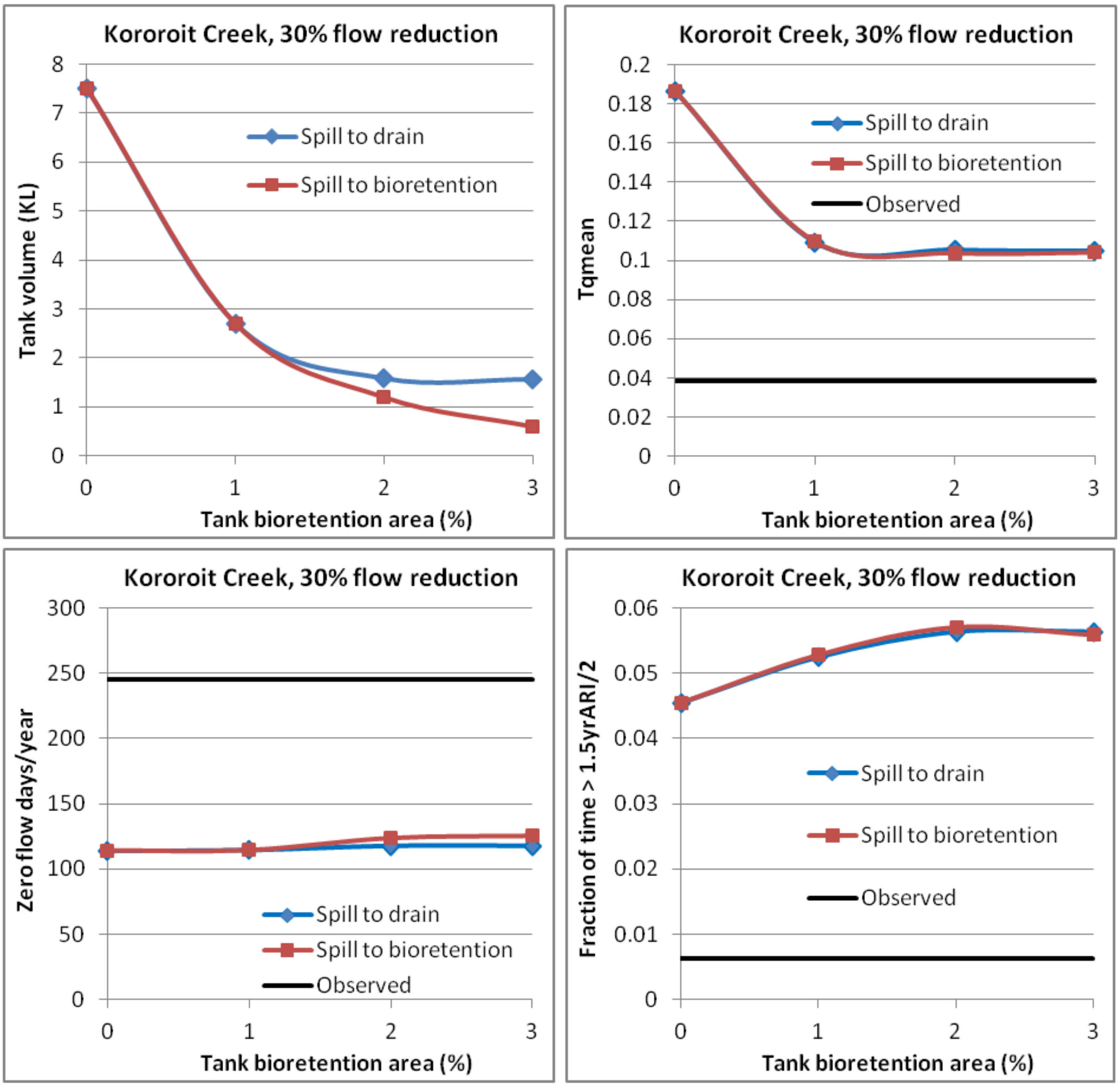
***The results of the Kororoit Creek catchment modelling indicate that, at least for ephemeral streams, unless a water balance close to natural is achieved, hydrologic and geomorphic characteristics key to ecological processes and functions will not be retained and the waterway will thus be significantly altered. In any case, the stream's ephemerality and the particular ecological values that are unique to ephemeral stream in Melbourne will be lost.***

### *30% volume reduction*

For a given pair of catchment interventions and specified volume reduction the results can be presented as in Figure 13. This figure shows the case of roof water tanks with a slow leak to bioretention, and a fixed flow volume reduction of 30%. A larger tank leak bioretention area requires a smaller tank volume to achieve the same volume reduction in streamflow (top left). The option of directing tank overflow to the bioretention area or directly to drain is also explored.

The match to current observed behaviour is poor for Tqmean when the bioretention area provided for the slow leak is very small, and rather better, but still not close to observed, when tank leak bioretention area exceeds 1% of roof area (top right). Tank spill to drain or to the bioretention area makes little difference for this metric. The number of zero flow days per year is almost unaffected by the factors modelled in this example – the match to observed behaviour is always equally poor (bottom left). The match to observed behaviour is also poor for the bed mobilisation metric (the fraction of time with flow greater than half the 1.5 year average recurrence interval flow), but is slightly less bad when tank bioretention area is small and tank volume is large (bottom right). In summary, this metric improves a little when tank bioretention area is small, but Tqmean improves a little when the area is large, and an overall ‘best’ scenario will need to be a compromise.

*Summarising this example of 30% volume reduction below fully urban flows, we could say that target metrics are never closely approached, and that there is no single preferred scenario that improves all the metrics together.*


Kororoit Creek, 30% flow reduction

Kororoit Creek, 30% flow reduction

Kororoit Creek, 30% flow reduction

Kororoit Creek, 30% flow reduction

Figure 14. Relationship between tank bioretention area (ie. the area of bioretention system provided to receive trickle release from the tank), tank volume, and metrics. The "Observed" line represents the pre-developed level, based on measured flows.

### *65% volume reduction*

Another example, this time for 65% volume reduction, is shown in Figure 14. This example models a case with ground level runoff directed to bioretention and roof runoff directed to tanks for reuse. A larger roofwater tank volume requires a smaller ground level runoff bioretention area to achieve the same volume reduction in streamflow (fig.14 left).

The Tqmean metric most closely approaches current observed behaviour at an intermediate tank volume of 8 KL per standard household roof (fig. 14 right). Tqmean is closer to its target value than it was with 30% volume reduction, but the target has still not been reached. In this example the other metrics follow the same pattern (not shown). All are closest to target at intermediate tank volumes of 8 to 10 KL, or are largely independent of tank volume, but in no case has the target been achieved.

The improved performance against metrics at intermediate tank volumes, and hence at intermediate bioretention areas, highlight the importance of intercepting runoff from *all* impervious runoff from the catchment. If significant impervious runoff enters the main watercourses unmodified, some of the fully urban flow signature in Figure 14 will carry through to the catchment outlet and degrade the flow metrics, particularly those describing zero flow behaviour. Balanced use of tanks for roof areas and bioretention for ground level impervious areas reduces the adverse effect.

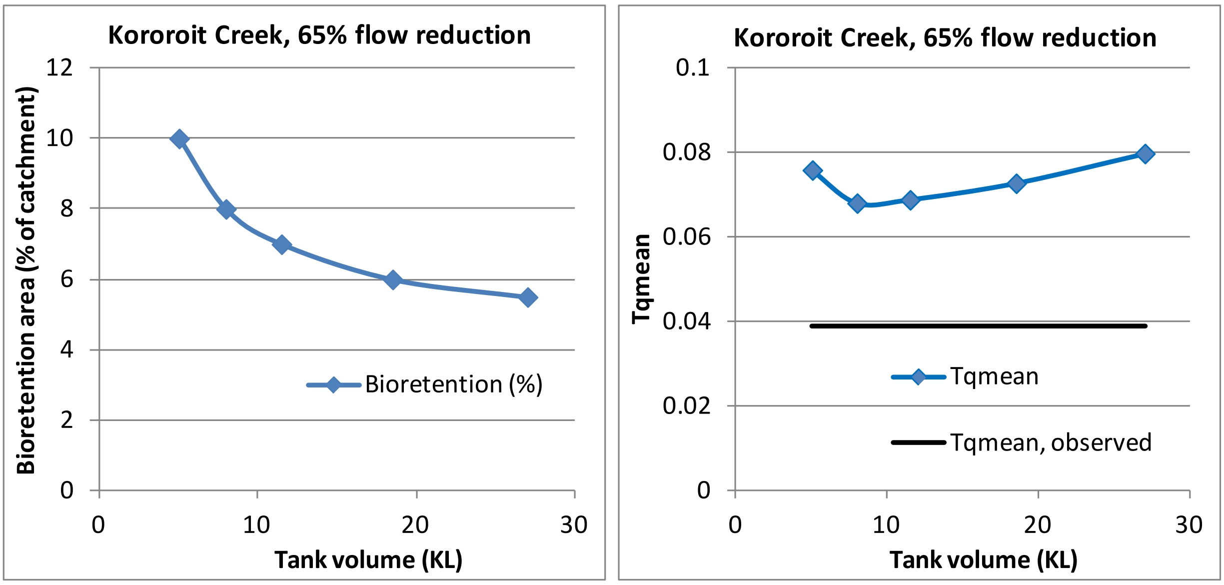


**Figure 15. Relationship between household tank volume, bioretention area, and Tqmean. The “Observed” line represents the pre-developed level, based on measured flows.**

### *Comparison of performance against the selected metrics for a range of volume reductions*

There has been an implicit assumption throughout this project that volume reduction is an important explanatory variable for the adopted flow metrics, and if total runoff volume is restored to pre-urban levels the flow metrics will also be restored to near their target values. This assumption can be explored using the simulated metrics.

Figure 15 shows modelled Tqmean plotted against volume reduction for all the simulated scenarios. There is indeed a strong relationship between Tqmean and volume reduction, which in this case explains 76% of the total variance in Tqmean. The variance due to changes in management strategy is small by comparison, and no scenario tested achieved the target Tqmean with a volume reduction of less than 80%.

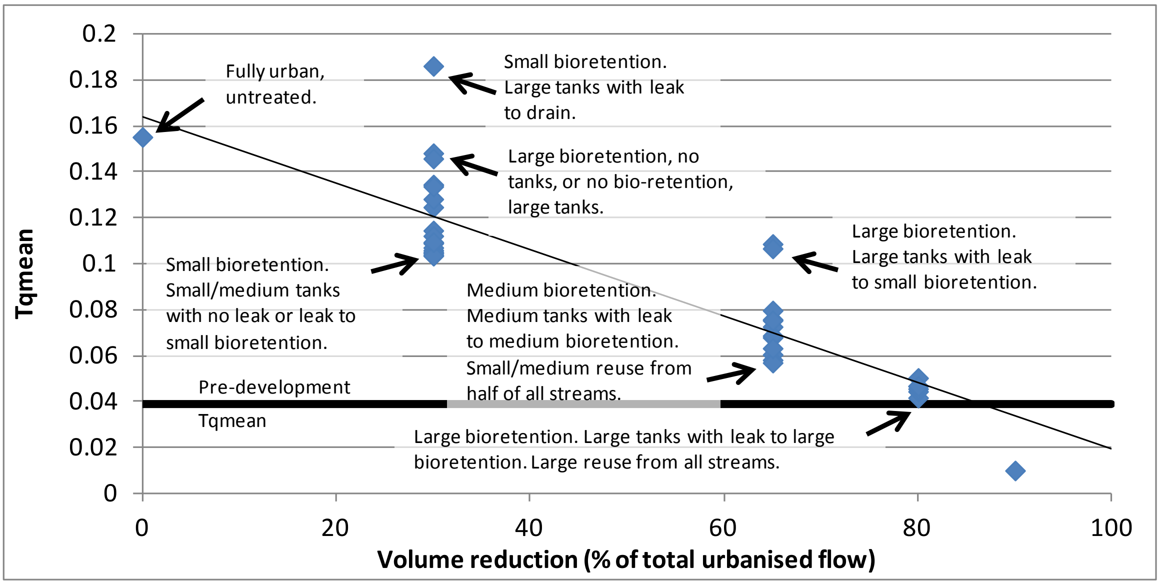


Figure 16. Relationship between Tqmean and volume reduction. The "Pre-development" line represents the pre-developed level, based on measured flows.

Behaviour is very similar for the two threshold metrics, representing bed mobilisation (time>1.9m$^3$/s) and bank mobilisation (time>3.8m$^3$/s), as shown in Figure 16 and Figure 17. Interpolation of the linear curve-fit suggests that a volume reduction between 80 and 90% is needed to restore these two metrics to their pre-urban targets.

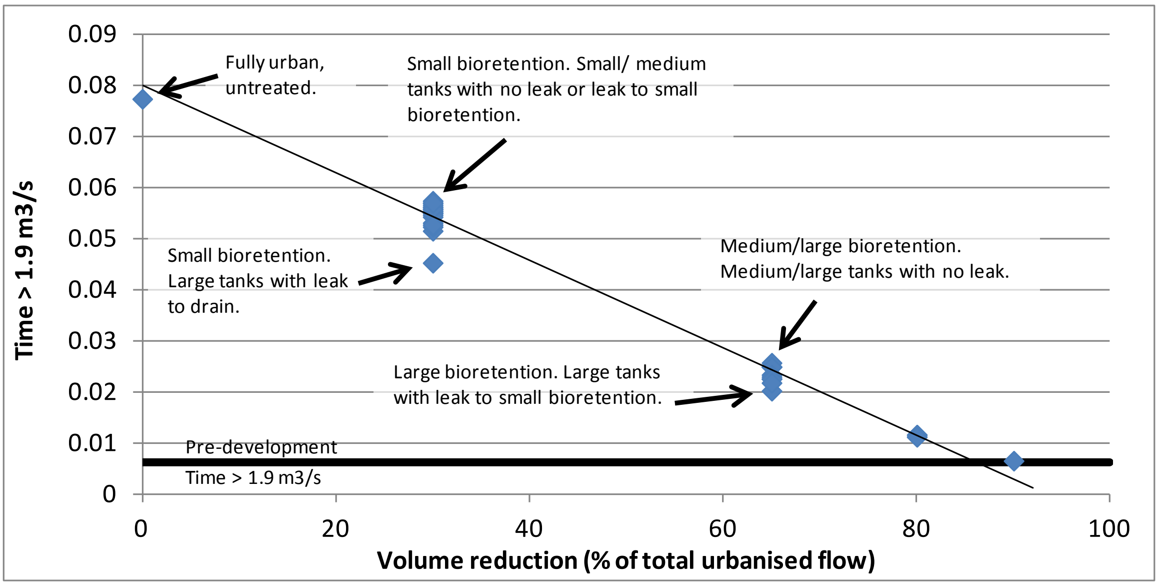


Figure 17. Relationship between fraction of time > 1.9 m$^3$/s and volume reduction. The "Pre-development" line represents the pre-developed level, based on measured flows.

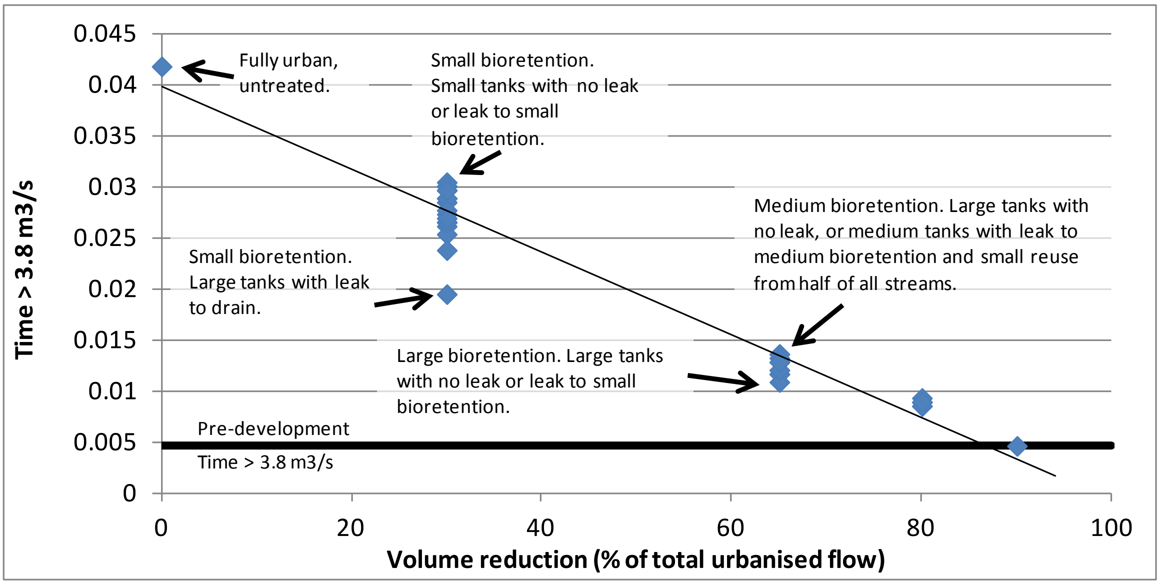


Figure 18. Relationship between fraction of time > 3.8 m$^3$/s and volume reduction. The "Pre-development" line represents the pre-developed level, based on measured flows.

Behaviour is again broadly similar for the two zero flow metrics in Figure 18 and Figure 19, although the curvefit for mean duration of zero flow periods is distinctly non-linear, and the pre-urban targets are reached at volume reductions of 70 to 80%. Therefore, a scenario which satisfied the flow threshold metrics could actually overshoot the zero flow metric targets in this case, which may not be desirable. It seems that a degree of compromise will be necessary when choosing a management scenario that comes close to satisfying all the flow metrics together.

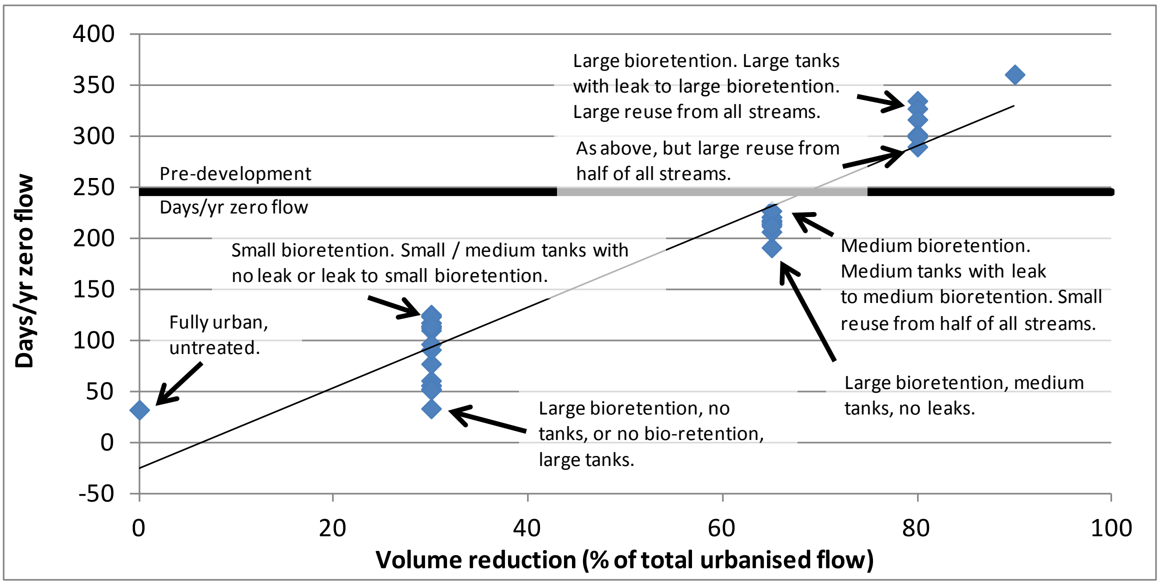


Figure 19. Relationship between days per year of zero flow and volume reduction. The "Pre-development" line represents the pre-developed level, based on measured flows.

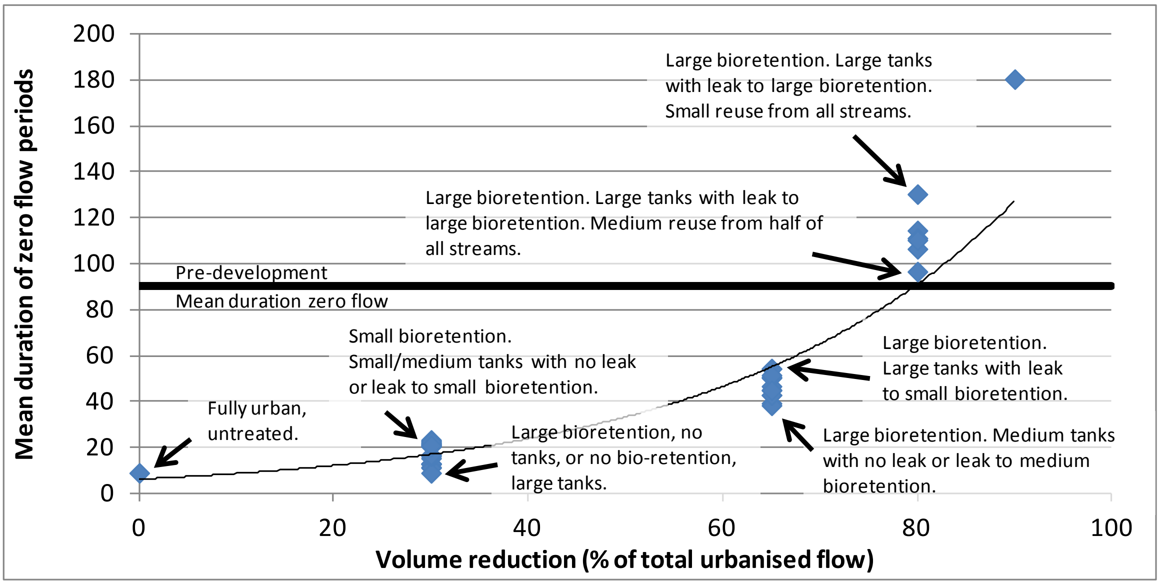


Figure 20. Relationship between mean duration of zero flow periods and volume reduction. The “Pre-development” line represents the pre-developed level, based on measured flows.

# Discussion

The results of the Kororoit Creek catchment modelling indicate that, at least for ephemeral streams, unless a water balance close to natural is achieved, hydrologic and geomorphic characteristics key to ecological processes and functions will not be retained and the waterway will thus be significantly altered. In any case, the stream's ephemerality and the particular associated fauna and flora values that are unique to ephemeral streams in Melbourne would be lost.

### *Appropriate metrics at appropriate scales*

As highlighted above, maintaining key characteristics of Kororoit Creek’s flow regime will require a runoff volume reduction of 70-90%. This relatively large range in required volume reduction depends on the metric being considered; this is because the metrics differ in the way in which they vary with changes in volume reduction. It is for this reason that volume reduction by itself is not an ideal indicator of the flow regime outcomes for a given stormwater management strategy.

The site-scale based “runoff frequency” and “contribution to baseflow” performance metrics (as outlined in the proposed “new BPEM” standards; see Wettenhall, 2013) have been established as having a direct mechanistic link to waterway condition. Application of the runoff frequency metric is relatively straightforward at the site-scale, but is more difficult at the whole-of-catchment scale, which is why the recent work on developing a new set of “BPEM” stormwater standards discussed the use of volume reduction as a simple surrogate. However, as discussed in the previous paragraph, changes in ecologically important flow metrics are not always well correlated with volume reduction. The outcomes of this project suggest that the optimal selection of metrics with the aim of ensuring appropriate flow regimes[5] should involve:

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[5] We note, of course, that water quality objectives should also be applied.

1. Two site-based metrics: (i) runoff frequency and (ii) contribution to baseflows. Both are easy to calculate for a given site or precinct. Such metrics could be applied to individual (small) developments. A volumetric reduction metric could (and probably should) also be applied at this scale.
2. Whole of catchment ecohydrological and geomorphic metrics (as proposed in this study); these are the most direct predictor of flow-related stream health outcomes. Such metrics should be applied to precinct structure plans, regional plans and large-scale developments.

***Implementation / practical feasibility considerations***

Without significant harvesting, the reductions in volume which are prerequisite to meeting the target flow regime (as assessed by the proposed ecohydrologic and geomorphic metrics) are unlikely to be practically possible. For example, if vegetated systems were used to act as 'evapotranspiration beds' for the 'excess' water, the area required for implementation likely would be unfeasibly large (ie around 50% of their impervious catchment areas, or greater). The results thus suggest that if ephemeral streams such as Kororoit Creek are to be protected, there will need to be significant stormwater harvesting at a range of scales.

Implementing sufficient harvesting may have practical challenges such as lack of demand in the catchment, or cost associated with storage infrastructure. An option to overcome this may be collecting stormwater at the precinct scale, prior to treating and then injecting the treated water into the potable network

It is important to note that stormwater needs to be harvested at a point upstream of the smallest tributaries within the catchment for all these receiving waters to be protected. This way flows are intercepted before they enter the natural drainage network, rather that harvesting downstream, where damage to upstream waterways will have already been done.

## Implications for future stages of project

We hypothesise that there may be more 'room to move' in wetter, perennial catchments, because some of the increased flow volume resulting from impervious areas could potentially be distributed through a small increase in low-flows, which we hypothesise could, as long as such flow was appropriately treated, be done without significant ecological degradation. It would thus seem appropriate to test these hypotheses on the next case study catchment, which will be a wetter catchment to the east of Melbourne.

This will also provide further information for the management of ephemeral and intermittent streams. In cases where the highest levels of flow reduction cannot be achieved, and thus where the ephemerality of a stream and its specific values will be lost, it may be useful to consider whether making the stream perennial with a flow regime that can support a healthy, but different, ecosystem can be achieved. Such a decision requires consideration of the local, catchment and regional implications of any loss of ephemerality or intermittency. As ephemeral and intermittent streams occur in limited areas of the Melbourne region, conversion to perennial status will mean an inevitable reduction in regional biodiversity, even though local biodiversity might be increased, because perennial streams typically support a larger (although different) assemblage of biota than do ephemeral and intermittent streams. Regardless of the flow regime outcome, the risks of degradation of the stream ecosystem will be large if the runoff volume is not reduced to a level sufficient to ensure that the frequency of untreated runoff being discharge to the stream is not significantly greater than natural (<5 days/year).

The geomorphic sensitivity of Kororoit Creek could be considered relatively low, since the creek has an often armoured, coarse-grained bed (gravel to cobble), and is well vegetated. These attributes make Kororoit

Creek possibly more resistant to increased disturbance events under urbanisation. How well a stream with fine-grained sediments can resist change under an urban flow regime will be important to test, and is intended to assist with putting bounds on erosion thresholds in a range of stream types managed by Melbourne Water. The challenge in this project with respect to geomorphic metrics is to make them appropriate to the range of stream sensitivities (e.g. differing sediments), but adequately generic so as to not add further assessment tasks when systems are assessed.

An important future challenge in this project is to use the hydrological predictions to make predictions about ecological and geomorphic consequences. To do so, we will use the models developed by Burns et al. (2014), which established relationships between macroinvertebrate community composition in Melbourne's streams and a range of ecohydrologic metrics. We aim to use the predictors in Burns et al.'s models to develop robust boosted regression-tree models.

## Conclusions

This project is testing the extent to which ecologically and geomorphically important flow metrics can be maintained at their pre-development level in the context of an increase in flow volume due to urbanisation. In this first stage of the project, we tested this question for the ephemeral Kororoit Creek catchment, using seven flow metrics:

- Tqmean
- Fraction of time > $Q_{1.5yrARI}/2$
- Fraction of time > $Q_{2yrARI}/2$
- R-B Index
- Days per year of zero flow
- Mean duration of zero flow periods
- Month of minimum monthly flow

The results demonstrated that each of the flow metrics is drastically changed by the level of urbanisation proposed for the catchment. The testing undertaken demonstrates that it is not possible to return these flow metrics to near their pre-development state without achieving total runoff volume reductions in the range of 70-90% below the fully urbanised state. It should also be noted that only a limited number of stormwater management strategies within that volume reduction range maintain flow metrics at their natural values. This result suggests that protection of the values of Kororoit Creek will only be possible with the widespread adoption of strict stormwater management standards that require significant stormwater harvesting. While such an approach currently presents challenges, it also opens up the possibility to deliver significant multiple benefits, including healthy waterways, alternative water supply, potential reduction in drainage infrastructure.

The next stages of the project will test the degree to which these results apply to wetter catchments, and will attempt to derive predictions of the ecological consequences of the modelled hydrologic outcomes.

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