Ecological scenarios for Gum Scrub Creek: informing water management plans in an urbanizing agricultural catchment

A report from the Gum Scrub Creek Ecological Scenarios workshop, April 2010

Cities as Water Supply Catchments Research Program

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Summary

Degradation of urban stream ecosystems around the world results from planning and implementation of drainage schemes that profoundly alter the flow regime and quality of water flowing to streams. Despite this, urban drainage that replicates pre-urban flow regimes is possible, and is most easily achieved through appropriate planning that allows for adequate loss of stormwater runoff to air (through evapo-transpiration by harvesting for irrigation) or to the wastewater stream (by harvesting for potable water substitution), which in turn facilitates the design of infiltration systems that can deliver good quality water to the stream in a pattern similar to the pre-urban state.

Gum Scrub Creek is a small stream to the east of Melbourne, Victoria, Australia with a largely agricultural catchment that will be urbanized over the next 20 years. It is the last stream flowing through Melbourne's urban growth boundary that has not yet been significantly damaged by the impacts of urban stormwater runoff.

We present an assessment of possible futures for the ecological condition of Gum Scrub Creek, compared to its current condition, and an estimation of its original condition prior to European settlement of its catchment. To achieve this assessment, we convened a workshop of stakeholders in the catchment with the aim of reaching a shared understanding of
a) the attributes of the Gum Scrub Creek ecosystem (and a smaller neighbouring creek) that are valued, and worthy of protection or restoration.
b) the likely nature of development in the catchment, and possible approaches to drainage in developments in the catchment;
The stakeholder workshop identified that Gum Scrub Creek, along with its riparian zone and the downstream coastal embayment, Westernport, have important ecological values that should be protected.

This report uses ecological, hydrologic and water quality models to make predictions of changes to the ecological values of Gum Scrub Creek under several development scenarios identified in the workshop: ranging from conventional stormwater drainage in all urban developments, designed to meet existing environmental protection objectives of pollutant load reductions, to widespread stormwater harvesting and dispersed bioretention systems to mimic pre-urban flows.

All in-stream ecological values are very likely to be severely degraded or lost under a conventionally-designed drainage scheme, while most could be protected (and some currently lost values restored) with harvesting and dispersed bioretention. The principle focus of this study is the 340 ha VicUrban@Officer development in the centre of the planned urban area, for which harvesting and dispersed bioretention is proposed. If such an approach is taken in this development, but not in other urban developments in the catchment, all in-stream ecological values will be degraded or lost, just as for the case of conventional drainage throughout.

Along with the importance of stormwater harvesting, we demonstrate that the 100-m wide riparian corridor is vital to the protection of Gum Scrub Creek, helping to restore the natural pre-development loss of water through evapotranspiration. With stormwater harvesting as the primary water source within the VicUrban development, ~9 ha of *Melaleuca* swamp would be necessary within the 100 m corridor, but this would increase substantially (to ~15 ha) if recycled wastewater were used instead of stormwater.

Protection of the ecological values of Gum Scrub Creek will therefore require new approaches to stormwater management in *all* urban developments of the catchment. Our analyses show that such an approach will not only allow Gum Scrub Creek to support important ecological values within its channel and riparian zones, but is likely to increase ecological resistance and resilience of the creek ecosystem to climate change, and also help protect Westernport from sediment and nutrient impacts.

The ecological values of Gum Scrub Creek can only be protected if VicUrban and other developers within the catchment adopt a low-impact approach to stormwater management, which must include extensive stormwater harvesting, to minimize hydrologic and water quality disturbances to the stream.

We therefore recommended that:

1. VicUrban and other stakeholders involved in the VicUrban@Officer project (e.g. Melbourne Water, South East Water, Shire of Cardinia) consider the recommended approach (Scenario 5) to urban stormwater management and to management of the 100-m wide Gum Scrub Creek corridor, within their integrated urban water management plan, to ensure that the important environmental values identified for Gum Scrub Creek and Westernport can be sustained.
2. Melbourne Water consider the findings of this report in determining an appropriate revision to the proposed drainage scheme within the Gum Scrub Creek and Gilbert Creek catchments.

Introduction

There is strong evidence from studies in Melbourne and in other cities of the world that stream ecosystems are severely damaged by conventional stormwater drainage systems that route runoff from roofs and paved areas to streams directly through pipes and sealed drains (e.g. Walsh *et al.* 2005b; Wenger *et al.* 2009). However, studies of small streams of eastern Melbourne (Walsh *et al.* 2005a) and of Sydney (Walsh 2009) have demonstrated that streams draining urban catchments can remain in good ecological condition if stormwater runoff is permitted to drain to sufficient pervious, vegetated land that can allow runoff from most rain events to infiltrate into soils.

In urban developments which lack sufficient vegetated land to allow adequate natural infiltration processes, new approaches to stormwater management are required if stream ecosystems are to be protected (Walsh and Kunapo 2009). Bioretention or infiltration systems are required that provide filtered flows from urban hard surfaces in a similar volume and pattern that were delivered to the stream by subsurface flows from the pre-urban vegetated land. Achieving a pre-urban hydrograph like this will require that most of the impervious runoff be kept out of the stream completely, through harvesting for uses that either result in the water being lost to the wastewater stream through the sewer, or to the air through evapo-transpiration of the urban vegetation.

Numerous studies of ecological structure and function of streams in eastern Melbourne (Hatt *et al.* 2004; Taylor *et al.* 2004; Walsh 2004b; Newall and Walsh 2005; Imberger *et al.* 2008) permit predictions of the response of a range of ecological indicators to urban development. While the total density of urban hard surfaces is not a good predictor of ecological condition (Fig. 1A), the density of those surfaces with direct piped connection to a stream is a good predictor of many ecological indicators (Fig. 1B, appendix 2). Therefore if, for a proposed development, we can estimate the areas of impervious surfaces that will be directly connected to streams, and those that will drain to treatment measures that adequately mimic pre-urban hydrology and water quality, then we can predict the ecological response of its receiving stream.

In this report, we aim to use such predictions of hydrology and ecological values to inform decisions on the drainage scheme and integrated water management of new developments in the Gum Scrub Creek catchment. In preparation for this report, we convened a workshop of stakeholders in the development (Appendix 2) to gain a shared understanding of the specifications of drainage schemes for future developments in the catchment, and of the ecological values of the waterways that are considered important to protect or restore.

For the purposes of this report, we distilled the possible drainage schemes into two contrasting plans: one a conventional stormwater management approach focussing on conveyance and treatment to required pollutant load standards (conventional), and a second focussing on replicating the pre-urban hydrology through stormwater harvesting and dispersed bioretention (low-impact). We estimated directly connected imperviousness (DCI) for the catchment under future urban development scenarios with different degrees of conventional and low-impact drainage.

We report the list of ecological values identified in the workshop as worthy or protection or restoration, and identify those for which we are able to make predictions (through appropriate indicators) of response to future developments. We then present the likely response of indicators—hydrologic, water quality and ecological—under each scenario compared to the contemporary condition of the development's waterway, and an estimate of its pre-European condition.

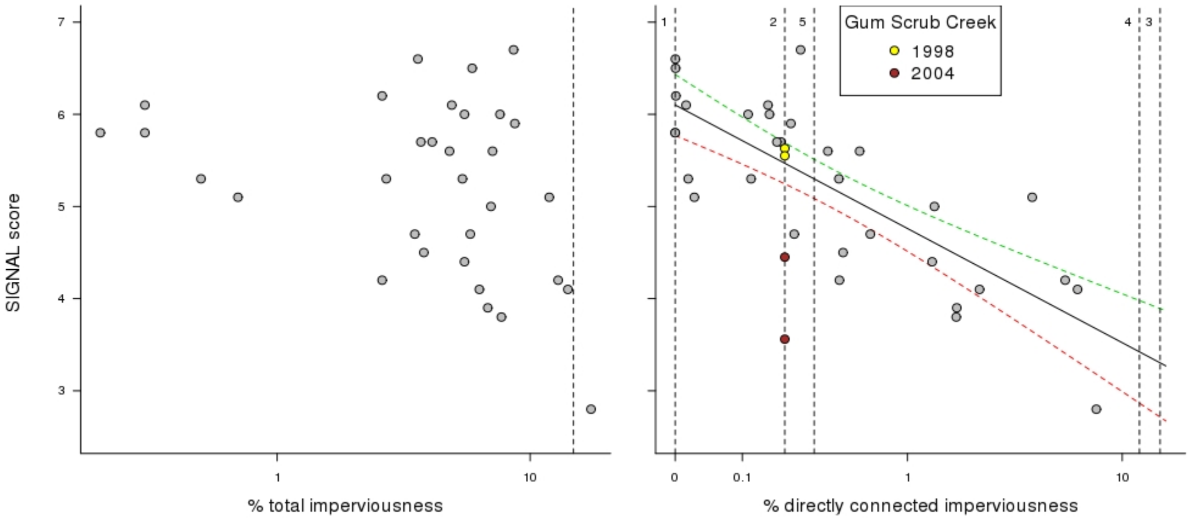

Fig. 1. Macroinvertebrate assemblage composition in eastern Melbourne streams is poorly predicted by urban density, as measured by total imperviousness (A), but is well predicted by directly connected imperviousness (B). The regression line (and 95% confidence limits) use data from 30 streams in eastern Melbourne (from Walsh and Kunapo 2009). The macroinvertebrate assemblage of Gum Scrub Creek at Princes Hwy was predicted well by the model in 1998 (yellow points), but had degraded significantly after 6 more years of drought (brown points). The vertical dashed lines in B indicate the predicted directly connected imperviousness values for the five development scenarios described in Table 1.

The Gum Scrub Creek catchment

We consider future development in the catchment of Gum Scrub Creek, which will be urbanized over the next 20 years (Fig. 2). It is the last stream flowing through Melbourne's urban growth boundary that has not yet been significantly damaged by the impacts of urban stormwater runoff.

The impetus for this study is the 340 ha VicUrban@Officer development, of which 197 ha fall within the Gum Scrub Creek catchment, and 97 ha fall within the catchment of a small agricultural drain to the east, Gilbert Creek (Fig. 2). VicUrban's intention is to minimize the environmental impact of this development, and achieve healthy waterways that are environmental assets to the development and to its coastal receiving water, Westernport. This report focuses primarily on the Gum Scrub Creek catchment.

To the north and south of the 197 ha of the VicUrban@Officer development in the Gum Scrub Creek catchment, an additional 622 ha is zoned for future urban development: 393 ha downstream, and 229 ha upstream. We therefore consider development scenarios for the entire urban zone in the catchment (and take into account the upstream agricultural and forested parts of the catchment), rather than of VicUrban@Officer alone, as it is likely that drainage from the surrounding developments will strongly influence environmental outcomes for the reaches flowing through the VicUrban development.

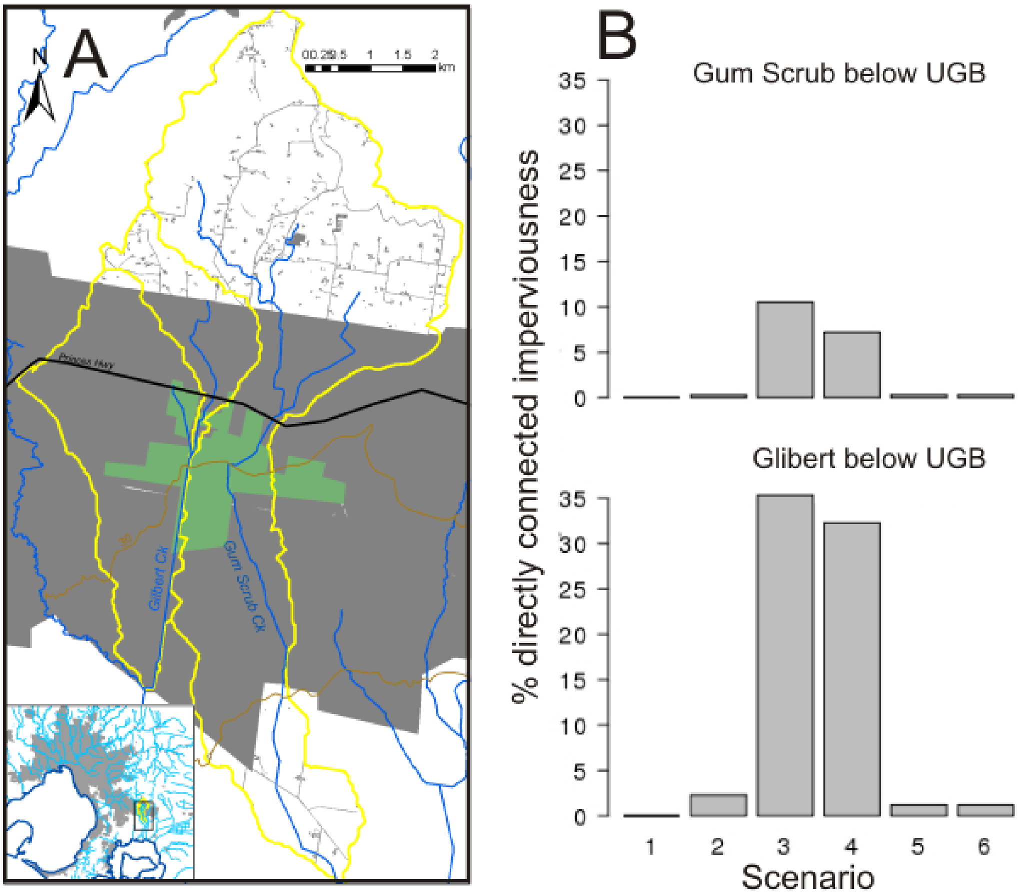

Fig. 2 A. Map of Gum Scrub and Gilbert creeks and their catchments (with inset showing the location of the catchments within the urban growth boundary of Melbourne in grey). The area zoned for urban development is bounded by the large grey area in the middle of the catchments. Existing impervious surfaces upstream of this area are also shown in grey, together with the Princes Highway (black line) and 15 m and 30 m contours (brown lines) The green area is the extent of the VicUrban development that is planned as a low-impact development. B. Estimated directly connected imperviousness for each creek at the most downstream point of the urban zone (UGB = urban growth boundary) for each of 5 scenarios (see Table 1 for the description of each scenario).

The upper 10 sq km of the Gum Scrub Creek catchment lie in the hills of Beaconsfield Upper, currently with predominantly rural residential land use, with some forest (including the 3.3-sq-km catchment of the disused Beaconsfield Reservoir), and a little grazing agriculture and annual horticulture. The catchment downstream is bisected by the 820 ha of low-lying land, currently used primarily for grazing agriculture, but zoned for urban development as described above.

The lowland segment of Gum Scrub Creek is an agricultural drain cut (together with Cardinia, Deep, Toomuc and Ararat creeks, and the Bunyip River) through the Koo-Wee-Rup or 'Great' swamp. While much of the land below the 30-m contour was originally swamp, the creeks upstream of this level (including Gum Scrub Creek upstream of around the Princes Freeway) would originally have been fluvial systems flowing through lowland forests of *Melaleuca* and swamp gum (Fig. 3; Roberts 1985).

The smaller agricultural drain of Gilbert Creek drains south to Cardinia Creek. At Officer, its catchment is 3.3 sq km, with only a little existing urban land around the Officer town centre. Two sq km of this catchment is zoned for urban development.

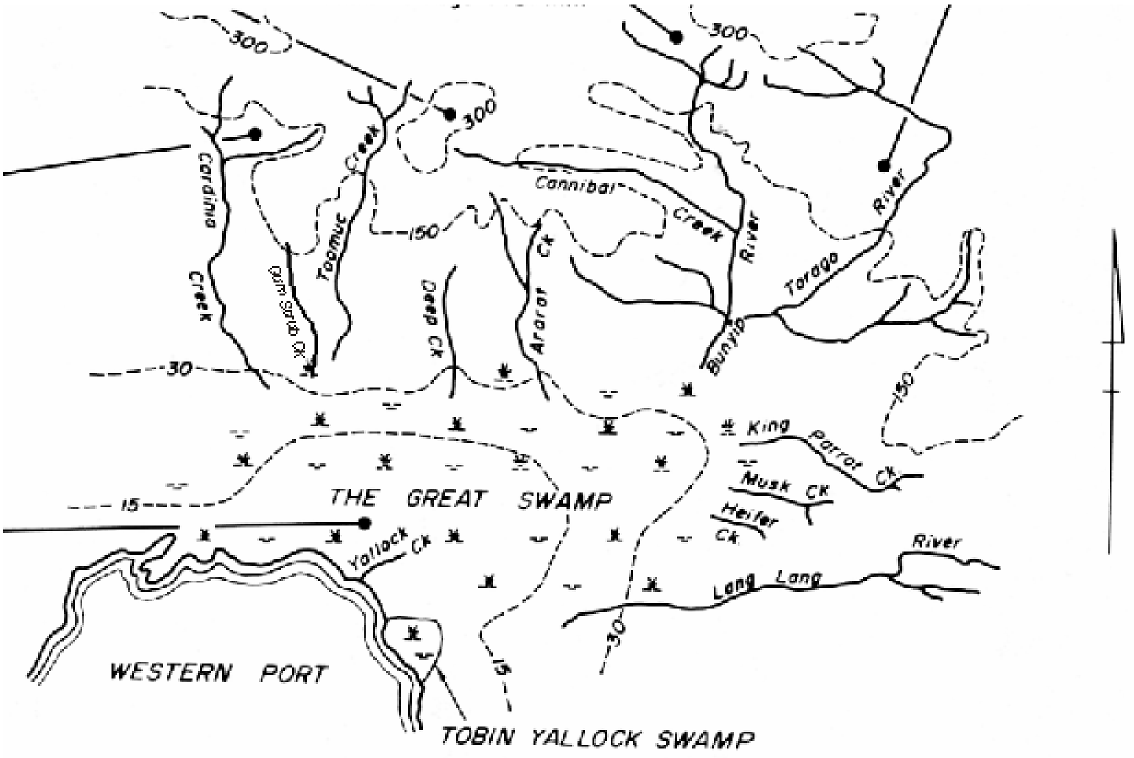

Fig. 3. Map of the original Koo-Wee-Rup swamp (adapted from Roberts 1985), with approximate location of Gum Scrub Creek drawn between Cardinia and Toomuc Creeks

There is limited information on the current ecological condition of Gum Scrub Creek. It was sampled for macroinvertebrates over two seasons in 1998, and again in 2004 (Melbourne Water macroinvertebrate database, unpublished). In 1998, the creek supported a range of sensitive invertebrate taxa (Fig. 1B) indicating moderately good health. Macroinvertebrate indices for the creek in 1998 were consistent with predictions for streams with comparable degree of urban impact in eastern Melbourne (Fig. 1B). In 2004, most sensitive taxa were absent from the creek, indicating a decline in condition over the intervening six years most likely resulting from drought, given that downstream perennial reaches (and neighbouring perennial streams) did not suffer the same decline.

We postulate that frequency of drying out has increased as a result of the cutting of agricultural drains through the KooWeeRup swamp. The more undulating land to the north of the 30 m contour, also contains cut drains through what were likely to be elevated swamp lands that provided extended dry-weather flow. It is therefore likely that in a pre-European state, the lower reaches of Gum Scrub Creek before it merged with the Great Swamp (Fig. 3) were more perennial and their biotic assemblages were more resistant to periods of drought than is the case for the contemporary agricultural drains.

Table 1. Five development scenarios for which ecological and hydrologic responses have been modelled. Directly connected imperviousness (DCI) of Gum Scrub Creek (GSC) and Gilbert Creek is indicated for each scenario. See Appendix 2 for method of determination of imperviousness.

Scenario	Description	DCI	
		GSC	Gilbert
1	Pre-European: no development, catchment all forest, natural streams draining to swamp	0.0%	0.0%
2	Current day: mixed rural residential, agriculture, forest, and a little urban development. Lowland streams agricultural drains cut through drained swamp.	0.2%	2.3%
3	After urban expansion: all areas within urban growth boundary developed (50% TI), with conventional stormwater drainage (40% DCI) =current VicUrban and MW drainage scheme	14.8%	35.3%
4	After urban expansion: all areas within urban growth boundary developed (50% TI), VicUrban low impact(maximum stormwater retention and harvest,DCI = 0.5%), All other urban development conventional (as per MW drainage scheme)	12.0%	32.3%
5	After urban expansion: all areas within urban growth boundary developed (50% TI), with low impact(maximum stormwater retention and harvest,0.5% DCI) throughout (existing DCI halved through retrofit during development)	0.3%	1.2%

Development scenarios for the Gum Scrub Creek catchment

Five development scenarios were considered (Table 1):

1. Pre-European
2. Contemporary condition (pre-drought)
3. Conventional drainage throughout the urban area.
4. Low-impact drainage in the VicUrban development (using drainage strategies developed by the *Cities as Water Supply Catchments* team: Deletic, 2010), but conventional drainage in other parts of the urban area.
5. Low-impact drainage throughout the urban area (again based on the strategies developed by the *Cities* team).

In its ***pre-European state (Scenario 1)***, the catchment of Gum Scrub Creek had zero impervious surfaces (Fig. 2, Table 1). The upper catchment was covered by forests, and the creek likely entered the Great Swamp near the current location of the Princes Hwy, ~1 km within the planned urban area, and ~500 m upstream of the VicUrban@Officer development (Fig. 2). While the creek was unlikely to have a defined channel through the swamp, which was dominated by a forest of *Melaleuca* and swamp gum, we assume the creek upstream of the swamp was a defined channel similar to streams of the region that remain in forested catchments today. We assume that elevated flat areas that today have cut drains through them and the forest of the more upland catchment stored substantial water in soils, providing a perennial flow to the stream. We thus use perennial forested streams of a similar size as the reference for our assessment of pre-European ecological condition.

For ***contemporary condition (Scenario 2)***, we infer from the 1998 macroinvertebrate data, that during a period of average rainfall, Gum Scrub Creek ran perennially in most years. In the last decade, during an extended period of below-average rainfall, the creek has dried out regularly over summer (personal observations). The cutting of agricultural drains through swamp areas in the catchment will certainly have reduced the perenniality of the creek. The wide variation in macroinvertebrate assemblage composition between 1998 and 2004 (Fig. 1) suggests the current agricultural landscape has increased the variability of ecological condition in the stream through reduced resistance of biological assemblages in the creek to dry periods. However, as our aim is to illustrate the likely changes to ecological values relative to contemporary conditions, we have chosen to use 1998 (at the end of an average period of rainfall) as our reference condition. The total imperviousness of the catchment at that time was 2.3%, with DCI of 0.2% (Fig. 2, Table 1), and the macroinvertebrate assemblage composition of 1998 was well predicted by our models of stream response to DCI.

Three developed scenarios (***Scenarios 3, 4, and 5***) were considered, consisting of varying degrees of implementation of two contrasting approaches to drainage design.

The initial plans for the drainage scheme of the catchment by Melbourne Water and that of the VicUrban@Officer development involve conventional stormwater drainage to the existing waterways, with treatment for current pollutant load reduction targets to be met by large in-stream wetlands. The VicUrban plan included sediment basins (with macrophytes to promote sediment adhesion) between each stormwater pipe and the creek, but as these systems would have little influence on the hydrology or water quality (with the exception of suspended sediment loads), we consider most of the impervious surfaces connected to the creek by such pipes as directly connected. This approach of using the waterway for conveyance of stormwater to large treatment wetlands is common practice in Melbourne. Certainly the reach of the creek upstream of a treatment wetland will receive the full effect of stormwater runoff in such developments. There is no evidence of improvement in stream health downstream of stormwater treatment wetlands in Melbourne, and some evidence of degradation resulting from increased temperatures and prolonged pollutographs (Walsh 2004a). Thus, although wetlands are effective reducers of pollutant loads, we consider their effect on most in-stream ecological indicators as neutral. For conventionally drained developments we assume that 80% of impervious surfaces are directly connected to the streams (based on typical current stormwater management practice).

Several alternative integrated water management plans involving stormwater harvesting and treatment have been developed for the VicUrban@Officer development as part of the *Cities as Water Supply Catchments* program (Deletic 2010). All four plans presented by Deletic (2010) at least partly mimic the pre-urban hydrology and water quality of Gum Scrub Creek. Her third option, which involves stormwater harvesting for all uses in the development and dispersed treatment through bioretention systems (both in the catchment, and as *Melaleuca* swamp along the 100-m wide riparian zone that has been set aside along the creek as open space) has the highest probability of retaining the most important elements of the pre-urban hydrology. . We define developments with stormwater management and drainage designed to these specifications as low-impact (LID), and assume that ~1% of the impervious surfaces in such developments will be directly connected to the stream by pipes.

For all development scenarios 3, 4 and 5, we assume total imperviousness throughout the urban area to be 50%, making the total imperviousness of the Gum Scrub Creek catchment at the southern end of the urban growth boundary 18.5%. However, the three scenarios differ in their DCI.

Scenario 3, all conventional drainage, assumes that all urban areas in the catchment will be drained conventionally, consistent with the initial Melbourne Water and VicUrban@Officer drainage scheme plans. Under this scenario DCI of the Gum Scrub Creek catchment at the southern end of the urban growth boundary equals 14.8% (Table 1, Fig. 2).

Development ***scenario 4, LID in VicUrban only***, assumes that the VicUrban development is built using low-impact stormwater management and drainage, but all other urban developments in the catchment are drained conventionally (DCI 12%, Table 1, Fig. 2).

Development ***scenario 5, all LID***, assumes that all urban development in the catchment is built using low-impact stormwater management and drainage (DCI 0.3%, Table 1, Fig. 2).

Ecological values of the development area

Important ecological values of the Gum Scrub Creek catchment were identified at a stakeholder workshop (Table 2). Values that were identified pertained not only to Gum Scrub and Gilbert creeks themselves (their channels and riparian zones), but also Westernport, to which they both drain. Within the stream itself, biodiversity, water quality and maintenance of flow regimes (water retention) were all identified as important (Table 2), Within the riparian zone, biodiversity was considered critical (including a population of the growling grass frog). Maintenance of water quality into Westernport is also considered an important value.

Table 2. Ecological values identified by stakeholders as worthy of protection or restoration in the stream (both its channel and riparian zone) and in the receiving coastal water of Westernport, and selected indicators of those values. Indicators in bold are those for which quantitative models of response to conventional urban development are used in this report. Italicized indicators are those for which a qualitative prediction of their response is possible. (See appendix 1 for a description of how these values and indicators were chosen.)

Value	**Indicators**		
	Stream		**Westernport**
	Channel	**Riparian zone**	
Biodiversity	Invertebrate diversity (**SIGNAL, family richness, EPT richness**)	Various vertebrates	
	Fish diversity (*Blackfish presence*, species richness)	EVC species	
	Algal diversity (**IDB**)	Frog diversity	
	Growling grass frog	*Growling grass frog*	
Water quality maintenance	TSS, TN, **TP, TDS** (Concs as in SEPP)		**Loads of**
	Algal biomass		**TSS, N, P**
Nutrient/ Water retention	**Baseflow index** **Flow frequency**	*Engagement with channel (Volume flowing through riparian sediments)*	
	------------------Water balance(subsurface runoff, ET, surface runoff)---------------------		
Connectivity			

Ecological scenarios

For each development scenario, two methods were used to estimate likely values of ecological indicators.

a) MUSIC (e-Water Cooperative Research Centre 2010) models were used to estimate the annual runoff volume and pollutant loads, and hydrologic indicators such as the volumes of evapotranspiration and stormwater harvesting, and the proportion of streamflow which enters the waterway via filtered sub-surface flow (rather than as untreated surface runoff). These models used a rainfall record representative of the dry conditions of the last decade, and are therefore indicative of a possible drier future climate.

b) Regression models using published data from studies of eastern Melbourne streams were used to estimate concentrations of filterable reactive phosphorus (FRP) and salinity (as estimated, by electrical conductivity, EC), algal biomass, an index of algal assemblage composition (the Indice Biologique Diatomees, IBD), and two indices of macroinvertebrate assemblage composition: SIGNAL, a biotic index that is a sensitive indicator of stream degradation, and number of families of Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) (EPT richness), three orders of insects that are sensitive to disturbance.

The methods used are outlined in detail in Appendix 2. We discuss likely trends for each scenario broadly here (Fig. 4): more detailed results are presented in Fig. A1, and Tables A1-3 in Appendix 2.

The current state of the creek is somewhat degraded compared to the pre-European state, as a result of agricultural land use and drainage in the catchment. It is likely that annual runoff volumes to the creek have increased as a result of loss of forest and the cutting of agricultural drains. Our estimate of slightly less runoff in the pre-European creek (Fig. 4C, Scenario 1) is likely to understate the increase in runoff resulting from draining the Great Swamp, as we have not modeled the hydrology of the swamp, which very likely stored and lost (through evapotranspiration) large volumes of water before discharging to Westernport at Yallock Creek (Fig. 3). Similarly our estimates of 59%, 81%, and 64% lower loads of TSS, TN, and TP, respectively (Fig. 4C), in the pre-urban creek are likely to understate the increase in current day loads of pollutants discharged to Westernport compared to the pre-European state. Despite these changes, the health of biological communities in the creek remained relatively healthy in 1998. The decline in health of the creek during the subsequent drought points to a lack of resistance, resulting from the agricultural drainage that increases the likelihood of the stream drying out.

Our analyses show that low-impact urban development has the potential to increase the resistance and resilience of the creek to drought by increasing baseflows, and restoring perenniality (1.9 GL/y delivered as subsurface flows, compared to 1.7 GL/y in its pre-urban state). In contrast, conventionally drained urban land in any part of the catchment will likely reduce baseflows (1.3 GL/y subsurface flow in scenario 3), and damage stream health further.

Conventional stormwater drainage greatly increases mean annual runoff volume: more than double the current runoff for scenario 3 (conventional drainage throughout: Fig 4C). This is because of reduced evapo-transpiration losses from areas covered by impervious surfaces, and lack of opportunity for losses along flow paths to the stream (less volume kept out of the creek, Fig. 4D). Associated with this increased runoff is an increase in pollutant loads compared to the current state, even with in-stream wetlands to meet current stormwater management targets (Fig. 4C). This increased runoff is damaging to in-stream ecological values because most of this flow reaches the stream directly through pipes rather than through subsurface flows (Fig. 4D). These piped flows represent a large increase in frequency of hydraulic and water quality disturbances to the stream (every time it rains: typically >100 days per year).

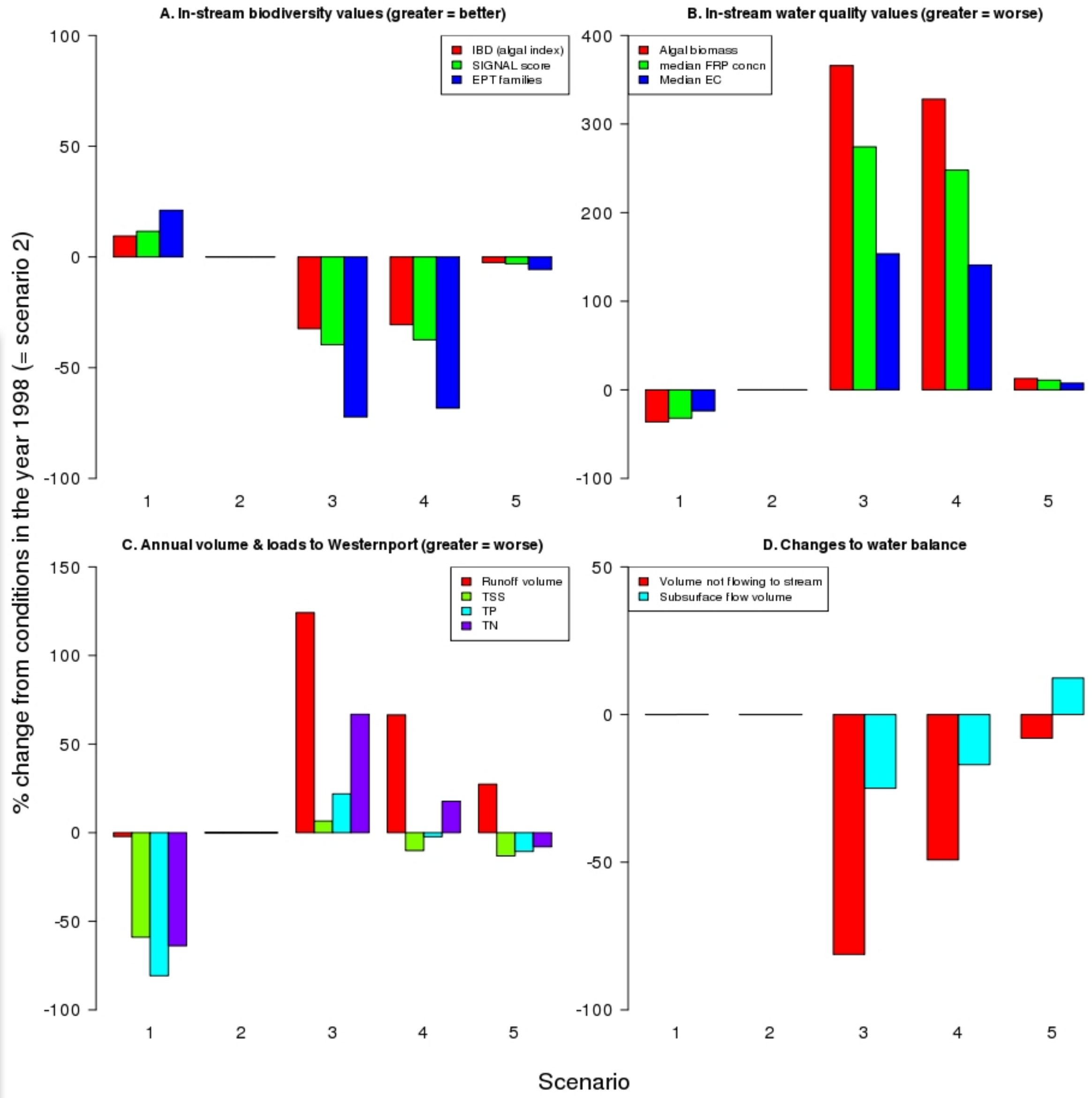

Fig. 4. Predicted change in indicators of important ecological values of Gum Scrub Creek relative to the inferred condition of the stream in 1998. Any development scenario that includes conventional stormwater drainage (Scenario 3 or 4) is predicted to result in decreases in biodiversity values (A), and large increases pollutant concentrations, algal growth (B), and volume of runoff delivered to Westernport (C). More of that water is delivered through piped flows rather than through subsurface flows, and less of it is lost to evapotranspiration (D)[1]. In contrast the low-impact drainage design throughout the urban area (Scenario 5) is predicted to maintain all values near current levels (Scenario 2), which is slightly degraded compared to the pre-European state (Scenario 1). Pollutant loads (C) are predicted to increase under scenario 3, but the combination of wetlands to treat most urban areas, and LID to treat the VicUrban development in scenario 4 is predicted to produce loads of a similar magnitude to the existing agricultural catchment, despite predicted loss of other environmental values. (See appendix 1 for models behind these predictions.)

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[1] Note: the volume not flowing to the stream was calculated just for the area that will ultimately be impervious. All of this volume is lost to evapo-transpiration in the pre-urban state. The volume kept out of the stream in scenarios 4 and 5 is a combination of water lost to evapo-transpiration, and water harvested, then used and sent to the wastewater stream. The % change to subsurface flow volumes was calculated for the whole catchment.

These hydrologic effects of conventional stormwater drainage in scenario 3 are likely to result in increased ambient concentrations in FRP and EC (Fig. 4B), at least in reaches upstream of treatment wetlands. Increased nutrient concentrations will likely drive very large increases in algal biomass (Fig. 4B). These effects, together with the increased disturbance regime are likely to degrade algal and macroinvertebrate assemblages in the stream, with a likely loss of almost all species of sensitive macroinvertebrates such as mayflies, stoneflies, and caddisflies.

If low-impact stormwater management is implemented in the VicUrban@Officer development, but not in other urban developments in the catchment, pollutant load reductions are improved (scenario 4, Fig 4C), but the problem of a large volume of stream flow being delivered frequently through stormwater drainage pipes remains (Fig. 4D). As a result, loss of ecological values in the stream, if VicUrban@Officer were to be the only development in the catchment to adopt low-impact design principles, will likely be as great as if all developments were drained conventionally (scenario 4 vs scenario 3, Fig. 4A, B).

The only future development scenario in which most ecological values are likely to be protected is one in which low-impact design is implemented throughout the urban area (Scenario 5). No significant changes to in-stream biodiversity and in-stream water quality values are predicted for this scenario compared to 1998 condition (Fig. 4, A, B). In fact the greater perenniality arising from increased subsurface flows (Fig. 4D), is likely to increase resistance to drought and result in a substantial improvement in ecological values of the stream compared to 2004 condition. Scenario 5 also produces the greatest reduction in pollutant loads of any urban scenario (Fig. 4C).

The increased perenniality afforded by scenario 5 increases the probability of colonization of Gum Scrub Creek by river blackfish, *Gadopsis marmoratus*, the presence of which is a State Environment Protection Policy (SEPP) objective for streams of this region (Government of Victoria 2001). Although records of river blackfish in Gum Scrub Creek are absent from Melbourne Water's fish database (unpublished), *G. marmoratus* have been recorded in the adjacent Cardinia and Toomuc creeks. River blackfish have not been recorded in any site in the Melbourne region with more than ~2% DCI, and are rarely caught in sites with >0.5% DCI (Danger and Walsh 2008). Thus, the only scenario in which the colonization of Gum Scrub Creek by river blackfish is a possibility is Scenario 5.

VicUrban aim to construct new wetlands in a wide riparian corridor along Gum Scrub Creek, as habitat for the growling grass frog, *Litoria raniformis*. While these wetlands will likely serve as adequate, albeit isolated, habitats for the frog, the broader conservation of the growling grass frog will be more effective if connectivity between populations is provided (Parris 2006). *L. raniformis* has been recorded in Gum Scrub Creek itself (R. Coleman, Melbourne Water, pers. comm.), and *L. raniformis* has been recorded in stream environments of the Melbourne region (http://frogs.melbournewater.com.au/). While there are a number of records of *L. raniformis* from urban wetlands in the Melbourne region, including stormwater treatment wetlands, the frog has not been recorded from streams with significant DCI. Therefore, it is likely that Gum Scrub Creek could potentially serve as additional habitat for *L. raniformis* (therefore providing a potential corridor to connect populations) under scenario 5. The creek is highly unlikely to be suitable habitat for the *L. raniformis* in the degraded state that would be the result of scenarios 3 or 4.

Connectivity is a critical element of stream ecosystems not only for blackfish and the growling grass frog, but for a wide range of stream fauna and flora (Lake *et al.* 2007). The construction of in-stream stormwater treatment wetlands is likely to disrupt connectivity for stream biota in Gum Scrub Creek, compounding the other impacts associated with scenarios 3 and 4.

Finally interaction between the stream channel and the riparian zone is a critical element for the healthy functioning of a creek that is commonly lost in conventionally drained urban areas (Groffman *et al.* 2003). Scenario 5's extensive use of the riparian zone for capturing and storing runoff from the urban areas, and allowing it to infiltrate into the creek, will ensure a strong interaction between the stream and the riparian zone. Such an interaction will certainly be absent from scenario 3, and will potentially be compromised in scenario 4 if upstream conventional drainage causes the need for a deeper and wider channel that is hydrologically isolated from the floodplain. Without the riparian engagement proposed in Scenario 5, increased nitrogen export from the catchment is likely, resulting from reduced rates of denitrification, and increased rates of nitrification in the drier riparian zone (Groffman *et al.* 2003).

In summary, the in-stream ecological values identified by the stakeholder workshop as worthy of protection can only be protected in a future, urbanized Gum Scrub Creek catchment if all developments are designed to incorporate substantial stormwater harvesting and bioretention systems to provide filtered baseflow (Scenario 5). In other scenarios, including the case of low-impact design in the VicUrban development, but conventional stormwater drainage in other developments (Scenario 4), all in-stream ecological values will be substantially degraded or lost. Neither of the scenarios that include conventional drainage have any chance of achieving SEPP objectives for in-stream biota (macroinvertebrates or river blackfish) or water quality, however, they could be achieved with universal low-impact design.

Conclusions and recommendations

A workshop of stakeholders with an interest in the Gum Scrub Creek catchment identified that the creek, along with its riparian zone and the downstream Westernport, have important ecological values. Our analyses demonstrate that the ecological values of Gum Scrub Creek can only be protected if VicUrban and other developers within the catchment adopt a low impact approach to stormwater management, incorporating extensive stormwater harvesting, to minimize hydrologic and water quality disturbances to the stream.

Our analyses suggest that such an approach could increase the ecological resistance and resilience of Gum Scrub Creek to drought (and therefore potential future climate change), through increased perennial baseflows. Conversely, if urbanization is allowed to proceed with conventional approaches to stormwater management, the important ecological values of the creek and riparian zone will certainly be severely degraded or lost.

We therefore recommend that:

1. VicUrban and other stakeholders involved in the VicUrban@Officer project (e.g. Melbourne Water, South East Water, Shire of Cardinia) consider the recommended approach (Scenario 5) to urban stormwater management and management of the 100 m Gum Scrub Creek riparian corridor within their integrated urban water management plan, to ensure that the important environmental values identified for Gum Scrub Creek and Westernport can be sustained.
2. Melbourne Water consider the findings of this report in determining an appropriate revision to the proposed drainage scheme within the Gum Scrub Creek and Gilbert Creek catchments.

References

Catford J. A., Walsh C. J., and Beardall J. (2007). Catchment urbanization increases benthic microalgal biomass in streams under controlled light conditions under controlled light conditions. *Aquatic Sciences* 69, 511-522.

Danger A., and Walsh C. J. (2008). Management options for conserving and restoring fauna and other ecological values of urban streams in the Melbourne Water region. Department of Resource Management and Geography, The University of Melbourne, A report to Melbourne Water, Melbourne.

Deletic A. (2010). Stormwater harvesting plans for the VicUrban@Officer development. Centre for Water Sensitive Cities, Monash University, Melbourne.

e-Water Cooperative Research Centre (2010). 'MUSIC (Model for Urban Stormwater Improvement Conceptualisation) Version 4.' e-Water Cooperative Research Centre. http://www.toolkit.net.au/music

Government of Victoria (2001). Variation to state environment protection policy (Waters of Victoria): insertion of Schedule F8, Waters of the Western Port and Catchment. The Craftsman Press, Victoria Government Gazette, Melbourne, Australia.

Groffman P. M., Bain D. J., Band L. E., Belt K. T., Brush G. S., Grove J. M., Pouyat R. V., Yesilonis I. C., and Zipperer W. C. (2003). Down by the riverside: urban riparian ecology. *Frontiers in Ecology and the Environment* 1, 315–321.

Harris G., Batley G., Fox D., Hall D., Jernakoff P., Molloy R., Murray A., Newell B., Parslow J., Skyring G., and Walker S. (1996). 'Port Phillip Bay Environmental Study Final Report.' (CSIRO: Canberra.)

Hatt B. E., Fletcher T. D., Walsh C. J., and Taylor S. L. (2004). The influence of urban density and drainage infrastructure on the concentrations and loads of pollutants in small streams. *Environmental Management* 34, 112–124.

Hero J.-M., Gillespie G., Lemckert F., Littlejohn M., Robertson P., Brereton R., and Brown P. (2004). *Litoria raniformis*. In 'IUCN Red List of Threatened Species.' (Ed. IUCN 2010.). (www.iucnredlist.org.)

Imberger S. J., Walsh C. J., and Grace M. R. (2008). More microbial activity, not abrasive flow or shredder abundance, accelerates breakdown of labile leaf litter in urban streams. *Journal of the North American Benthological Society* 27, 549–561.

Kunapo J., Chandra S., and Peterson J. (2007). Spatial data integration for accurate parcel level sub-catchment delineation for hydrological modelling. In 'Proceedings of the Spatial Science Institute Biennial International Conference (SSC2007)'pp. 824–833. (Hobart, Tasmania, Australia.)

Lake P. S., Bond N., and Reich P. (2007). Linking ecological theory with stream restoration. *Freshwater Biology* 52, 597-615.

Newall P., and Walsh C. J. (2005). Response of epilithic diatom assemblages to urbanization influences. *Hydrobiologia* 532, 53–67.

Parris K. M. (2006). Urban amphibian assemblages as metacommunities. *Journal of Animal Ecology* 75, 757–764.

Resh V. H., and Jackson J. K. (1993). Rapid assessment approaches to biomonitoring using benthic macroinvertebrates. In 'Freshwater biomonitoring and benthic macroinvertebrates'. (Eds D. M. Rosenberg and V. H. Resh.) pp. 195–233. (Chapman and Hall: New York.)

Roberts D. (1985). 'From swampland to farmland: a history of the Koo-Wee-Rup flood protection district.' (Rural Water Commission of Victoria: Melbourne.)

Taylor S. L., Roberts S. C., Walsh C. J., and Hatt B. E. (2004). Catchment urbanisation and increased benthic algal biomass in streams: linking mechanisms to management. *Freshwater Biology* 49, 835–851.

Victoria Stormwater Committee (1999). 'Urban stormwater: best practice environmental management guidelines.' (CSIRO: Melbourne.)

Wallbrink P. J., Hancock G. J., Oley J. M., Hughes A., Prosser I. P., Hunt D., Rooney G., Coleman R., and Stevenson J. (2003). The Westernport sediment study. CSIRO Land and Water, Consultancy Report, Canberra.

Walsh C. J. (2004a). Impacts of stormwater treatment wetlands on stream macroinvertebrates: a study of four wetlands constructed by Melbourne Water on streams in eastern Melbourne. Water Studies Centre, Monash University, Report for Melbourne Water, Melbourne.

Walsh C. J. (2004b). Protection of in-stream biota from urban impacts: minimise catchment imperviousness or improve drainage design? *Marine and Freshwater Research* 55, 317–326.

Walsh C. J. (2009). Patterns of urban stormwater impacts on stream macroinvertebrate assemblages in three parts of the Sydney metropolitan area: evidence for new, flow-based stormwater management objectives for the Sydney region. Department of Resource Management and Geography, The University of Melbourne, Final report for Sydney Metropolitan Catchment Management Authority, Melbourne.

Walsh C. J., Fletcher T. D., and Ladson A. R. (2005a). Stream restoration in urban catchments through re-designing stormwater systems: looking to the catchment to save the stream. *Journal of the North American Benthological Society* 24, 690–705.

Walsh C. J., and Kunapo J. (2009). The importance of upland flow paths in determining urban effects on stream ecosystems. *Journal of the North American Benthological Society* 28, 977-990.

Walsh C. J., Roy A. H., Feminella J. W., Cottingham P. D., Groffman P. M., and Morgan R. P. (2005b). The urban stream syndrome: current knowledge and the search for a cure. *Journal of the North American Benthological Society* 24, 706–723.

Wenger S. J., Roy A. H., Jackson C. R., Bernhardt E. S., Carter T. L., Filoso S., Gibson C. A., Hession W. C., Kaushal S. S., Martí E., Meyer J. L., Palmer M. A., Paul M. J., Purcell A. H., Ramirez A., Rosemond A. D., Schofield K. A., Sudduth E. B., and Walsh C. J. (2009). Twenty-six key research questions in urban stream ecology: an assessment of the state of the science. *Journal of the North American Benthological Society* 28, 1080-1098.

Appendix 1. The Gum Scrub Creek ecological scenario workshop

Selection of ecological values and indicators

A workshop was held at the University of Melbourne on 20 April, 2010, to identify the important ecological values of the Gum Scrub Creek catchment.

In discussing ecological values, the stakeholder workshop first sought to identify the ecosystems that were of relevance to a discussion of drainage design and water management for the VicUrban@Officer development. Of primary importance are Gum Scrub and Gilbert creeks, both their channels and riparian zones, and Westernport into which they drain. The list of values and their indicators identified by the workshop encapsulate sufficient elements to describe the ecological condition of the ecosystems.

Westernport

Existing stormwater management objectives of reductions in loads of suspended solids, nitrogen and phosphorus (from untreated, conventional drainage) were primarily driven by concerns for coastal waters, particularly Port Phillip Bay (Harris *et al.* 1996; Victoria Stormwater Committee 1999). The coastal receiving water of this development is Westernport, a semi-enclosed marine embayment, dominated by mudflats and seagrass meadows that have declined in recent decades, probably as a result of increased sediment loads from streams now cut through the Great Swamp (Wallbrink *et al.* 2003). Discharge from the swamp is also likely to have increased substantially since the rivers and streams were cut through the swamp, permitting multiple discharge points to the bay in contrast to the original single outlet of Yallock Creek (Figs. 2, 3). Protection of the many ecological (and social and economic) values of Westernport primarily requires management of loads of sediments and nutrients, as well as volume of discharge (Table 2).

Gum Scrub Creek (in-stream)

In considering the creeks, biodiversity was the value that dominated discussion. Ecosystem processes, such as nutrient and water retention and cycling, maintenance of water quality and connectivity between ecosystems were also identified as important values (Table 2). Values in riparian zones and those in stream channels were considered separately, as the latter are likely to be more directly influenced by stormwater runoff impacts than the former (Danger and Walsh 2008).

In-stream biodiversity values spanned a wide range of biotic groups (Table 2). Invertebrate diversity was considered a primary value for several reasons. Macroinvertebrates are a diverse group with a range of sensitivities to environmental disturbance. This and other attributes make macroinvertebrate assemblage composition a sensitive indicator of in-stream ecological condition (Resh and Jackson 1993). Macroinvertebrate indicators are used as objectives in the State Environment Protection Policy (Waters of Victoria) (Government of Victoria 2001), and empirical models of their response to DCI are available (Walsh 2004b; Walsh *et al.* 2005a). Algal diversity was also considered important, and similar empirical models are available (Newall and Walsh 2005). Fish diversity was also considered important, although limited data on historical fish distribution in streams of the Koo Wee Rup swamp and its rivers is available, and empirical models are lacking. However, the distribution of river blackfish is strongly correlated with DCI (Danger and Walsh 2008), and some qualitative assessment of the likelihood of future occurrence in Gum Scrub Creek is considered in this report. Frog diversity was considered primarily a value associated with riparian wetlands, although the growling grass frog occurs in streams (see discussion below of riparian values).

Water quality was considered a value, primarily as a driver of in-stream ecological processes. Concentrations of total suspended solids (TSS), nitrogen (TN), phosphorus (TP) and dissolved salts (TDS), are important indicators of water quality as they are also objectives in the State Environment Protection Policy (Government of Victoria 2001). Median concentrations of TDS (measured as electrical conductivity, EC) and filterable reactive phosphorus are well predicted by DCI in streams of eastern Melbourne (Hatt *et al.* 2004). Excess algal biomass can be an aesthetic problem and a signal of poor in-stream ecological health. Algal biomass accrual is a process that can be influenced by riparian shading and flow processes, but in streams of eastern Melbourne, appears to be most strongly influenced by nutrient concentrations (particularly phosphorus) delivered by stormwater drainage systems (Taylor *et al.* 2004; Catford *et al.* 2007). The work of Taylor *et al.* (2004) permits prediction of algal biomass in response to DCI.

Water retention was considered a value in light of the problems associated with excess stormwater runoff, and reduction in baseflows resulting from reduced infiltration in conventionally drained urban developments. Indicators of the volume streamflow contributed by subsurface flows and untreated flow frequency are important indicators of these stormwater impacts that can be modelled using MUSIC. More broadly, the total water balance between evapo-transpiration loss, infiltration flows, and untreated surface flows is a good indicator of changes wrought by urban development that can also be modelled in MUSIC.

Riparian zones

Ecological values of the riparian zone considered in the workshop were primarily concerned with biodiversity, although the ecological functioning of the riparian zone was also considered (Table 2). A number of mammal, bird and reptile species that might be associated with riparian zones were identified as being of conservation significance in the workshop, together with vegetation types classified by the Victorian Government into Ecological Vegetation Classes (EVCs). We do not consider these values further in this report, as their management will likely be the result of direct actions in the riparian zones rather than a direct influence of stormwater drainage (although indirect effects associated with soil processes are likely: see below).

Frog diversity was identified as a primary value of riparian zones in the region, with a strong driver of management of the creek lines being the presence of the endangered growling grass frog, *Litoria raniformis* (Hero *et al.* 2004) in constructed dams currently adjacent to the creek in the VicUrban@Officer development. Constructed wetlands in the riparian corridor are planned as new habitat for the growling grass frog, prior to the existing farm dams being decommissioned. It should however, be noted that the growling grass frog also occurs in stream ecosystems, and has been recorded in Gum Scrub Creek itself (R. Coleman, Melbourne Water, pers. comm.). While we are limited in the predictions that can be made of frog responses to DCI, some qualitative assessment of responses of the growling grass frog are possible both in the riparian zone and in the creek.

The ecological functioning of riparian zones and their interaction with stream channels is an important factor in the capacity of stream ecosystems to retain and cycle nutrients and other contaminants. This capacity is commonly lost following catchment urbanization through the processes of stream incision and bypass of water flows by stormwater pipes causing riparian zones to dry out (Groffman *et al.* 2003). Undoubtedly some of this capacity has already been lost through the draining of the swamp, and low-impact stormwater drainage could restore it through increasing water flows through the riparian sediments.

The riparian values considered here are also applicable to Gilbert Creek. We did not consider in-stream values for Gilbert Creek, as its small catchment size makes it highly unlikely that it was ever a natural stream but rather a low-lying part of the great swamp. An appropriate reference condition for Gilbert Creek would therefore be swamp vegetation with only subsurface flows of water most of the time.

List of attendees

The Cities as Catchments Research Program.

The stream ecology team (Project 4):

Chris Walsh (Uni Melbourne: convenor), Tim Fletcher (Monash), Mike Stewardson (Uni Melbourne) Perrine Hamel (Monash), Belinda Hatt (Monash, also representing *the technology team [Project 1]*)

The microclimate team (Project 3): Andy Coutts (Monash)

The integration team (Project 8) Ross Allen, Peter Breen (Aecom), Tony Wong (Aecom and Monash)

Melbourne Water

Toby Prosser, Phil Edwards (Stormwater quality), Joanna Frame (River Health), David Reginato (Developer Planning), Lucy Rose (Biodiversity)

Department of Sustainability and Environment

Mandy Bolton, Ann Allworth (Office of Water)

Southeast Water

Justin Lewis

VicUrban

James Gallagher (Development Director), Victoria Leavold (Environment Development Manager, Water), David Knight (Development officer – Biodiversity), Martin Reeves (Outlines, Landscape design consultant to VicUrban), Neil Craigie (Drainage consultant to VicUrban)

Cardinia Shire Council

Angie Dean (Engineering Department), apology from Desiree Lovell (Sustainability and Climate Change).

Appendix 2. Methods and results

Methods

(i) Estimates of imperviousness

Current total area of impervious surfaces was estimated from 2006 aerial imagery by J. Kunapo (Grace detailed-GIS Services, Melbourne) as part of a larger mapping exercise commissioned by Melbourne Water. Catchment boundaries were estimated using a digital elevation model (DEM) conditioned to the stream network and to the stormwater drainage network (Kunapo *et al.* 2007). This DEM was used to estimate overland flow distances from the most downslope edge of each impervious surface to the nearest stormwater drain or stream. DCI was calculated by weighting each impervious area by this distance, using an exponential decay function with a half-decay distance of 9.4 m (the maximum most-plausible value determined by Walsh and Kunapo, 2009).

Directly connected imperviousness of conventionally drained urban land was estimated as 80% of total imperviousness, as this is typical of existing metropolitan suburban areas in which many of the private paved areas are informally drained, and a small proportion of house roofs drain to rainwater tanks connected to frequent uses.

Directly connected imperviousness of urban surfaces with low-impact drainage is assumed to be zero, as the water balance achieved by the preferred option of Deletic (2010: see below) is assumed to adequately approximate pre-urban conditions to effectively 'disconnect' each impervious surface. A DCI of 1% is assumed across such a development because it will not be feasible to disconnect the few surfaces that cross or are very close to the stream.

(ii) Ecological predictions

Linear regression models were calculated for a range of ecological indicators against $\log_{10}(x + 0.001)$-transformed DCI. Data used were taken from the following sources: Walsh (2004), macroinvertebrate assemblage composition (SIGNAL and EPT richness); Newall and Walsh (2005), algal assemblage composition (IBD); Taylor *et al.* (2004), algal biomass; and Hatt *et al.* (2004), FRP and EC. 95% confidence intervals around each regression were calculated. These confidence intervals are intended only as an indication of the size of differences between scenarios relative to unexplained variation in the model, rather than as a statistical test of differences. For each scenario, a mean value of each indicator (± 95% confidence limits) were estimated from the regression.

(iii) MUSIC modelling

MUSIC modelling was undertaken for the five scenarios (see *Development scenarios for the Gum Scrub Creek catchment*), along with some additional cases involving alternative design strategies for the VicUrban development (Table A1). All impervious areas managed using 'conventional stormwater drainage' were assumed to be treated to current Clause 56 requirements (a reduction of 80, 45 and 45% in the mean annual loads of TSS, TP and TN, respectively); this was modelled using a wetland optimised in size and detention time to meet these targets.

The modelling was undertaken for the entire Gum Scrub Creek catchment to the southern-most limit of the urban growth boundary (Fig. 2).

The MUSIC model was based initially on a calibrated model of the catchment developed by Ecological Engineering for Melbourne Water (T. Wong, Monash University, pers. comm.). The model was run for the period 1977-1987 using a 6-minute time step. The average annual rainfall during this period was 841 mm. For each scenario, the pollutant loads were modelled, along with a wide range of hydrological indicators, including mean annual flow volume, evapotranspiration loss, volume harvested, total 'loss' from impervious areas, and the proportion of flow which enters the stream via filtered sub-surface flow. The methods used to calculate each of these statistics are described in Table A2.

Pollutant concentrations are not reported because it was not possible to accurately quantify the effect of the stormwater retention strategies within the VicUrban site (and other urban areas, depending on the scenario) on the median concentrations. Given that a key part of the proposed strategy involves a large bioretention swamp, which will allow water to slowly filter through the riparian zone into the creek, this would significantly impact on the dry weather flow water quality concentrations. However, since MUSIC does not track the quality of this infiltrated water, its influence on concentrations could not be reliably simulated within the time available. An attempt to include this component could be made at a later stage, by constructing a model capable of representing the contribution of water from this riparian zone back into the stream, and estimating (using literature-derived values) the likely concentration of those sub-surface flow contributions.

Modelling of the pre-developed scenario assumed 100% forest with no impervious areas. Given that no specific calibration data was available for the pre-development period, the same soil calibration values were assumed for the pre-development as for the current day and all future scenarios.

Table A1. Scenarios modelled in MUSIC, including alternative drainage design strategies (adapted from Deletic 2010). All scenarios except the *VicUrban site only* scenarios are based on the Gum Scrub Creek catchment to the southern limit of the urban growth boundary (total catchment area = 27.4 km^2).

Scenario	**Description**
1	Pre-European: no development, catchment all forest, natural streams draining to swamp
2	Current day: mixed rural residential, agriculture, forest, and a little urban development. Lowland streams agricultural drains cut through drained swamp.
3	After urban expansion: all areas within urban growth boundary developed, with conventional stormwater drainage =current VicUrban and MW drainage scheme
4a	After urban expansion: all areas within urban growth boundary developed, VicUrban low impact (maximum stormwater retention and harvest) (Strategy 1 in Deletic 2010 = Strategy A, below), All other urban development conventional (as per MW drainage scheme)
4b	After urban expansion: all areas within urban growth boundary developed, VicUrban low impact (maximum stormwater retention and harvest) (Strategy 3 in Deletic 2010 = Strategy B, below), All other urban development conventional (as per MW drainage scheme)
5a	After urban expansion: all areas within urban growth boundary developed, with low impact: maximum stormwater retention and harvest (Strategy 1 in Deletic 2010 = Strategy A, below) throughout urban growth area.
5b	After urban expansion: all areas within urban growth boundary developed, with low impact: maximum stormwater retention and harvest (Strategy 3 in Deletic 2010 = Strategy B, below), throughout urban growth area.
VicUrban only: Strategy A	Same as Scenario 4a but analysis undertaken for VicUrban site only. Strategy A = strategy 1 of Deletic (2010), involving Demand Option 1 (Rainwater harvesting + stormwater for non-potable) with Treatment Option 1 (biofilter treatment in development, storage pond for stormwater harvesting and 9 ha riparian zone *Melaleuca* bioretention swamp)
VicUrban only: Strategy B	Same as Scenario 4a but analysis undertaken for VicUrban site only. Strategy 3 = strategy 3 of Deletic (2010), involving Demand Option 2 (stormwater harvesting for all uses) with Treatment Option 1 (biofilter treatment in development, storage pond for stormwater harvesting and 9ha riparian zone *Melaleuca* bioretention swamp)

In scenarios 4a–5b (Table A1), the strategies applied to the new urban development were derived from Deletic (2010). Scenarios 4a and 5a involve a combination of rainwater harvesting, bioretention throughout the urban areas, along with a stormwater collection pond (for non-potable uses) within the Gum Scrub Creek corridor, discharging to a *Melaleuca*-dominated bioretention swamp. Scenarios 4b and 5b involved stormwater harvesting for all uses, along with biofiltration throughout the urban areas and the same *Melaleuca*-dominated bioretention swamp receiving discharge from the stormwater storage pond. The *Melaleuca* swamp was modelled as having an area of 9 ha, distributed through the creek corridor, with the riparian soils assumed to have an infiltration rate of 5 mm/hr in their upper layer 20 cm, dropping to around 1.5 mm below this depth (on-site testing will be necessary in subsequent stages to confirm this).

Table A2. Methods used to model and calculate each of the water quality and hydrologic statistics.

Statistic (units)	**Modelling and calculation methods**
Mean Annual Loads of TSS, TP and TN (t/yr)	Treatment train effectiveness from catchment outlet.
Annual runoff volume (ML/yr)	Treatment train effectiveness from catchment outlet, adjusted to include swamp baseflow contribution volume, as described above.
Total catchment losses through ET and harvesting (% of rainfall)	1. Mean annual rainfall volume (Vr) calculated as 23043 ML/yr. 2. Total catchment loss (%) = (Vr-Vs)/Vr, where Vs = mean annual streamflow (runoff) volume.
ET losses from impervious areas only (ML/yr)	This analysis is done only for Scenarios 3-5 (all based on the same impervious area of 14.8% of the catchment), with the aim of comparing the ET losses from the same impervious area, under varying drainage strategies. The total ET losses from impervious areas = the sum of ET loss (given in Node Water Balance) of each impervious area plus ET loss (given in Node Water Balance) calculated for each treatment measure (within development biofiltration systems, storage pond, Melaleuca bioretention swamp).
Volume harvested from impervious areas only (ML/yr)	Calculated as the sum of harvested volumes (given in Node Water Balance) from all rainwater and stormwater harvesting nodes.
Total volume 'lost' from impervious areas only (ML/yr)	The sum of impervious area ET and harvested volumes from above.
Proportion of streamflow delivered through filtered sub-surface flow (%)	In the pre-development case the proportion of streamflow resulting from sub-surface flows is assumed to be 95% (L. Bren, University of Melbourne, pers. comm. 2010). For each other strategy, the calculated proportion of filtered sub-surface contribution (SSC) is calculated as: SSC = 0.95 – ((∑Vi)/Vs), where Vi = mean annual runoff from impervious areas).

Water infiltrated through the *Melaleuca* swamp was quantified using MUSIC's *node water balance* function. A proportion of this was then assumed to enter Gum Scrub Creek as filtered baseflow. This volume of water was estimated simply as the infiltrated flow minus the loss due to evapotranspiration:

$$\text{Swamp baseflow contribution in ML/y} = Vol_{inf} - (PET \times A)/1000,$$

where Vol_{inf} is the volume of water infiltrated from the swamp (in ML/y), A is the area of the swamp (90,000 m^2), PET is the annual potential evapotranspiration (1.016 m/y).

Results

Regression models for ecological indicators, and values for each scenario are illustrated in Fig. A1.

The results of the MUSIC analysis are detailed in table A3.

Of the two scenarios aiming for universal low-impact design (5a and 5b, Tables A1, A3), 5b performed significantly better, ensuring that a high proportion (80%) of streamflow derives from sub-surface flows, minimising direct discharges from impervious areas into the creek, and producing slightly smaller pollutant loads compared to current day levels. Whilst the loads of pollutants are not increased dramatically by urbanisation, due to the already-high loads being produced by agriculture within the lowland areas of the catchment, it is imperative that post-development loads be minimised, given the sensitivity of Westernport to increased loads of nitrogen and sediment. It is clear that ensuring maximal stormwater retention will be necessary not only to minimise hydrologic disturbance, but to minimise the risk from increased pollutant loads to Westernport Bay.

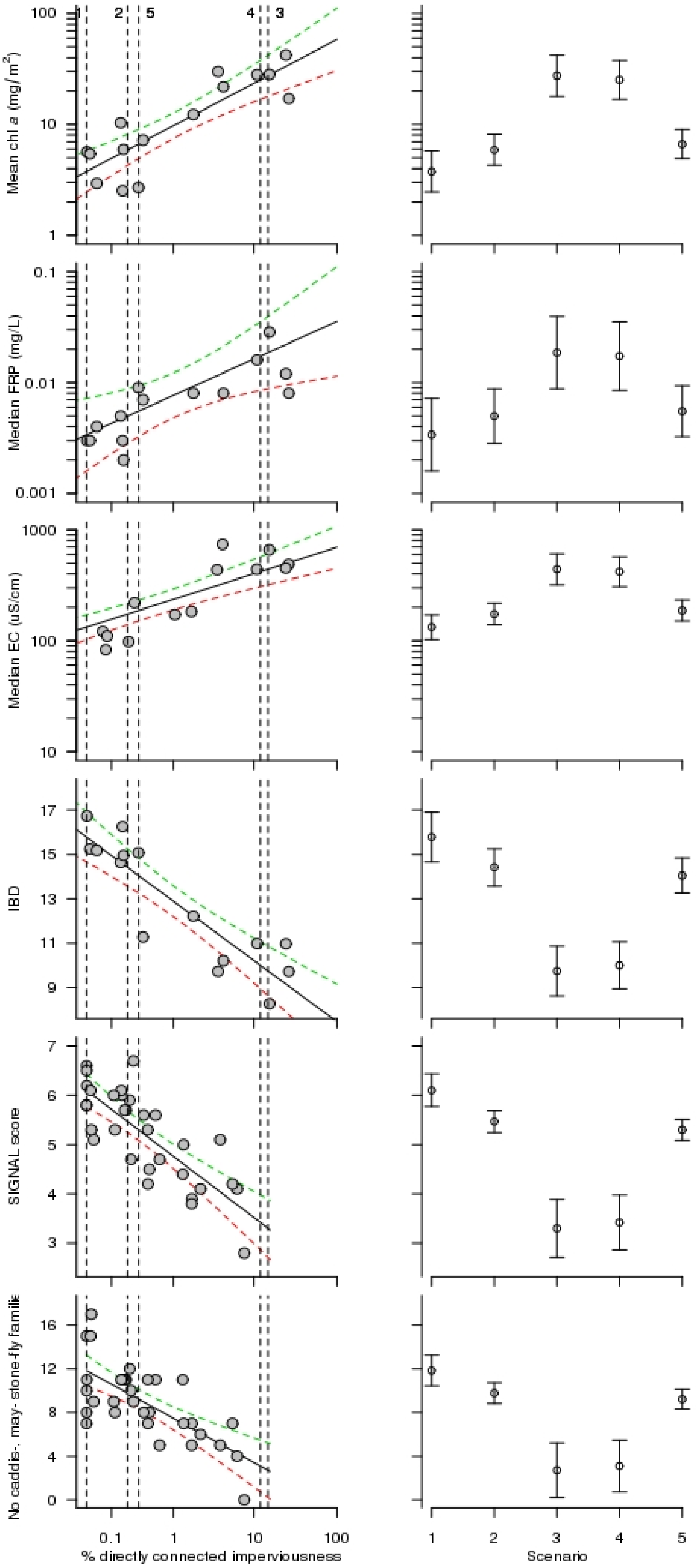

Fig. A1. Relationships between six important ecological indicators and directly connected imperviousness. For each variable, a regression line and 95% confidence limits (green and red dashed lines) is shown. The vertical dashed lines indicate the estimated directly connected imperviousness value for each of 5 development scenarios. On the right, the mean value (± 95% confidence limits of the regression) is shown for each of the scenarios. Data from: Taylor *et al.* 2004 (algal biomass, chl *a*); Hatt *et al.* 2005 (filterable reactive phosphorus, FRP and electrical conductivity, EC—a measure of salinity); Newall and Walsh 2005 (Indice Biologique Diatomees, IBD, an index of algal assemblage composition); Walsh 2004 (SIGNAL score an index of macroinvertebrate assemblage composition, and number of families from three sensitive orders of insects).

Table A3. MUSIC modelling results for pollutant loads and hydrological indicators, for each of the tested scenarios (1-5b). Results for the VicUrban site alone are also shown (bottom two rows). A (and 4a and 5a) and B (and 4b and 5b) refer to Deletic (2010)'s scenarios 1 and 3, respectively. Scenarios 4 and 5 in the main body of this report refer to Scenarios 4b and 5b in this table.

	Pollutant loads (t/yr)			**Hydrological indicators**						
Scenario	TSS	TP	TN	Annual runoff volume (ML/yr)	Total catchment losses (ET & harvesting) (% of annual rainfall)	ET losses from impervious areas (ML/a)	Volume harvested from impervious areas(ML/a)	Total 'loss' from impervious areas (ML/a)	Filtered sub-surface flow (ML/a)	Filtered sub-surface flow (% of annual runoff volume)
1	81	0.11	1.6	1780	92.3%	-	-	-	1691	95%
2	198	0.57	4.4	1820	92.1%	-	-	-	1690	93%
3	211	0.69	7.3	4080	82.3%	579	0	579	1268	31%
4a	179	0.56	5.3	3174	87.6%	873	571	1353	1469	46%
4b	178	0.55	5.2	3030	87.9%	877	780	1566	1403	46%
5a	176	0.53	4.3	2621	88.6%	1024	1181	2205	2078	79%
5b	172	0.51	4.1	2318	89.9%	1222	1614	2836	1899	82%
VicUrban only: Opt. A	4	0.026	0.29	521	88%	583	571	1063	298	62%
VicUrban only: Opt. B	3	0.017	0.18	378	92%	588	780	1276	232	66%