Habitat Suitability Models, Scenarios and Quantitative Action Prioritisation (using Zonation) for the Healthy Waterways Strategy 2018:

A Resource Document

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Melbourne Waterway Research-Practice Partnership

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Acknowledgement of Traditional Owners

We acknowledge and pay our respects to all the Traditional Owners, and Elders past and present, who have long cared for the lands and waters that this research addresses. From the west to the east, this includes the Wadawurrung People, the Wurundjeri People and the Bunurong People.

We acknowledge and recognise the primacy of Traditional Owners' obligations, rights and responsibilities to use and care for their traditional lands and waters.

Preamble

This report describes the development and application of habitat suitability models (HSMs) for aquatic macroinvertebrates, native fish species and platypus, scenarios and action prioritisation across the Port Phillip and Westernport region (hereafter, 'Melbourne Water region') using the conservation planning software, Zonation.

Focusing on natural environmental and human-induced catchment influences on aquatic biodiversity, these tools integrated best-available data and knowledge and enabled a range of scenario analyses and outputs that were used to support multiple stages of the community co-developed Healthy Waterways Strategy 2018.

Spatially explicit quantitative modelling and mapping of species habitat suitability and action prioritisation has delivered a range of benefits. In particular, we think it:

- has provided greater rigour and detail in characterising instream biodiversity patterns across all Melbourne's waterways
- has substantially enhanced Melbourne Water's capabilities for exploring concerns of strategic importance for long-term planning
- has enabled clear communication of stream biodiversity patterns, future impacts under different scenarios and benefits of actions to multiple audiences
- has produced useful insights that have deepened and enriched deliberations within Melbourne Water, in the Healthy Waterways Strategy community co-design workshops and amongst natural resource management stakeholders (e.g. DELWP, local government councils, CMA environmental water managers, and environmental consultants)
- has provided a valuable set of quantitative tools for tractable, defensible, data-based decision support

Some specific examples of these benefits for industry and the community are as follows:

- better use of biological data: from discrete, point data to spatially continuous estimates of instream biodiversity across all Melbourne's waterways
- fine-grain mapping of stream biodiversity patterns helped alert stakeholders (especially in the co-design workshops) to values, constraints and opportunities they had not been unaware of
- ability to model strategic considerations such as different aspects of climate change impacts (e.g. warming, drying), land use change and their interactive effects
- ability to incorporate a degree of ecological realism with respect to taxa/species-specific connectivity requirements
- ability to quantify the expected difference made by management actions, and to account for costs so that action planning can be based on cost-effectiveness
- ability to spatially prioritise management actions, and to interrogate and critically debate alternative actions at specific locations for action planning and target-setting
- improved ability to map, summarise and communicate decision-relevant data to different audiences
- repeatable analyses that can be scrutinised, error-checked, critiqued and built upon as the Healthy Waterways Strategy 2018 progresses to implementation, and monitoring, evaluation, reporting and improvement (MERI) stages

Introduction

Melbourne Water (MW) manages ~24,000 km of stream and rivers throughout the 12,783 km^2 greater Melbourne region. The catchments of these waterways (Box 1) vary in their land use from natural, intact, protected water supply catchments to agricultural and forested rural, and urban, leading to waterways that vary from near-pristine to severely degraded. Melbourne Water's challenge is to manage these waterways sustainably against a backdrop of population growth, increasing urbanisation, changes to temperature and flow patterns resulting from climate change and community aspirations for healthy waterways.

To help MW meet this challenge, the Waterway Ecosystem Research Group (WERG) at the University of Melbourne and MW developed spatially-explicit quantitative models and methods that contributed to prioritisation of management actions in Melbourne's Healthy Waterways Strategy 2018. This document describes the development of the models and their application. (If a brief, overview account is desired, please refer to Coleman *et al*. 2018).

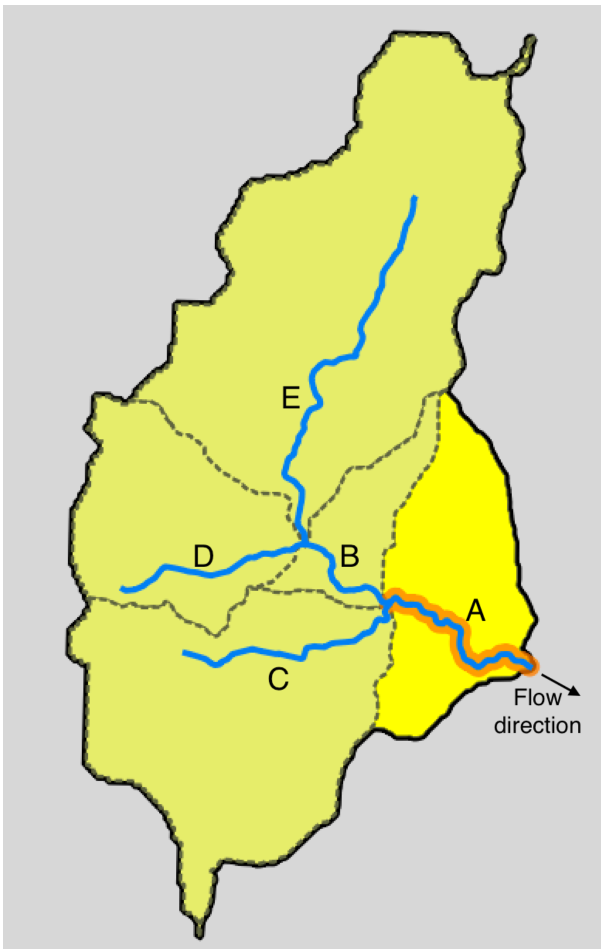
Our unit of spatial analysis for this study is the stream **reach.** In Box 1 we illustrate key terms and concepts relating to stream network structure that we use throughout this document.

Box 1: Spatial unit of analysis

Our unit of spatial analysis is the ***reach***. Reaches are segments of stream, divided for analysis, usually between confluences (e.g. reach B). Each reach has a ***subwatershed*** where the land drains directly to it (yellow area around A), but flow in the reach also comes from all subwatersheds upstream (B-E). All contributing subwatersheds of a reach (A-E) make up its ***watershed***[1].

Note that the influences on a reach can be multi-scale *and* directional. For instance, areas of influence can include the:

- ***riparian*** (streamside) ***zone*** (highlighted in pink)
- immediate subwatershed (yellow, A)
- upstream contributing catchment (green plus yellow, A-E) and
- downstream flow path (for animals that can move upstream)



[1] We use the term ***watershed*** to distinguish our hydrological segmentation of the region from MW's use of the terms "catchment" and "subcatchment" for their 5 management regions and 69 management units, respectively, which are, in most cases, groupings of convenience that are not necessarily hydrologically-

We developed habitat suitability models (HSMs) for 59 macroinvertebrate families (7 of which are weedy/invasive), 13 native fish species, and platypus. We used these models to explore and depict expected stream biodiversity responses to projected warmer and drier conditions resulting from climate change, human impacts such as increasing urbanisation and mitigating actions such as riparian revegetation, stormwater treatment and the removal of fish barriers. Mapped predictions of stream biota under different scenarios were shared with MW stakeholders at catchment collaboration workshops to illustrate instream biodiversity patterns and values, and to help inform stakeholder deliberations on actions and targets for ecological values within each major catchment in the MW region (i.e. Werribee, Maribyrnong, Yarra, Dandenong and Westernport).

In parallel, we undertook a quantitative spatial prioritisation analysis of a suite of 'candidate actions' that reflect core waterway management activities. The aim was to identify *what* action to deploy *where* in order to optimise the conservation and restoration of instream animal diversity throughout the stream network.

In the sections that follow, we describe the:

- i) development and evaluation of the HSMs for macroinvertebrates, native fish and platypus (Section 1);
- ii) scenarios of management interest that we generated predictions for (including ones not used in the final action prioritisation analysis, Section 2);
- iii) process of identifying the most cost-effective action at each of the 8,233 reaches that constitute the MW stream network (Sections 3-3.3);
- iv) process of spatially prioritising actions across the stream network using the Zonation software tool (Sections 3.4-3.5)
- v) achievements and plans for continuous improvement (Section 4)

1 Habitat Suitability Models

Habitat Suitability Models (HSMs) analyse the relationships between the environmental characteristics at sites where a species is detected (and also at sites where a species is *not* detected) to develop a quantitative model that predicts how suitable any given stream reach is for each species. Higher habitat suitability implies higher probability of observation/catch.

Importantly, descriptors of environmental characteristics should be theoretically informed variables that represent ecologically meaningful influences (Austin 2002). In stream ecosystems, these include variables such as temperature, flow permanence and variability, and aspects of instream and/or streamside habitat. In the Melbourne region, human land use changes such as vegetation clearing and the drainage of stormwater runoff directly into stream systems have had profound impacts on stream ecosystems. So it is important to also include within our models, variables that can represent the extent and intensity of such human impacts.

correct catchments. Where we use the term "catchment" in this document, we are referring to MW's management region. However, note that we retain the variable name, Catchment_Area, that was used in model formulation (Table 4).

In summary, these habitat suitability (or 'species distribution') models provide a rational and transparent means of using existing data from surveyed locations to make predictions to unsampled locations, based on the relationships in the environmental descriptors. Figure 1 gives a schematic overview and serves as a guide to our explanations of essential components and stages in the modelling process (that are described in in Sections 1.2 and 1.3-1.6).

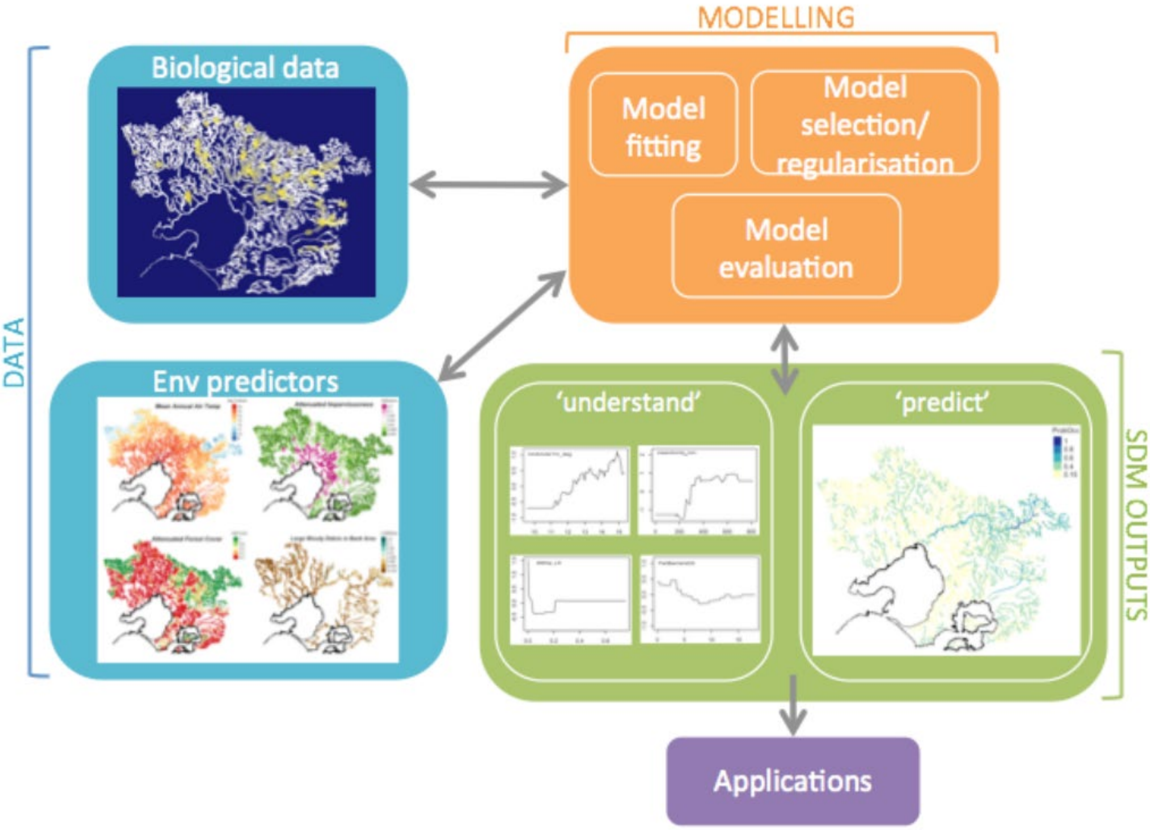


Figure 1 Overview of the steps in the habitat suitability modelling process (after Lahoz-Monfort, Guillera-Arroita & Elith, *personal communication*).

1.2 Usage of Habitat Suitability Models in the Healthy Waterways Strategy 2018

By quantifying taxa-habitat relationships, HSMs help us understand important environmental drivers and interactions, and provide a rational and transparent means of using existing, patchily-occurring, discrete, point location data to make spatially-continuous predictions to unsampled locations.

Box 2 Example applications of habitat suitability (species distribution) models:

- data-informed survey design for poorly-known regions (e.g. for Environmental Impact Assessments and Strategic Environmental Assessments) (Chee *et al*. 2011);
- identifying unsurveyed sites of high potential occurrence for rare species (e.g. Engler et al. 2004);
- modeling assemblages or constructing composition-based indices from individual distribution models (e.g. SIGNAL, LUMaR (Walsh & Webb 2013);
- assessing impacts of climate and land-use changes on species distribution (Thuiller et

al. 2008);

- contributing inputs for systematic spatial conservation planning (e.g. Moilanen *et al*. 2008, Leathwick *et al*. 2008);
- supporting species recovery, reintroduction and/or translocation plans (e.g. Steel et al. 2004; Martínez-Meyer et al. 2006);
- predicting species invasion (e.g. Hartley *et al*. 2006); and
- designing cost-effective surveillance for invasive species (e.g. Hauser & McCarthy 2009)

With respect to the HWS development process, the macroinvertebrate, fish and platypus HSMs were used to:

1. illustrate where instream taxa of interest occur in the landscape;
2. develop indices/summary measures to represent the biodiversity value of macroinvertebrates and fish;
3. illustrate and assess the impacts on patterns of habitat suitability of instream taxa arising from different scenarios of land-use and climate change (see Section 2);
4. develop a biodiversity priority rank map for the streams in the Melbourne region using the conservation planning software tool, Zonation (*sensu* Moilanen *et al*. 2008); and
5. develop a quantitative action prioritization map, again, using Zonation (*sensu* Moilanen *et al*. 2011, 2014; see Section 3).

1.3 Biological Data

Biological survey data were collated from Melbourne Water studies, Victorian State Government surveys, and surveys by environmental consultants and researchers over the period from 1990 to 2009 (inclusive) across all taxa. We only accepted data from surveys that used standardised and comprehensive survey methods so that the biological data could be regarded as presence-absence data for the purposes of modelling. Sampling occurred extensively throughout the MW region, and there is no obvious bias in sampling coverage (though generally speaking, very small and/or intermittent streams are not as well-sampled as larger, perennial systems).

1.3.1 Macroinvertebrates

Survey data used for model development spanned the period from 1990 to 2009. There were a total of 1,724 survey samples collected at 562 unique reaches.

Collection of macroinvertebrate data used standard rapid bioassessment protocol (Anon 1994) either from riffles or pool edges, and either in autumn (Feb–Jun) or spring (Sep–Dec). 84% of samples were sorted using a standard 30-min sort in the field, and 16% were subsampled in the laboratory, and sorted to 10% or 200 individuals, whichever was greater. Each survey sample from a site combined the data from a pair of samples: sample-pairs could be combinations of riffle and edge samples collected in spring or autumn.

We developed models for 59 macroinvertebrate taxa (Walsh *in prep*). Seven of the 59 macroinvertebrate families were deemed to be 'weedy' or invasive (Table 1). For the purposes of the HWS, we concentrated on the **52** non-weedy/invasive macroinvertebrate families. 23 of the 52 families were sensitive to urban stormwater impacts or deforestation. Table 1 provides a summary of these details.

Table 1 Summary details of 59 modelled macroinvertebrate families, their *sensitivity group membership, prevalence (i.e. proportion of presences across sampled sites), and prediction performance metrics for the fitted models: cross-validation (CV) percentage deviance explained and cross-validation area under the receiver operating characteristic curve (AUC).

Family	Code	*Sensitivity Group	Prevalence	CV % deviance explained	CV AUC
Leptoceridae	QT25	B	0.790	17.4	0.782
Calamoceratidae	QT24	A	0.263	8.7	0.764
Atriplectididae	QT23	A	0.203	2.9	0.679
Philorheithridae	QT21	A	0.214	46.7	0.883
Calocidae	QT18	A	0.231	45.8	0.890
Helicopsychidae	QT17	A	0.082	40.8	0.888
Conoesucidae	QT15	A	0.302	18.2	0.771
Ecnomidae	QT08	B	0.340	5.1	0.713
Hydropsychidae	QT06	B	0.480	33.4	0.822
Philopotamidae	QT04	A	0.158	42.5	0.853
Hydroptilidae	QT03	C	0.525	-5.1	0.570
Glossosomatidae	QT02	A	0.141	38.9	0.787
Hydrobiosidae	QT01	B	0.468	34.2	0.846
Notonemouridae	QP04	A	0.176	6.9	0.697
Gripopterygidae	QP03	B	0.496	42.6	0.885
Austroperlidae	QP02	A	0.171	38.2	0.879
Eustheniidae	QP01	A	0.114	54.5	0.884
Corduliidae	QO16	weedy	0.566	-4.5	0.613
Aeshnidae	Q012	B	0.664	-1.1	0.631
Synlestidae	QO08	A	0.247	6.6	0.726
Megapodagrionidae	QO07	B	0.274	2.3	0.684
Lestidae	QO05	D	0.251	2.8	0.748
Coenagrionidae	QO02	weedy	0.630	21.0	0.751
Corydalidae	QM01	A	0.121	16.7	0.839
Notonectidae	QH67	weedy	0.589	0.9	0.691
Corixidae	QH65	D	0.767	17.1	0.806
Veliidae	QH56	C	0.827	9.1	0.716
Caenidae	QE08	D	0.308	14.8	0.778
Leptophlebiidae	QE06	A	0.587	55.7	??
Coloburiscidae	QE05	A	0.142	46.9	0.841
Oniscigastridae	QE03	A	0.153	16.4	0.757
Baetidae	QE02	B	0.585	10.1	0.739
Tanypodinae	QDAE	B	0.827	2.0	0.619
Podonominae	QDAD	A	0.107	18.2	0.746

Empididae	QD35	A	0.233	20.8	0.752
Athericidae	QD22	A	0.130	40.6	0.847
Simuliidae	QD10	B	0.696	24.1	0.763
Ceratopogonidae	QD09	B	0.601	5.2	0.733
Culicidae	QD07	B	0.335	2.9	0.729
Dixidae	QD06	A	0.326	14.2	0.800
Tipulidae	QD01	B	0.552	18.4	0.731
Ptilodactylidae	QC39	A	0.199	43.7	0.863
Psephenidae	QC37	B	0.370	21.8	0.757
Elmidae	QC34	B	0.601	30.4	0.751
Scirtidae	QC20	A	0.525	11.4	0.715
Hydraenidae	QC13	D	0.315	-2.6	0.679
Hydrophilidae	QC11	D	0.637	2.3	0.653
Gyrinidae	QC10	A	0.210	4.4	0.664
Dytiscidae	QC09	D	0.754	8.7	0.681
Atyidae	OT01	C	0.587	21.1	0.797
Paramelitidae	OP06	D	0.176	-0.8	0.593
Pontongeneiidae	OP03	C	0.201	46.5	0.747
Ceinidae	OP02	D	0.616	22.0	0.732
Glossiphoniidae	LH01	weedy	0.500	5.3	0.733
Physidae	KG08	invas	0.680	12.2	0.764
Planorbidae	KG07	D	0.311	12.4	0.675
Ancylidae	KG06	C	0.427	-2.9	0.581
Lymnaeidae	KG05	weedy	0.308	2.4	0.718
Dugesiidae	IF61	weedy	0.596	8.0	0.751

*Following Walsh and Webb (2016), families were classified on the basis of their response to attenuated imperviousness (AI) and attenuated forest cover (AF) into six sensitivity groups of families (for use in weighting indices, below):

A. Very sensitive; showing a strong decline in probability of occurrence at low levels of AI, and a positive correlation with AF
B. Moderately sensitive; negatively correlated with AI, but recorded in sites with AI >3%, and a positive correlation with AF
C. Negatively associated with one impact, but uncorrelated with the other.
D. Sensitive to AI, but positively associated with land clearance; negatively correlated with AI, and negatively correlated with AF

Weedy and Invasive; positively correlated with AI or negatively correlated with AF, and if not affected by both human impacts, then uncorrelated with the second.

1.3.2 Fish

Survey data used for model development spanned a 20-year period from 1990 to 2009 (inclusive). Fish surveys were undertaken using a range of techniques, most notably backpack electrofishing, fyke nets, bait traps and dip netting, resulting in a total of 2293 survey samples collected at 1058 unique reaches.

We developed models for 11 native freshwater fish species and 9 exotic fish species in the Melbourne region. Estuarine fish species such as small-mouthed hardyhead (*Atherinosoma microstoma*) were **not** modelled. The number of individual records for shorthead lamprey (*Mordacia mordax*) and pouched lamprey (*Geotria australis*) was sufficiently sparse that we felt it would be inappropriate to develop models for them individually. Instead, we opted to pool the data for shorthead lamprey and pouched lamprey and modelled them together as 'lampreys' (Table 2). Two freshwater fish species of conservation concern, namely, the Yarra pygmy perch (*Nannoperca obscura*) and the Australian grayling (*Prototroctes maraena*), both of which are listed as 'threatened' under Victoria's *Flora and Fauna Guarantee Act 1988* and as 'vulnerable' under the Federal Government's *Environment Protection and Biodiversity Conservation Act 1999* were not explicitly modelled due to a lack of adequate data. But given their conservation importance, we felt it was important that they be represented in order to inform the prioritisation of management interventions. Our workaround was to use predictions from 'surrogate' species deemed to be sufficiently similar in their habitat requirements (Dr Tarmo Raadik, Arthur Rylah Institute for Environmental Research, *pers. comm.*). Specifically, southern pygmy perch (*Nannoperca australis*) was used as the surrogate for Yarra pygmy perch and common galaxias (*Galaxias maculatus*) was the surrogate for Australian grayling. Guided by the expert knowledge of Tarmo Raadik (*pers. comm.*) we applied predictions from each respective surrogate in just the catchments and river reaches Yarra pygmy perch and Australian grayling were known to occur in. For Yarra pygmy perch, that meant Deep Creek in the Maribyrnong catchment, and for Australian grayling, that meant just the mainstems of the Werribee, Maribyrnong, Yarra, Cardinia, Bunyip and Lang Lang rivers, downstream of major instream barriers.

For the purposes of environmental value assessment for the HWS, we concentrated on just the 13 native fish species as indicators of waterway 'naturalness' rather than recreational potential. Table 2 provides a summary of these details.

Table 2 Summary details of modelled fish species, their prevalence (i.e. proportion of presences across sampled reaches), and prediction performance metrics for the fitted models: cross-validation percentage deviance explained and cross-validation area under the receiver operating characteristic curve (AUC). Non-native species are indicated by shading.

Species	Code	Prevalence	CV % deviance explained	CV AUC
Short-finned eel	ANGUAUST	0.654	12.1	0.744
Goldfish	CARAAURA	0.148	14.2	0.822
Common carp	CYPRCARP	0.099	31.6	0.889
River blackfish	GADOMARM	0.176	46.6	0.952
Broad-finned galaxias	GALABREV	0.068	29.0	0.877
Common galaxias	GALAMACU	0.343	26.6	0.845
Mountain galaxias	GALAORNA	0.194	35.0	0.916
Spotted galaxias	GALATRUT	0.069	14.0	0.758
Mosquitofish	GAMBHOLB	0.284	22.4	0.793

Pouched lamprey & Short-headed lamprey	LAMPREYS	0.084*	36.3	0.909
Oriental weatherloach	MISGANGU	0.106	43.7	0.930
Southern pygmy perch	NANNAUST	0.153	35.7	0.918
Yarra pygmy perch	NANNOBSC	NA	-NA-	-NA-
Rainbow trout	ONCOMYKI	0.021	24.3	0.861
English perch	PERCFLUV	0.145	20.3	0.811
Flathead gudgeon	PHILGRAN	0.127	43.0	0.934
Australian grayling	PROTMARA	NA	-NA-	-NA-
Tupong	PSEUURVI	0.078	41.2	0.918
Australian smelt	RETRSEMO	0.110	32.3	0.893
Roach	RUTIRUTI	0.168	22.7	0.861
Brown trout	SALMTRUT	0.265	35.2	0.889
Tench	TINCTINC	0.051	38.8	0.906

*prevalence calculated from pooled presences

1.3.3 Platypus

Survey data used for model development spanned a 14-year period from 1995 to 2009 (inclusive). There were a total of 2506 survey samples collected at 609 unique reaches.

Platypus surveys were conducted by setting two fyke nets overnight at each site (one facing upstream, the other facing downstream) with mesh wings at either side of the net entrance positioned so that the two nets blocked the entire width of the stream channel. Platypus sex and age class was assigned based on the presence and morphology of calcaneal spurs, with three male age classes (juvenile ≤ 10 months, sub-adult 11-23 months or adult ≥ 23 months) and two female age classes (juvenile ≤ 10 months or sub-adult/adult > 10 months).

We developed two models for platypus: all platypus of all life-stages (i.e. male and female, sub-adults/adults), and just female sub-adult/adults that have smaller home ranges and much higher food resource requirements during certain times of the year (e.g. during lactation). Table 3 provides a summary of the details.

Table 3 Summary details of the platypus models, prevalence of the relevant modelled entity, and prediction performance metrics for the fitted models: cross-validation percentage deviance explained and cross-validation area under the receiver operating characteristic curve (AUC).

Platypus	Prevalence (%)	CV % deviance explained	CV AUC
ALL: includes all observations on male and female, sub-adults/adults	0.399	16.4	0.739
FEMALE only: includes only female sub-adults/adults	0.266	9.6	0.731

1.4 Environmental Data (Predictors)

For each taxonomic group that we modelled (i.e. macroinvertebrate families, fish species and platypus), we used a carefully selected candidate set of 10-12 environmental predictors to describe:

a) ecologically-relevant aspects of natural environmental variability across the region (*sensu* Austin 2002) and
b) human impact variables that reflect primary mechanisms by which they alter natural environmental variation (e.g. land cover change)

Given our interest in strategic planning for future challenges, we focused on climatic, physiographic and catchment land use (human impact) predictors. We aimed to ensure that influences of human impact were restricted to land use variables, which were quantified as effective imperviousness (as an indicator of urbanisation and all its attendant impacts on flow regimes and water quality), and forest cover (as an indicator of land clearance) (Walsh & Webb 2014). The rationale for our approach to predictor selection was to develop models that would provide direct predictions of the biotic response to climatic changes, land use changes, mitigating management actions, and their interactions.

Our choice of predictors for influential aspects of natural environmental variability was informed by ecological information reported in the published literature. For instance, for macroinvertebrates, key sources included Walsh and Webb (2013, 2014, 2016). For the various fish species, we reviewed key sources such as Cadwallader & Backhouse (1983), Koehn & O'Connor (1990), McDowall (1996), Morris *et al*. (2001), and Allen *et al*. (2002). For platypus, we reviewed Gardner & Serena (1995), Ellem *et al*. (1998), Grant & Bishop (1998), Grant & Temple-Smith (1998, 2003), Serena *et al*. (1998, 2001), Serena & Pettigrove (2005), Grant & Fanning (2007), Serena & Williams (2008, 2010a, 2010b), Milione & Harding (2009) and Martin *et al*. (2014).

Examples of predictors that are expected to be broadly influential in shaping habitat suitability for instream taxa include catchment area, mean annual air temperature, mean annual runoff depth (an indicator of stream perenniality and variability), attenuated imperviousness (a measure of the amount of impervious cover that drains into a stream reach, and reflects stormwater runoff impact; Walsh & Kunapo 2009) and attenuated forest cover (a measure of the influence of forest cover alongside, upstream and elsewhere within the watershed of a given reach; Walsh & Webb, 2013, 2014)(Figure 2 and Table 4). The impact of impervious surfaces and forest cover on a given reach depends on its distribution and spatial configuration within the catchment and dissipates with overland distance from the reach. So attenuated imperviousness and forest cover were spatially optimised (weighted by overland distance) to match the most plausible mechanistic pathways of influence (Table 4).

As noted in Box 1, stream habitats can be influenced not only by the immediate area that drains a stream reach (i.e. the subwatershed), but also the entire contributing area upstream of the reach (i.e. the watershed). In addition, if the taxon in question has long-range upstream-downstream movement requirements, then longitudinal connectivity along the stream flow path is also important. We represented multi-scale influences by specifically developing ecologically relevant environmental descriptors at both subwatershed and watershed scales, and also along the stream flow path (Chee & Elith 2012; Walsh & Webb 2014).

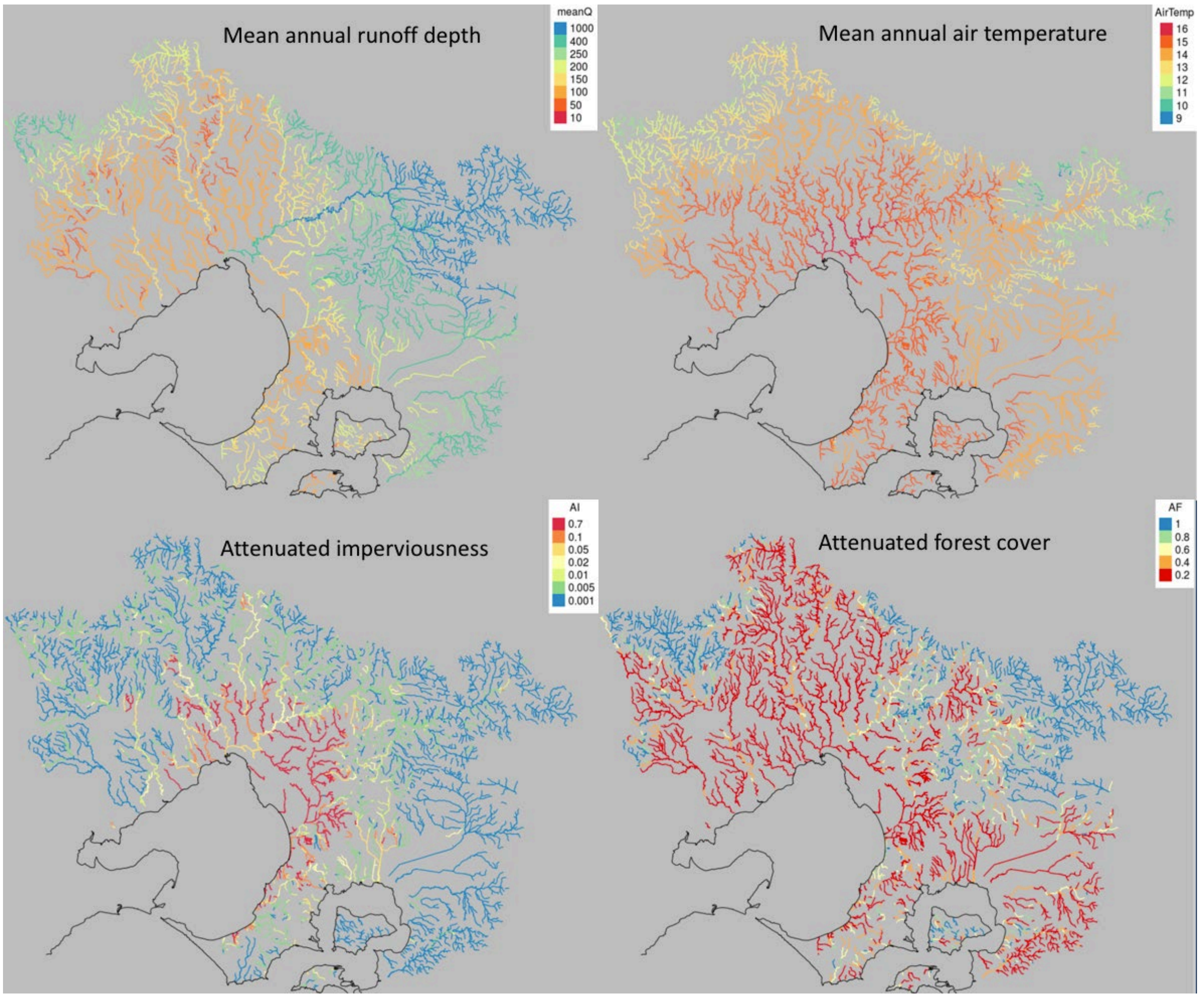


Figure 2 Maps showing how four important environmental predictors vary spatially across the Melbourne Water region. Mean annual runoff depth (in mm) is an indicator of flow perenniality). Mean annual air temperature (in ^{0}C) is an excellent proxy for mean annual stream temperature. Attenuated imperviousness is a weighted measure of the amount of impervious cover connected to a reach, and attenuated forest cover is a weighted measure of riparian forest alongside and upstream of a reach.

The set of environmental descriptors we use for modelling macroinvertebrates, fish and platypus is a balance of three considerations:

i) theoretically-informed ecological relevance;
ii) availability of spatially explicit data (for both model development and prediction across the Melbourne region); and
iii) the amenability of a variable to management intervention

The motivation for including in our models, predictors that can be modified by management, is to enable us to use our habitat suitability models to predict expected responses under different environmental and/or management scenarios. The predictors that are amenable to management represent 'levers' that management can modify via one or more means to maintain or improve habitat suitability for instream biota (Figure 3). We use the predicted change in habitat suitability as our measure of *benefit* due to a candidate action (*sensu* DELWP 2017a).

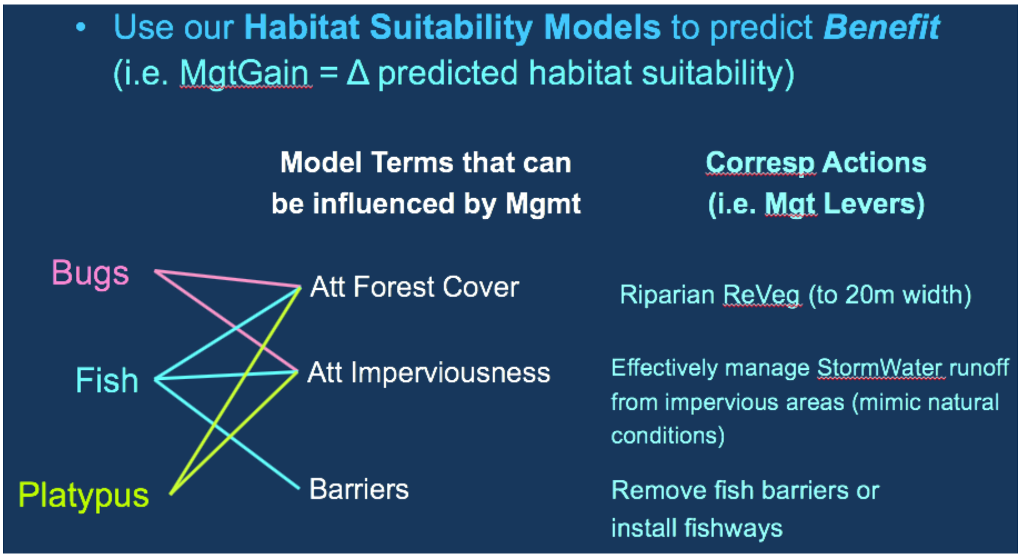


Figure 3 Environmental predictors in our macroinvertebrate, fish and platypus models that can be influenced by management, and examples of corresponding 'levers' that can modify each candidate environmental predictor.

Table 4 provides details and explanations of each of the predictors used in our macroinvertebrate, fish and platypus models. In the case of fish, predictors relating to full and partial instream barriers to movement vary over time as barriers are removed or fishways installed at specific locations. We account for this explicitly by calculating the total number of known full and partial barriers encountered along the downstream flowpath of every reach in the stream network, at multiple time points (Table 4). Each fish presence-absence survey record can then be matched to the temporally-appropriate estimate of total number of full and partial instream barriers encountered along the downstream flowpath.

Table 4 Definition/description, units and source of environmental variables used in the development of the macroinvertebrate, fish, and platypus habitat suitability (species distribution) models.

	Environmental Predictor	Definition/Description	Units	Source	Macro-invertebrates	Fish	Platypus
1	CatIgneous	Percentage of catchment overlying igneous rocks (e.g. granites, basalts, grandiorite, rhyolite and gabbro).	%	Derived from CAT_IGNEOUS in Stein *et al.*'s (2011) Environmental Stream Attributes v1.1 dataset that supplements the Australian Bureau of Meteorology's ***Geofabric*** product suite	✔	✔	✔
2	Catchment Area [CatchmentArea_km2_InclDams]	Area of the watershed (i.e. sum of area of all upstream contributing subwatersheds, *including* large dams and all the subwatersheds that drain into the large dams)	km^2		✔	✔	✔
3	Mean Annual Runoff Depth [meanAnnQ_mm]	Mean annual runoff depth in the absence of human impacts (mm/year). This measure is a watershed-standardized measure of annual stream discharge. It is calculated by taking mean annual totals of monthly accumulated surface water surplus (derived from a simple water balance model using long-term rainfall and potential evapotranspiration data) and dividing by watershed area (Walsh & Webb 2014).	mm/yr	Calculated as RUNANNMEAN/CATAREA from Stein *et al.*'s (2011) Environmental Stream Attributes v1.1 dataset that supplements the Australian Bureau of Meteorology's ***Geofabric*** product suite	✔	✔	✔
4	Antecedent Runoff [SRI_48mth_weighted]	48 month (long-term) standardised runoff index (SRI), which is derived by fitting a log-normal distribution to long-term monthly estimates of average upstream runoff depth transformed to a standard normal-deviate (i.e. with zero mean and unit variance). A weighted moving average (window width of 48 months) with a linear	NA	Calculated from runoff estimates from the Australian Water Availability Project (Raupach *et al.*, 2009) using functions from the SPEI (Standardised Precipitation-Evapotranspiration Index) R package (Beguería & Vincente-Serrano 2017).	✔	✔	✔

		decay function was applied to SRI values derived from monthly runoff data. Default = 0, which denotes ***mean*** 48mth weighted antecedent runoff. -1 denotes drier than mean antecedent runoff conditions; +1 indicates wetter than mean antecedent runoff conditions					
5	Instream Full Barriers (at multiple timepoints) [nFullBarriersDS_pre2007, nFullBarriersDS_2007, nFullBarriersDS_2008, nFullBarriersDS_2009, nFullBarriersDS_2012, nFullBarriersDS_2014]	Total number of instream *full* barriers to movement along the downstream flowpath at multiple timepoints including pre-2007, 2007, 2008, 2009, 2012 and 2014. (Gaps in timepoints reflect years where no additional full barriers were removed relative to the preceding timepoint.) Full barriers include structures, generally >5 m in height, such as high dam walls that are likely to block fish passage even during large flow events.	NA	Computation based on Melbourne Water database of instream barriers, information on fishway installation works, and tracing analysis of the number of full barriers encountered along a reach's downstream flowpath for each of the timepoints (i.e. pre-2007, 2007, 2008, 2009, 2012 and 2014).	--	✔	--
6	Instream Part Barriers (at multiple timepoints) [nPartBarriersDS_pre1997, nPartBarriersDS_1997, nPartBarriersDS_1999, nPartBarriersDS_2000, nPartBarriersDS_2002, nPartBarriersDS_2004, nPartBarriersDS_2005, nPartBarriersDS_2006, nPartBarriersDS_2007, nPartBarriersDS_2008, nPartBarriersDS_2009, nPartBarriersDS_2010, nPartBarriersDS_2016]	Total number of instream *partial* barriers to movement along the downstream flowpath at multiple timepoints including pre-1997, 1997, 1999, 2000, 2002, 2004, 2005, 2006, 2007, 2008, 2009, 2010 and 2016). (Gaps in timepoints reflect years where no additional partial barriers were removed relative to the preceding timepoint.) Partial barriers refers to features, generally <5 m in height that have the potential to permit fish passage on occasion, such as during high flow events.	NA	Computation based on Melbourne Water database of instream barriers, information on fishway installation works, and tracing analysis of the number of partial barriers encountered along a reach's downstream flowpath for each of the timepoints (i.e. pre-1997, 1997, 1999, 2000, 2002, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2016).		✔	
7	Mean Annual Air Temperature [mnAnnAirTm_deg]	Average annual mean (monthly) air temperature for the reach and immediate environs.	^{0}C	Derived from STRANNTEMP in Stein *et al.*'s (2011) Environmental Stream Attributes v1.1 dataset that	✔	✔	✔

				supplements the Australian Bureau of Meteorology's ***Geofabric*** product suite. STRANNTEMP is the average value of BIOCLIM variable 'Annual Mean Temperature' of all grid cells (in the 9" DEM of Australia ver 3 2008) comprising the reach segment and associated valley bottoms.			
8	Attenuated Forest Cover (in 2006) [AttForest_L35W1000_2006]	A measure of the amount of forest cover alongside as well as upstream of the stream segment in 2006. Laterally, attenuated forest cover is calculated as exponentially weighted overland with a half-decay distance of 35 m from the stream AND exponentially weighted upstream with a half-decay distance of 1000 m. Range = 0–1.	NA	See Walsh & Webb (2014) for full details of calculation	✔	✔	
9	Attenuated Forest Cover (in 2006; laterally unweighted variant) [AFb10L1000]	A measure of the amount of forest cover alongside as well as upstream of the stream segment. Laterally, Afb10L1000 is calculated as unweighted ≤ 10m from the stream, and exponentially weighted upstream with a half-decay distance of 1000 m. Range = 0-1.	NA	A variant measure of attenuated forest cover in 2006			✔
10	Attenuated Imperviousness (in 2006) [AttImp_L9]	A measure of the influence of runoff from impervious surfaces extant in 2006 on the reach through the stormwater drainage system associated with urban land. Computed as the ratio of attenuated impervious area in the watershed (using a half-decay distance of 9.4 m) to watershed area. Range = 0–1.	NA	See Walsh & Webb (2014) for full details of calculation	✔	✔	--
11	Minimum Attenuated Imperviousness within 4km (in 2006) [AttImpMin4k_L9]	A measure of the influence of runoff from impervious surfaces on the reach through the stormwater drainage system associated with urban land. Computed as	NA	See Walsh & Webb (2014) and Martin *et al*. (2014) for full details of calculation	--	--	✔

		the ratio of attenuated impervious area in the watershed (using a half-decay distance of 9.4 m) to watershed area. Range = 0 – 1. This variant selects the minimum AI value within 4km of a site in the downstream direction. The value of 4 km closely approximates the mean maximum home range length of radio-tagged adult males and females occupying lotic systems in south-eastern Australia.				
12	Nspring	Number of spring sample units per sample-pair. This predictor allows us to account for seasonal variation. Range = 0-2; Default = 2	NA	✔	--	--
13	Nriff	Number of riffle sample units per sample-pair. This predictor allows us to account for inter-habitat variation. Range = 0–2; Default = 1	NA	✔	--	--
14	processN	Sorting method; 0 = 'lab-sorted'; 1 = 'field-sorted'	NA	✔	--	--

1.5 Modeling Method

We selected Boosted Regression Trees, a statistical learning (or 'machine learning') method, because it has a number of strengths:

i) it performs well in direct comparison with other modelling techniques (Elith *et al.* 2006);
ii) it has the ability to fit non-linear relationships, and naturally model interactions — both features that are particularly valuable in ecological contexts (De'ath 2007; Elith *et al*. 2008; Hastie *et al*. 2009; Vesk *et al*. 2010); and
iii) it can accommodate outliers and missing data with minimal loss of information (Breiman *et al*. 1984; Hastie *et al*. 2009).

In addition, methods are available for estimating the relative importance of environmental variables, for depicting fitted response curves, and detecting interactions amongst environmental descriptors (if present) (Elith *et al*. 2008). These tools are valuable for model evaluation (discussed below, Section1.6).

All analyses were carried out in R (R Foundation for Statistical Computing 2008) using the 'gbm' package (v2.1.3, Ridgeway 2012) plus additional code written by Elith *et al*. (2008) (now included in the 'dismo' package v1.1-4, Hijmans *et al*. 2017).

Model fitting for the 59 macroinvertebrate families used custom code to implement an auto-fitting process. This process used 10 input variables (see Table 4) and fitted a range of models using different combinations for the three main parameters that are 'tuned' in BRT models, namely, learning rate, tree complexity and bag fraction (see Elith *et al*. 2008 for detailed explanations of the role and function of these parameters). Table 5 lists the candidate values of each parameter used in model fitting for each taxa group. From the suite of resulting models, the 'best' model was selected by the amount of deviance explained.

Table 5 Candidate values used for learning rate, tree complexity and bag fraction in the course of developing BRT models for families/species in each taxa group.

Taxa group	Candidate values for		
	learning rate	tree complexity	bag fraction
Macroinvertebrate families	0.001, 0.005, 0.01	1, 2, 3, 4, 5	0.5, 0.75
Fish	0.005, 0.0025	2, 3, 4, 5	0.75
Platypus	0.005, 0.0025	2, 3, 4, 5	0.5, 0.75

Model fitting and final selection for fish and platypus used a more involved manual and iterative process. In the first instance, we fitted models using the full suite of input predictors (9 and 7 in the case of fish and platypus respectively, Table 4) and the candidate learning rates, tree complexity values and bag fraction values (Table 5). We then ranked the resulting models for each species by percentage deviance explained and reviewed the fitted response curves of predictors for the top ranked models to assess predictor importance/relevance, and whether any predictors should be set to vary monotonically for the species in question. From this process, predictors of negligible (or potentially spurious) influence might be dropped, and one or more predictors set to vary monotonically (either positively or negatively). Model fitting was then repeated with the simplified (and possibly, monotonically restricted) set of predictors, and the process repeated until it was judged that we had arrived at one or more parsimonious and ecologically plausible models. If there were multiple equally parsimonious and plausible models, we then produced mapped predictions across the full stream network from each model and visually assessed the mapped predictions for congruence with observed data and expert knowledge of the species' distribution. We then made a final selection after discussing the response curves, mapped predictions and quantitative evaluation metrics.

1.6 Model Evaluation

Model evaluation probes the fitted models in different ways to help us gauge how 'trustworthy' a model is. We do this both qualitatively and quantitatively. Our evaluation process focuses on the following questions:

i) how sensible is the fitted model? Are the fitted environmental variable relationships ecologically plausible and sensible? Are there any 'red flags' that require further investigation?

ii) are the spatial (mapped) model predictions congruent with observed data and expert knowledge of a species' distribution?

iii) how good is the model at predicting? (Is it useful? Does it perform better than guessing?)

We address the first question by reviewing the fitted response curves of environmental variables for each species model, taking into account what ecological knowledge there is about the species. For example, a species might prefer temperatures within a certain range—this might manifest in the fitted response as a bell-shaped curve, with probability of occurrence increasing as it approaches an 'optimum' mean annual temperature before declining again. At a minimum, the environmental variable responses should be ecologically plausible.

We do a 'reasonableness' check of the congruence of the spatial (mapped) model predictions by overlaying the point observations of biological data on the mapped predictions. Where possible, the mapped predictions have been qualitatively reviewed by a species expert who is knowledgeable about the species' distribution in the MW region.

Finally, we use two commonly applied metrics: 'percentage deviance explained' and 'area under the receiver operating characteristics curve' (AUC) to quantify goodness-of-fit and predictive performance, respectively.

Deviance explained measures the goodness-of-fit between predicted and observed values. We express it as a percentage of the null deviance (i.e. the deviance of a model containing no terms and having a fitted value for all observations equal to the mean probability across the observations) for each taxon. We report the percentage deviance explained that has been calculated from 'held-out' data in the cross-validation process (i.e. data that wasn't used to train the model). These statistics for macroinvertebrates, fish and platypus models are given in Tables 1, 2 and 3, respectively.

AUC measures a model's ability to discriminate between sites where the taxon is present and where it is absent. The AUC value is equivalent to the probability that a randomly selected presence record will have a higher fitted probability value than a randomly chosen absence record. AUC ranges from 0 to 1, where a value of 1 indicates perfect discrimination, and a value of 0.5 implies predictive ability that is no better than a random guess. These statistics for macroinvertebrates, fish and platypus models are given in Tables 1, 2 and 3, respectively.

1.7 Model Output

The models predict probability of occurrence (for the taxa in question) at the reach scale. Example maps of the spatial patterns of probability of occurrence for two macroinvertebrate families, a fish species and platypus are shown in Figure 4.

One can think of probability of occurrence as an index of habitat suitability. A larger number indicates higher habitat suitability or probability of occurrence.

For instance, if there are 100 stream segments that each has a predicted probability of occurrence of 0.5 for species X, then one would expect to find species X at ~50 of those 100 stream segments. Similarly, if there are 100 stream segments that each have a predicted probability of occurrence of 0.2 for species X, then one would expect to find species X at ~20 of those 100 stream segments.

It is important to note that high predicted habitat suitability in a reach does not mean that a species will definitely occur there. High habitat suitability reflects habitat conditions which is an enabler for occurrence, but whether a species takes up use of and becomes established in that area also depends on additional factors such as resource availability (e.g. instream substrates for attachment) and population processes such as dispersal, survival, establishment, reproduction and maintenance of a viable population.

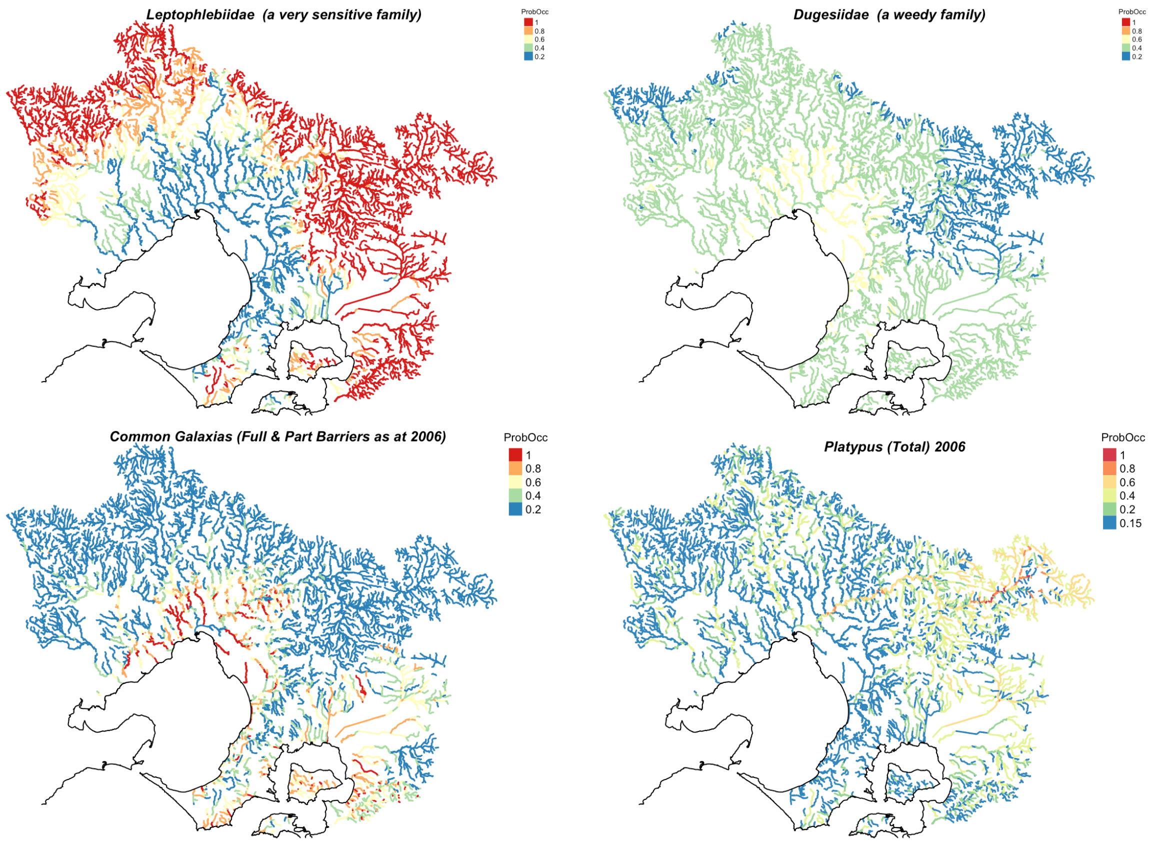


Figure 4 Example predicted probability of occurrence maps for Leptophlebiidae (a very sensitive macroinvertebrate family), Dugesiidae (a 'weedy' macroinvertebrate family), common galaxias (*Galaxias maculatus*), and platypus.

In most cases, the scenario predictions we will use the HSMs to explore, will be *inter*polations across the Melbourne region, **not** *extra*polations. If however, we wish to use the models to predict scenario conditions *outside* the range of our modelling input data, we will have to carefully consider if this can be justified, and what caveats apply.

2 Scenarios of Interest

Scenarios of interest were used to explore the impacts of strategic considerations and key mitigating actions operating on their own or in particular combinations.

The current (CURR) scenario reflects estimates of various environmental measures as at 2016 (Table 6). For the purposes of long-term strategic planning over a 50-year horizon, we devised a scenario called the business-as-usual future (BAUF). This scenario focused on important widespread threats in the form of warming, drying and increased impervious cover (due to urbanisation). Warming was represented by a 1.5°C increase in mean annual temperature and drying was represented by a reduction in mean annual runoff depth (equivalent to a 25% reduction in long term mean annual discharge at the mouth of the Yarra River, Table 6). These values for temperature increase and reduction in 'wetness' were chosen to be broadly consistent with DELWP (2016), and still largely within the 'experience' of the training data used to develop our models. (The exception here is the Little River catchment where the assumed magnitude of future warming and drying went beyond the 'experience' of training data.) The extent of future impervious land cover was estimated using Victoria's VicMap Planning dataset's planning scheme zone data (downloaded 21 Sept 2017 from https://www.data.vic.gov.au/data/dataset/vicmap-planning).

Table 6 Details of the current (CURR) scenario and the business-as-usual-future (BAUF) scenario.

Scenario Code	Mean annual air temperature (^{0}C)	Mean annual runoff depth (mm)	Attenuated Forest	Attenuated Imperviousness	Instream Barriers	
					Full	Partial
CURR	2016 values	2016 values	2016 values	2016 values	Barriers in place at 2016	Barriers in place at 2016
BAUF	2016 values + 1.5 ^{0}C	Equivalent to a 25% reduction in the long term mean value at the mouth of the Yarra River*	2016 values	Values reflecting attenuated imperviousness (calculated as noted in Table 4) when all parcels within the MW region with 'urban' planning scheme zone codes have been developed to their full capacity. Includes infill in existing urban areas and future—planned but as yet undeveloped—new urban areas.	Barriers in place at 2016	Barriers in place at 2016

*To represent drier conditions reflecting a 25% reduction in the long term mean annual flows at the mouth of the Yarra River, Walsh & Webb (2013) identified a 4-year period (that happened to be the 48 months prior to December 2000) where mean annual discharge was 75% of the long-term average. The monthly discharge estimates for this particular 4-year period was used as an analogue for drier conditions. (In practice, dryMeanQ for each reach was set to mean annual discharge calculated from monthly discharge estimates in Geofabric (Bureau of Meteorology 2011) over that particular 4-year period.)

Table 7 List of actions/scenarios explored in the course of developing the Healthy Waterways Strategy. All candidate scenarios explore changes *relative* to the business-as-usual future (BAUF) conditions (described in Table 6).

	Scenario Code	Description
5 Key Scenarios for the HWS action prioritization process (the scenarios focused on from **Section 3** onwards)		
1	RV20	Like BAUF, but revegetate riparian zones on both stream sides, to 20m width along all streams in the MW region

2	SW2	Like BAUF, but treat all future impervious cover such that Attenuated Imperviousness is maintained at 2016 levels. Definition of 'future impervious cover' includes infill in existing urban areas and future—planned but as yet undeveloped—new urban areas.
3	SW1	Like BAUF, but treat all future *and* existing impervious cover such that Attenuated Imperviousness is effectively zero
4	RV20_SW2	Like BAUF, but revegetate riparian zones on both stream sides, to 20m width along all streams in the MW region AND treat all future impervious cover such that Attenuated Imperviousness is maintained at 2016 levels. Definition of 'future impervious cover' includes infill in existing urban areas and future—planned but as yet undeveloped—new urban areas.
5	RV20_SW1	Like BAUF, but revegetate riparian zones on both stream sides, to 20m width along all streams in the MW region AND treat all future *and* existing impervious cover such that Attenuated Imperviousness is effectively zero
Below, we document scenarios that were explored in the course of developing the Healthy Waterways Strategy, but which are ***not*** the scenarios of focus of the action prioritization analysis described in Section 3 onwards.		
1 'Action'		
6	RV10	Like BAUF, but revegetate riparian zones on both stream sides, to 10m width along all streams in the MW region
7	SW3	Like BAUF, but treat all future *and* some existing impervious cover such that Attenuated Imperviousness in existing urban areas is reduced to 75% of 2016 levels. Definition of 'future impervious cover' includes infill in existing urban areas and future—planned but as yet undeveloped—new urban areas.
8	SW4	Like BAUF, but treat all future *and* some existing impervious cover such that Attenuated Imperviousness in existing urban areas is reduced to 50% of 2016 levels. Definition of 'future impervious cover' includes infill in existing urban areas and future—planned but as yet undeveloped—new urban areas.
9	BAUF_NoDry	Like BAUF, but set Mean Annual Runoff Depth at 2016 values
2 'Actions'		
10	RV20_SW3	Like BAUF, but revegetate riparian zones on both stream sides, to 20m width along all streams in the MW region AND treat all future *and* some existing impervious cover such that Attenuated Imperviousness in existing urban areas is reduced to 75% of 2016 levels. Definition of 'future impervious cover' includes infill in existing urban areas and future—planned but as yet undeveloped—new urban areas.
11	RV20_SW4	Like BAUF, but revegetate riparian zones on both stream sides, to 20m width along all streams in the MW region AND

		treat all future *and* some existing impervious cover such that Attenuated Imperviousness in existing urban areas is reduced to 50% of 2016 levels. Definition of 'future impervious cover' includes infill in existing urban areas and future—planned but as yet undeveloped—new urban areas.
12	RV20_NoDry	Like BAUF, but revegetate riparian zones on both stream sides, to 20m width along all streams in the MW region AND set Mean Annual Runoff Depth at 2016 values
13	RV10_SW2	Like BAUF, but revegetate riparian zones on both stream sides, to 10m width along all streams in the MW region AND treat all future impervious cover such that Attenuated Imperviousness is maintained at 2016 levels. Definition of 'future impervious cover' includes infill in existing urban areas and future—planned but as yet undeveloped—new urban areas.
14	RV10_SW1	Like BAUF, but revegetate riparian zones on both stream sides, to 10m width along all streams in the MW region AND treat all future *and* existing impervious cover such that Attenuated Imperviousness is effectively zero
15	RV10_SW3	Like BAUF, but revegetate riparian zones on both stream sides, to 10m width along all streams in the MW region AND treat all future *and* some existing impervious cover such that Attenuated Imperviousness in existing urban areas is reduced to 75% of 2016 levels. Definition of 'future impervious cover' includes infill in existing urban areas and future—planned but as yet undeveloped—new urban areas.
16	RV10_NoDry	Like BAUF, but revegetate riparian zones on both stream sides, to 10m width along all streams in the MW region AND set Mean Annual Runoff Depth at 2016 values
3 'Actions'		
17	RV20_SW2_NoDry	Like BAUF, but revegetate riparian zones on both stream sides, to 20m width along all streams in the MW region AND treat all future impervious cover such that Attenuated Imperviousness is maintained at 2016 levels AND set Mean Annual Runoff Depth at 2016 values. Definition of 'future impervious cover' includes infill in existing urban areas and future—planned but as yet undeveloped—new urban areas.
18	RV20_SW1_NoDry	Like BAUF, but revegetate riparian zones on both stream sides, to 20m width along all streams in the MW region AND treat all future *and* existing impervious cover such that Attenuated Imperviousness is effectively zero AND set Mean Annual Runoff Depth at 2016 values.
19	RV20_SW3_NoDry	Like BAUF, but revegetate riparian zones on both stream sides, to 20m width along all streams in the MW region AND treat all future *and* some existing impervious cover such that Attenuated Imperviousness in existing urban areas is reduced to 75% of 2016 levels AND set Mean Annual Runoff Depth at 2016 values. Definition of 'future impervious cover' includes infill in existing urban areas and future—planned but as yet undeveloped—new urban areas.

20	RV10_SW2_NoDry	Like BAUF, but revegetate riparian zones on both stream sides, to 10m width along all streams in the MW region AND treat all future impervious cover such that Attenuated Imperviousness is maintained at 2016 levels AND set Mean Annual Runoff Depth at 2016 values. Definition of 'future impervious cover' includes infill in existing urban areas and future—planned but as yet undeveloped—new urban areas.
21	RV10_SW1_NoDry	Like BAUF, but revegetate riparian zones on both stream sides, to 10m width along all streams in the MW region AND treat all future *and* existing impervious cover such that Attenuated Imperviousness is effectively zero AND set Mean Annual Runoff Depth at 2016 values.
22	RV10_SW3_NoDry	Like BAUF, but revegetate riparian zones on both stream sides, to 10m width along all streams in the MW region AND treat all future *and* some existing impervious cover such that Attenuated Imperviousness in existing urban areas is reduced to 75% of 2016 levels AND set Mean Annual Runoff Depth at 2016 values. Definition of 'future impervious cover' includes infill in existing urban areas and future—planned but as yet undeveloped—new urban areas.
'Actions' that affect native Fish (and not Macroinvertebrates and Platypus)		
Fish barrier removal-related scenarios, were based around the removal of instream barriers (full or partial) from the mainstem of major rivers within each catchment, so as to open up larger sections of habitat. A further consideration was the feasibility of barrier removal and this meant leaving dam walls of major dams in place, as is. Note: for details of estimated costs of removing different types of instream fish barriers, please see Appendix A.		
23	FW2	Like BAUF, but remove instream barriers along the mainstem of major rivers in each catchment but excluding major dams. Specifically, this involves removing the following FULL Barriers in the: WERRIBEE catchment: ID 749 (Skeleton Ck) & ID 352 (Werribee R) MARIBYRNONG catchment: ID 840, 870 & 841 (Jacksons Ck) and 703 (Moonee Ponds Ck) YARRA catchment: ID 747 (Darebin Ck), 44 (Donnellys Ck), 361 (Grace Burn Ck), 358 (McMahons Creek) and 2 (Armstrong Creek) DANDENONG catchment: No FULL barriers removed WESTERNPORT catchment: ID 716 (Lang Lang R) And also the following PARTIAL Barriers in the: WERRIBEE catchment: ID 715, 759, 321, 879 & 880 (Kororoit Ck), 750, 754 & 751 (Laverton Ck), 748 & 343 (Skeleton Ck), 881, 882, 883, 884, 885, 886, 887, 888, 889 & 354 (Werribee R), 344 & 347 (Toolern Ck), 891, 892, 893, 894 & 895 (Little R)

		MARIBYRNONG catchment: ID 706, 707 (Maribyrnong R), 842, 871, 872, 873 & 171 (Jacksons Ck), 702 & 733 (Moonee Ponds Ck) YARRA catchment: ID 684, 742, 741, 744, 745, 685 (Merri Ck), 760 (Darebin Ck), 763, 677, 678, 114 (Plenty R), 773, 40 & 39 (Diamond Ck), 164 (Yarra R), 829 (Sawpit Ck), 784, 782 & 783 (Corranderrk Ck), 8 (Big Pats Ck), 135 (Starvation Ck), 787, 11 & 788 (Britannia Ck) DANDENONG catchment: ID 387, 815, 241 (Dandenong Ck), 717 (Eastern Contour Drain), 266 (Kananook Ck) WESTERNPORT catchment: ID 836 (Main Ck), 856 (Bass R), 808 (Lang Lang R), 837 & 805 (Cannibal Ck), 249 (Diamond Ck), 301 & 803 (Toomuc Ck)
24	FWX	Like BAUF, but involves removing all FULL and PARTIAL barriers across the WERRIBEE, MARIBYRNONG, YARRA, DANDENONG and WESTERNPORT catchments. (For this hypothetical scenario we ignored the feasibility consideration.)
25	SW2_FW2	Like BAUF, but treat all future impervious cover such that Attenuated Imperviousness is maintained at 2016 levels AND remove Full and Partial Barriers as per FW2. Definition of 'future impervious cover' includes infill in existing urban areas and future—planned but as yet undeveloped—new urban areas.
26	RV20_SW2_FW2	Like BAUF, but revegetate riparian zones on both stream sides, to 20m width along all streams in the MW region AND treat all future impervious cover such that Attenuated Imperviousness is maintained at 2016 levels AND remove Full and Partial Barriers as per FW2. Definition of 'future impervious cover' includes infill in existing urban areas and future—planned but as yet undeveloped—new urban areas.

To engage stakeholders in understanding and visualising waterway values under CURR and BAUF, we predicted and mapped these scenarios for each of the five major catchments in the region (see example for the Yarra catchment in Figure 5). In workshops for each major catchment, stakeholders deliberated over predictions like these ones as they developed ideas for mitigating actions.

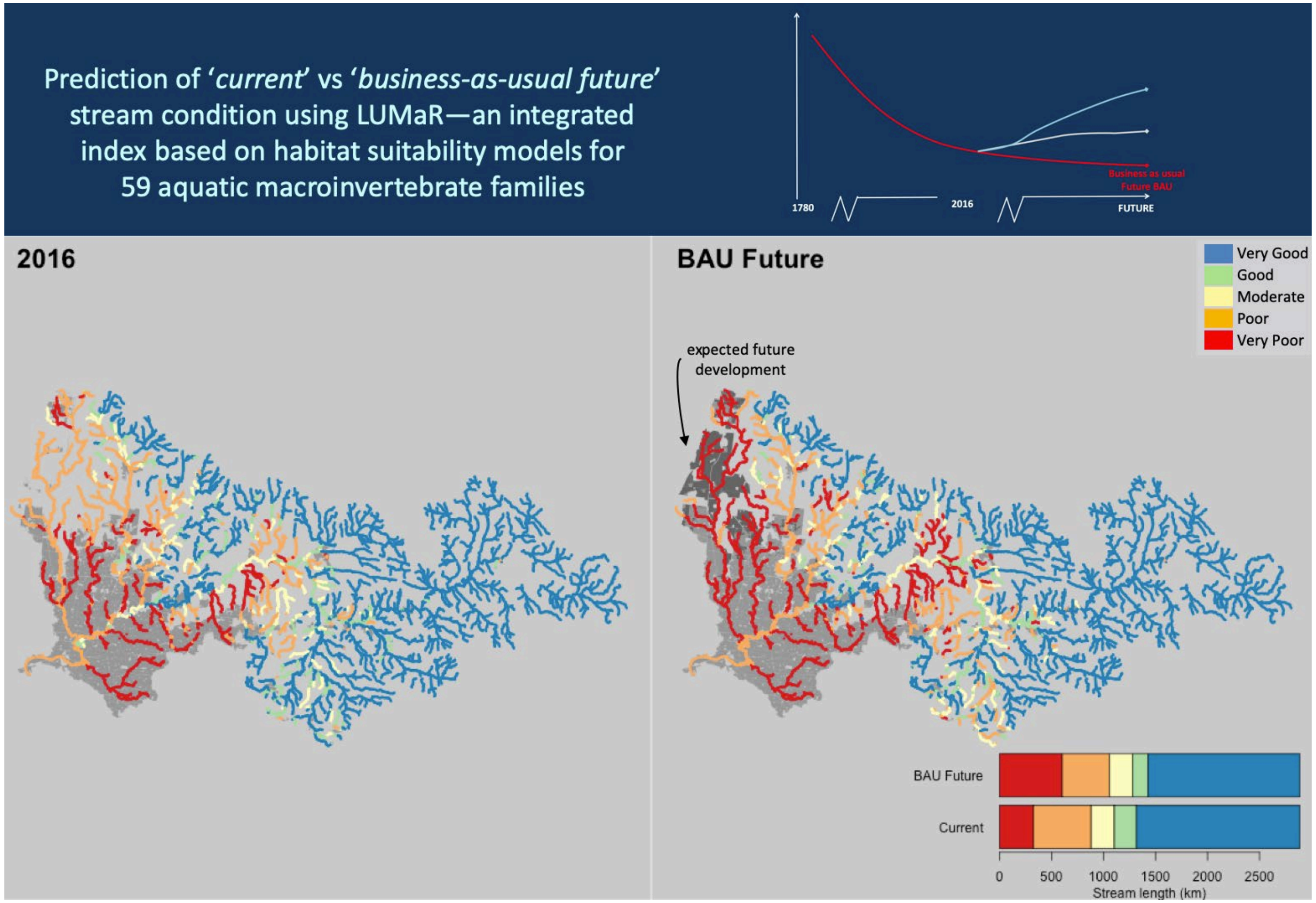


Figure 5 These maps use LUMaR, an integrated index of macroinvertebrate assemblage composition (Walsh, *in prep*) to summarise instream condition of waterways across the catchment. The maps show the distribution of LUMaR scores under current (CURR, left) and business-as-usual future) (BAU Future, right) conditions. Mid-grey shading denotes existing impervious cover and dark grey indicates expected future impervious cover. Bar charts summarise the total lengths of stream in each LUMaR score category for each scenario.

We investigated the following primary intervention actions:

- riparian revegetation ('**RV**')
- management of stormwater runoff ('**SW**') and
- management of full/partial instream fish barriers via removal or installation of fishways ('**FW**')

These key interventions can also be combined in various ways to explore their combined impact on instream habitat suitability for macroinvertebrates, native fish and platypus. For the quantitative action prioritisation analysis for the HWS, we focussed on *broadly applicable* actions that were *relevant to all taxa*, and for which unit-based costs could be obtained, so that action prioritisation could account for cost-effectiveness. Quantitative action prioritisation therefore focussed on five main actions/scenarios: RV20, SW2, SW1, RV20_SW2 and RV20_SW1 (the first five scenarios fully described in Table 7).

Riparian vegetation provides natural protection for stream banks and floodplains (Corenblit *et al*. 2007) and the stream health benefits of riparian vegetation increase with increasing widths (Walsh & Webb 2014), particularly for large floodplain rivers such as the Yarra River. The choice of a 20 m width for riparian revegetation reflects a compromise between what is geomorphologically and ecologically desirable, and what is socially acceptable and operationally feasible given adjacent landholders. In built-up urban areas, there are often greater constraints along stream reaches and thus we also investigated 10 m riparian revegetation widths. The use of both 20 m and 10 m riparian revegetation widths reflects long-standing practice at Melbourne Water.

Beyond the five main actions/scenarios listed above, we also explored alternative scenarios by varying factors such as the:

- width of riparian revegetation (e.g. RV10)
- extent of management of stormwater runoff (expressed as percentage reduction in attenuated imperviousness from CURR conditions, e.g. SW3 and SW4)
- degree of drying expected in the future (e.g. NoDry)
- selection of instream fish barriers to be treated (e.g. FW2, FWX)

These actions were applied individually and in combination. We note that actions/scenarios such as NoDry and fish barrier-related ones (e.g. FW2, FWX) do *not* fit the criteria above of being broadly applicable and relevant to all taxa. There was no specific investigation into the means of how 'NoDry' could be achieved in practice—something that would likely involve coordination of multiple measures such as management of water extraction, stormwater infiltration, and provision of environmental flows depending on landscape context, practical logistics and feasibility. We sidestepped all that and simply explored the predicted outcome of scenarios including a 'NoDry' component. All the additional scenarios that were explored in the course of developing the HWS, but not actually used in the target identification process, are listed and described in Table 7.

3 Spatially Prioritising (Cost-effective) Actions to Maximise Conservation & Restoration of Instream Biodiversity

We used our 67 habitat suitability models for macroinvertebrates, native fish and platypus to estimate the *benefit* due to candidate actions/scenarios. In essence, the management gain or benefit to a taxon is the *change* in predicted habitat suitability due to the action/scenario.

For the HWS, quantitative action prioritization concentrated on RV20, SW2, SW1, RV20_SW2 and RV20_SW1 (the first five actions/scenarios fully described in Table 7). In all cases, management gain/benefit is measured relative to the BAUF.

As stated in the section heading, the objective was to spatially prioritise actions to cost-effectively maximise instream biodiversity across the Melbourne Water region. This objective is actually a complex multi-criteria task, requiring us to address biodiversity, the possibility of multiple actions for each reach, the performance of each action (which depending on what it is, may involve action wholly within the target reach, up to 6 km upstream of the target reach and/or in the entire upstream watershed of the target reach), its cost, and finally, the overall biodiversity outcome at the scale of the MW region. We use a systematic conservation planning software tool called Zonation (Moilanen *et al*. 2005, 2014, see Box 3) to analyse input maps for all the taxa and to produce a solution that is a continuous rank map of action priorities across the MW landscape.

Box 3 Zonation: what is it? What does it aim to do? And how does it work?

Zonation is a set of methods implemented in a software tool to support large-scale systematic spatial conservation prioritisation and planning (Moilanen *et al*. 2005, 2014). The ultimate goal of conservation is to ensure the *persistence of biodiversity in the long term*. Three key concepts in systematic conservation planning are:

i) ***representativeness*** - representing the full variety of biodiversity in the study area
ii) ***irreplaceability*** - prioritising unique or rare species occurrences without which we would fail to achieve *representativeness* and
iii) ***complementarity*** – ensuring that the selection of additional sites complements or adds new species rather than duplicating the species present in sites already selected

Zonation provides quantitative methods to operationalise these three principles when identifying priority areas that are important for retaining habitat quality and connectivity simultaneously for many species, ecological communities or ecosystem types to support persistence.

Zonation has been used in conservation applications worldwide. A notable international example is the high spatial resolution (~0.86 km^2) conservation blueprint that was developed for Madagascar (areal extent 587,040 km^2) that involved 2,315 species across 6 major taxonomic groups (ants, butterflies, frogs, geckos lemurs and plants)(Kremen *et al*. 2008). In Australia, Zonation has been used for large-scale land use planning in the Lower Hunter region (Kujala *et al*. 2015), for strategic environmental assessment in West Australia's Perth-Peel region (Whitehead *et al*. 2016), for the Victorian Department of Environment, Land, Water and Planning's Strategic Biodiversity Values map (DELWP 2017b), and their Strategic Management Prospects (DELWP 2017 c, d).

How does Zonation operationalise *complementarity* to generate a spatial prioritisation solution that satisfies our requirements for *representativeness* and *irreplaceability*? Zonation does this via a meta-algorithm that proceeds as follows:

1. Start with the full landscape
2. For each reach (or 'planning unit' in Zonation terminology) calculate the marginal loss value, δ, that would result if that reach were to be removed. The marginal loss value, δ, of any given reach depends upon multiple factors such as habitat suitability for taxa/species present ('occurrence levels of biodiversity features in Zonation terminology) and how important the reach is for species connectivity. Identify the reach that has the smallest marginal loss value, *δ*, and remove it.
3. Recalculate marginal loss values of remaining reaches (planning units) and repeat step 2. (Following the removal of reaches, the remaining instances of reaches of strong habitat suitability for species could become more valuable, Zonation tracks this via this step of recalculating the marginal loss values for the remaining reaches.)
4. Repeat steps 2 and 4 until no reaches (planning units) are left

In summary, the meta-algorithm iteratively removes the least valuable reaches (planning units) from the landscape while minimizing marginal loss of conservation value and accounting for connectivity needs and taxa/species weights. This process generates a nested sequence of connected landscape structures with increasingly important core areas of species habitats (or distributions) remaining last. The Zonation solution is mapped as a hierarchical, continuous ranking of spatial priorities across the study area that is easy to visualise and interpret.

Zonation offers many features and capabilities for addressing different questions and needs. For instance, there are different methods for (Moilanen *et al*. 2014):

- quantifying conservation value (known as 'cell removal rules' in Zonation terminology)
- inducing aggregation and connectivity (to minimize fragmentation and isolated patches in the solution)
- accounting for different types of costs
- accounting for landscape condition and biodiversity retention

These features and capabilities can be combined and configured to create customised Zonation analysis set-ups to suit user-needs.

We took a two-stage approach that involved first, identifying the most cost-effective action for each of the 8,233 reaches (described in Sections 3.1 and 3.2). Then using our 67 HSMs, we 'implemented' the most cost-effective action at each reach, generated habitat suitability predictions, calculated the management gain due to the 'implemented' action, and supplied the management gain estimates, along with other inputs, to Zonation for the region-wide spatial prioritisation analysis. Some of the other key required inputs to Zonation include species weights and designation of species-specific connectivity requirements (described in Sections 3.4.1 and 3.4.2 respectively).

In attempting to spatially prioritise cost-effective actions, we actually want to take into account three considerations:

a) what's valuable at *present* (i.e. under CURR conditions),
b) what's predicted to be valuable assuming a business-as-usual-future (i.e. under BAUF conditions), and
c) what's expected to produce the most cost-effective improvement in instream biodiversity (relative to BAUF)

The idea is that it is preferable to ensure that a Zonation solution will capture high-quality areas that are good for instream biodiversity *both at present and at the future timepoint*. In other words, we seek to promote continuity of high instream biodiversity areas from now through to the future (*sensu* Thomson *et al*. 2009). Furthermore, management gains that come off a high base or starting value are preferred to management gains that come off a low base/starting value. For instance, consider two reaches, one with a starting habitat suitability value of 0.01 for species X and another with a starting value of 0.5 for the same species. If the change in predicted habitat suitability of species X due to an action was 0.1, then all else being equal, we would prefer the reaches where the starting value was 0.5.

To ensure a Zonation solution that will promote continuity of high biodiversity quality areas through time, and also preference management gains in areas with higher starting biodiversity values, we use a Zonation set-up constructed with three sets of maps representing CURR, BAUF and management gain predictions for all taxa (i.e. 3 x 67 maps). See Section 3.4.3 for discussion about what we considered when deciding upon what would be an appropriate balance between representation and expected condition under BAUF, and management gain via action.

3.1 Unit Costs of Candidate Actions

The two basic actions are riparian revegetation ('**RV**') and stormwater management of impervious cover ('**SW**'). Variants and combinations of these two basic actions give us the five main actions/scenarios: RV20, SW2, SW1, RV20_SW2 and RV20_SW1 (see Table 7). In this section, we document the cost components of each action, determinants of spatial cost variation of each action, and the final estimated unit-based cost of each action. The actual cost estimation work was undertaken by MW, using a variety of approaches (see Melbourne Water (2020)). Here, we simply report the cost estimates and the underlying assumptions.)

With respect to riparian revegetation, the intent was to estimate the cost of works at the standard required to achieve successful revegetation with a high degree of confidence. Cost estimation for riparian revegetation was based on actual costs from examples of recent works undertaken by the Melbourne Water delivery team (key informant: David Fisher). The assumptions used in developing the estimated cost per kilometre of riparian revegetation are as follows:

- width of riparian revegetation on both sides of the reach is 20 metres
- if woody weeds are present within the riparian revegetation zone, cost includes the cost of their removal and follow-up control (fine-resolution spatial mapping of deciduous woody weeds was available via a Melbourne Water GIS layer called 'Willows_2016_Within_Stream20m')
- revegetation costs include cost of trees and shrubs (1.5 m spacing), fencing and weed control
- includes capital costs incurred over 3 years and 7 years' worth of maintenance costs
- no discounting was applied

Table 8 summarises the cost per kilometre of woody weed removal and riparian revegetation for four regions within the MW area, along with a brief explanation of the reasons for spatial variations in the costs.

Table 8 Summary of the costs per kilometre (inclusive of both streamsides) of woody weed removal and riparian revegetation for four broad regions within the MW region.

Activity	Region	Cost/km	Comment
Woody weed removal (WdyWeedRemCost)	South-east	$541,316	Generally easy access to sites. Based on recent costs for Gisborne and Allsops Creek
	Yarra	$735,144	Often no direct access, crews may have to walk a moderate distance. Based on recent costs for Bunyip River and Running Creek
	West	$1,439,380	Difficult access and rocky terrain
	within UGB	$1,439,380	Assumed same unit costs as the 'West' due to presence of many constraints in the urban setting
Riparian revegetation (RipRevegCost)	South-east	$233,392	Plants tend to establish easily (no supplementary watering required). Generally easy access to sites.
	Yarra	$427,220	No supplementary watering of plants required. Often no direct access, crews may have to walk a moderate distance. Based on recent costs for Macclesfield Creek and Diamond Creek.
	West	$933,064	Difficult rocky terrain which affects access and fencing. Drier conditions means supplementary watering over first summer required to aid plant establishment. Rabbit baiting required. Based on costs for Little River and Upper Maribyrnong.
	Within UGB	$933,064	Assumed same unit costs as the 'West' due to presence of many constraints in the urban setting

The cost modeling of stormwater treatment is based on data from the Modelling Analysis for Potential Stormwater Standards – DesignFlow 2014 (Phase C pg 57) for the full details of cost estimation. As there is considerable uncertainty around the costs required to effectively manage stormwater runoff, MW developed low, medium and high estimates for the costs of managing stormwater. Table 9 summarises the cost estimates of effectively managing stormwater runoff per hectare of impervious area from future and existing impervious cover.

Table 9 Summary of the low, medium and high cost estimates of effectively managing stormwater runoff per hectare of impervious area from future and existing impervious cover.

Impervious Cover Type	Cost/ha		
	Low est	Med est	High est
Existing (SWExistingImpervAreaCost)	$423,400	**$712,310**	$890,388
Future (SWFutureImpervAreaCost)	$185,420	**$423,400**	$712,310

For the purposes of the estimating the most cost-effective action for each reach, we used the medium stormwater management cost estimate values for future and existing impervious cover.

3.2 *What* is the Most Cost-effective Action for each reach?

As mentioned in Section 3, the first stage of our approach was to first identify for each of the 8,233 reaches, which of the five possible actions is the most cost-effective action. In this section, we describe how we calculate the cost of each action for each reach. The 'Attenuated Forest Cover' and 'Attenuated Imperviousness' predictors that are used in the HSMs are spatially weighted measures that are affected not only by the immediate local characteristics of a given reach, but also by characteristics in reaches and subwatersheds upstream of the target reach. Below, we describe the nature of the spatial dependency associated with each action and how this is handled in the cost (and later, benefit) calculations.

3.2.1 Reach-level Costs of Candidate Actions

Riparian revegetation (RV20)

Reach-level spatial data for woody weeds and native vegetation within 20 metres of the stream centerline were mapped (for larger waterways the 20 metres was measured from the top of bank, rather than the stream centerline) and the following attributes computed for our use by GraceGIS:

- length of stream, StreamLen (km)
- size of riparian area, RiparianArea (ha)
- amount of woody weed cover in the riparian area, WdyWeedRiparianArea (ha)
- amount of vegetation cover in the riparian area, VegRiparianArea (ha)
- amount of unvegetated area in the riparian area, NoVegRiparianArea (ha)

We used the base attribute data from above as inputs for our calculations relating to the riparian revegetation (**RV20**) action. To compute the length of woody weeds within the riparian zone for each reach *i*, we first calculated the proportion of woody weed cover within the riparian area (PropWdyWeedRiparianArea) by dividing the amount of woody weed cover in the riparian area (WdyWeedRiparianArea) by the total size of the riparian area (RiparianArea):

$$PropWdyWeedRiparianArea_i = WdyWeedRiparianArea_i / RiparianArea_i$$

We then estimated the length of riparian woody weed cover (WdyWeedLen) as the product of stream length (StreamLen) and the proportion of woody weed cover within the riparian area:

$$WdyWeedLen_i = PropWdyWeedRiparianArea_i * StreamLen_i$$

The length of stream requiring riparian revegetation within a reach ($NoVegLen_i$) was calculated in an analogous manner, by first calculating the proportion of unvegetated cover within the riparian area, and then multiplying that by stream length:

$$PropNoVegRiparianArea_i = NoVegRiparianArea_i / RiparianArea_i$$

$$NoVegLen_i = PropNoVegRiparianArea_i * StreamLen_i$$

The attenuated forest cover predictor that we use in our HSMs is actually a weighted measure of riparian cover alongside and ***upstream*** of a reach (Table 4). So when we apply the RV20 action to a particular reach, it implies that riparian areas up to 6 km upstream of the target reach are treated for woody weed removal (where applicable) and revegetated. The RV20 action costs need to reflect this. For each reach *i*, RV20 cost is therefore calculated as:

$$RV20Cost_i = \sum_{i \epsilon |R|} WdyWeedLen_i * WdyWeedRemCost + NoVegLen_i * RipRevegCost$$

where $|R|$ is the set of reaches up to 6 km upstream of reach *i*.

Stormwater management (SW2, SW1)

Recall that action SW2 is to treat all future impervious cover such that the Attenuated Imperviousness predictor used in our HSMs (a dimensionless measure that is the ratio of attenuated impervious area in the watershed to watershed area, Table 4) is maintained at 2016 levels. The definition of 'future impervious cover' includes infill in existing urban areas and future—planned but as yet undeveloped—new urban areas. And action SW1 is to treat all future and existing impervious cover such that the Attenuated Imperviousness predictor value is effectively zero (a much more ambitious action).

Measures of reach-level spatial data for attenuated imperviousness were estimated for existing as well as future impervious cover ($AttImp\_L9Area\_m2\_2014_i$ and $FutDevAttImp\_L9Area\_m2_i$ respectively). When we apply the SW2 action to a particular reach *i*, it implies that all expected future impervious cover in the upstream contributing watershed of the target reach is 'treated'. And the SW2 action costs need to reflect this. For each reach *i*, SW2 cost is therefore calculated as:

$$SW2Cost_i = \sum_{i\epsilon|S|} FutDevAttImp\_L9Area\_m2_i/10000 * SWFutureImpervAreaCost$$

where $|S|$ is the set of upstream contributing subwatersheds to subwatershed *i*.

And for each reach *i*, SW1 cost is calculated as:

$$SW1Cost_i = \sum_{i\epsilon|S|} FutDevAttImp\_L9Area\_m2_i/10000 * SWFutureImpervAreaCost \\ + AttImp\_L9Area\_m2\_2014_i/10000 * SWExistingImpervAreaCost$$

where $|S|$ is the set of upstream contributing subwatersheds to subwatershed *i*.

Combination actions (RV20_SW2, RV20_SW1)

When we apply a combination action like RV20_SW2 to a particular reach, it implies that riparian areas up to 6 km upstream of the target reach are treated for woody weed removal (where applicable) and revegetated, and all future impervious cover in the upstream contributing watershed of the target reach is 'treated'. For each reach *i*, RV20_SW2 cost is therefore calculated as:

$$RV20\_SW2Cost_i \\ = \sum_{i\epsilon|R|} WdyWeedLen_i * WdyWeedRemCost + NoVegLen_i * RipRevegCost \\ + \sum_{i\epsilon|S|} FutDevAttImp\_L9Area\_m2_i/10000 * SWFutureImpervAreaCost$$

where $|R|$ is the set of subwatersheds up to 6 km upstream of reach *i*, and $|S|$ is the full set of upstream contributing subwatersheds to reach *i*.

And the RV20_SW1 cost is calculated as:

$$
\begin{aligned}
RV20\_SW1Cost_i &= \sum_{i\epsilon|R|} WdyWeedLen_i * WdyWeedRemCost + NoVegLen_i * RipRevegCost \\
&+ \sum_{i\epsilon|S|} FutDevAttImp\_L9Area\_m2_i/10000 * SWFutureImpervAreaCost \\
&+ AttImp\_L9Area\_m2\_2014_i/10000 * SWExistingImpervAreaCost
\end{aligned}
$$

where $|R|$ is the set of subwatersheds up to 6 km upstream of reach *i*, and $|S|$ is the full set of upstream contributing subwatersheds to reach *i*.

3.2.2 Reach-level Benefits of Candidate Actions

Recall that the management gain or benefit to a taxon is the *change* in predicted habitat suitability (relative to habitat suitability under BAUF) as a result of the action/scenario. As explained above, RV20, SW2 and SW1 modify the values of 'Attenuated Forest Cover' and 'Attenuated Imperviousness' which are spatially weighted measures that involve the subwatershed of the target reach, as well as subwatersheds upstream of it. So, as was the case with cost calculations, this spatial dependency of actions must also be accounted for in our biodiversity benefit calculations.

For each reach *i*, we compute the biodiversity benefit score due to an action by summing across all 67 taxa, the product of (positive) change in predicted habitat suitability for each taxa *j*, its weighting (used in Zonation, W_j) and stream length.

So for example, for each reach *i*, the benefit score for action RV20 is calculated as:

$$
RV20Benefit_i = \sum_{j=1}^{67} \max\{RV20HabSuit_{ij} - BAUFHabSuit_{ij}, 0\} * W_j * StreamLen_i
$$

Note that though we 'implement' RV20 by revegetating riparian areas up to 6 km upstream of reach *i*, we do **not** get to claim biodiversity benefit across the set of reaches in subwatersheds up to 6 km upstream of the target reach.

For each reach, the benefit score for action SW2 is calculated as:

$$SW2Benefit_i = \sum_{i \in |S|} \sum_{j=1}^{67} \max\{SW2HabSuit_{ij} - \ BAUFHabSuit_{ij}\ , 0\} * W_j * StreamLen_i$$

where $|S|$ is the set of reaches in upstream contributing subwatersheds to reach *i*.

Very similarly, for each reach *i*, the benefit score for action SW1 is calculated as:

$$SW1Benefit_i = \sum_{i \in |S|} \sum_{j=1}^{67} \max\{SW1HabSuit_{ij} - \ BAUFHabSuit_{ij}\ , 0\}\ * W_j * StreamLen_i$$

where $|S|$ is the set of reaches in upstream contributing subwatersheds to reach *i*.

Note that when the action is SW2 or SW1, impervious areas, whether future or existing, within the entire upstream contributing watershed area of the target reach must be 'treated'. Hence, we are entitled to include the biodiversity benefit from reaches in all upstream contributing subwatersheds of the target reach.

For each reach *i*, the benefit score for action RV20_SW2 is calculated as:

$$\begin{aligned} RV20\_SW2Benefit_i \\ &= \sum_{j=1}^{67} \max\{RV20\_SW2HabSuit_{ij} - \ BAUFHabSuit_{ij}\ , 0\} * W_j * StreamLen_i \\ &+ \sum_{i \in |S-i|} \sum_{j=1}^{67} \max\{SW2HabSuit_{ij} - \ BAUFHabSuit_{ij}\ , 0\} * W_j * StreamLen_i \end{aligned}$$

where $|S - i|$ is the set of all reaches upstream of reach *i*, but excluding reach *i* itself which is already accounted for in the first line of the equation.

Very similarly, for each reach *i*, the benefit score for action RV20_SW1 is calculated as:

$$\begin{aligned} RV20\_SW1Benefit_i \\ &= \sum_{j=1}^{67} \max\{RV20\_SW1HabSuit_{ij} - BAUFHabSuit_{ij}\ , 0\} * W_j * StreamLen_i \\ &+ \sum_{i \in |S-i|} \sum_{j=1}^{67} \max\{SW1HabSuit_{ij} - \ BAUFHabSuit_{ij}\ , 0\} * W_j * StreamLen_i \end{aligned}$$

where $|S - i|$ is the set of all reaches upstream of reach *i*, but excluding reach *i* itself which is already accounted for in the first line of the equation.

3.2.3 Reach-level Cost-effectiveness of Candidate Actions

The cost-effectiveness score of each candidate action for reach *i* is obtained by dividing the benefit score for the action by the cost of implementing that action for reach *i*:

$$ACTIONCostEff_i = ACTIONBenefit_i / ACTIONCost_i$$

where $ACTION = \{RV20, SW2, SW1, RV20\_SW2, RV20\_SW1\}$

With the cost-effectiveness score calculated for each action, all five actions for a given reach can be ranked by cost-effectiveness. For the most part, the most cost-effective action for each of the 8,233 reaches was selected as the action to 'apply'. However, there were particular situations that required a different choice, as well as some customisations, and these are described below.

3.2.4 Customisations

For some reaches the benefit score was zero or practically zero. This implied that undertaking action provided virtually no improvement there. There were two possible reasons for this. One is that the riparian vegetation in the subwatershed and subwatersheds up to 6 km upstream of the target reach are intact, and no future development is expected anywhere within its upstream contributing watershed area. In other words, it is in the best possible shape and no further improvement can be expected. Some reaches within Melbourne's protected water supply catchments (e.g. in the Yarra Ranges National Park) and within State Parks (e.g. Bunyip and Lerderderg State Parks) fall into this category. A second possible reason is that conditions under BAUF are expected to be so dire, that even with action, expected improvement in instream biodiversity is negligible. This was the case with a small number of already highly degraded reaches in the west which were expected to experience harsh drying conditions and further urbanization in their catchment areas. For these reaches where the benefit score was effectively zero, we devised a sixth action that we called maintaining the *status quo* ('**SQ**'). For reaches deemed to be in excellent shape, we seek to ensure that they do not deteriorate, and for highly degraded reaches where no biodiversity improvement seems possible, we should recognise that and do not direct any investment there.

Under certain conditions, MW wanted to disallow the riparian revegetation action (planting of trees or shrubs) along particular reaches. These conditions included the following:

a) riparian revegetation along the stream channel would pose a potential threat to flood protection levees. This applied to 9 reaches.
b) the designated Ecological Vegetation Class (EVC) of the subcatchment is deemed to be incompatible with planting of trees and large shrubs. The 6 EVCs identified by MW to

be incompatible with riparian revegetation were: 'Plains Grassy Wetland', 'Plains Grassland', 'Coastal Saltmarsh', 'Sand Heathland', 'Cane Grass Wetland' and 'Brackish Grassland'.

In total 445 reaches were affected by one or more of these conditions and RV20 was disallowed for these reaches. This meant that for these 445 reaches the only 2 possible actions that could be 'applied' were SW2 or SW1, and the more cost-effective option was selected.

Now, all things being equal, a combined action such as RV20_SW2 tends to deliver greater biodiversity benefit than a single action such as RV20 or SW2. But when cost is brought into consideration, single actions tend to be cheaper and therefore most cost-effective. However, MW reasoned that there could be particular situations where it might be reasonable to bend the 'most cost-effective' rule a little to achieve higher benefits. Specifically, if impervious cover of future development could be avoided as a result of regulation rather than a direct cost to an agency. On the basis of this reasoning, we devised the following customization:

- if for a given reach, the most cost-effective action is RV20 and the second most cost-effective action is RV20_SW2 *or* SW2, then we would select RV20_SW2 as the action to 'apply' for that reach.

This adjustment to the 'most cost-effective action' rule resulted in RV20_SW2 being identified as the 'optimal' action for 378 (as opposed to just 10) reaches, when using the medium cost estimates for stormwater management.

Figure 6 shows the resulting map of 'optimal' action for each of the 8,233 reaches after the process of identifying the most cost-effective action at each reach, and incorporating the various customisations described above. Whilst Figure 6 shows *what* the 'optimal' action for each reach is according to cost-effectiveness and customisations, budget and resource limitations mean that we cannot afford to apply the 'optimal' action for every reach. Instead, we will need to prioritise *where* it would be most profitable to take action. We develop a Zonation analysis to generate the quantitative spatial prioritisation 'solution'.

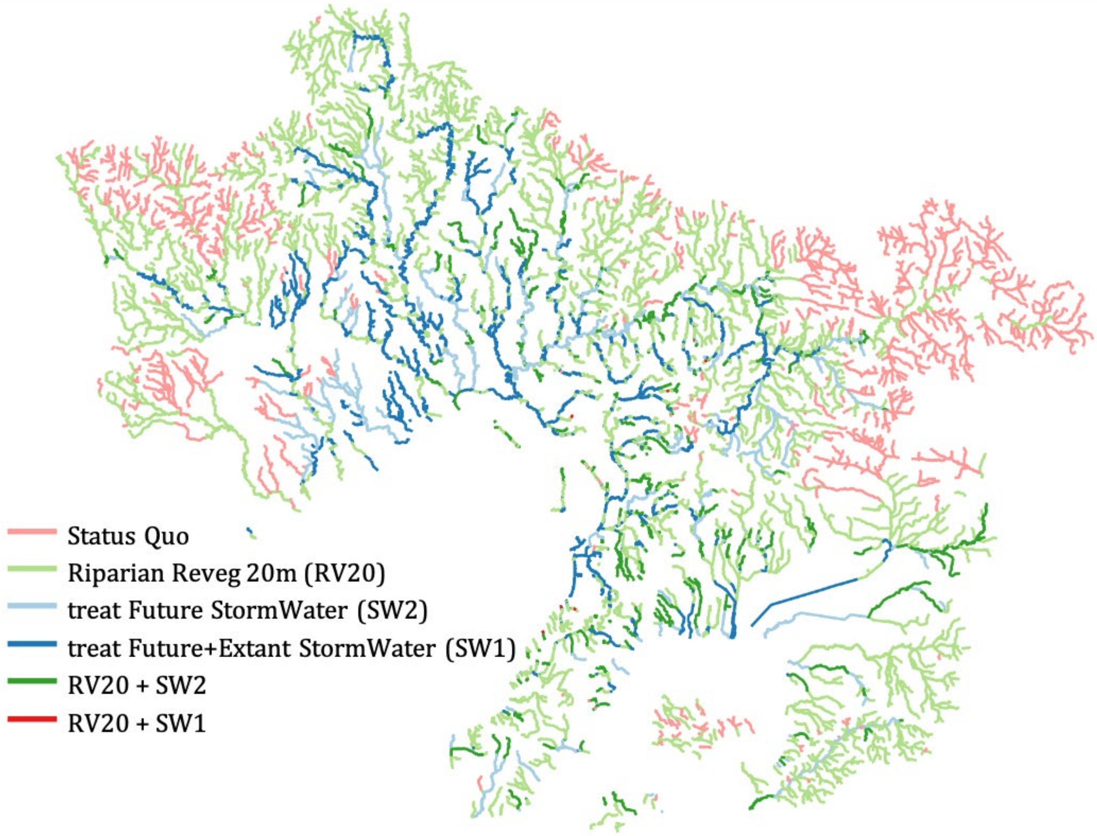


Figure 6. The 'optimal' action 'applied' at each of the 8,233 reaches in the MW region after identifying the most cost-effective action and including the various customisations. SQ: Status Quo, RV20: Riparian Revegetation to 20 m width, SW2: treat all *future* impervious cover such that Attenuated Imperviousness is maintained at 2016 levels, SW1: treat all *existing* and *future* impervious cover such that Attenuated Imperviousness is effectively zero, RV20_SW2: Riparian Revegetation to 20 m width *and* treat all *future* impervious cover such that Attenuated Imperviousness is maintained at 2016 levels, RV20_SW1: Riparian Revegetation to 20 m width *and* treat all *existing* and *future* impervious cover such that Attenuated Imperviousness is effectively zero.

Caveat: In hindsight, the customisation step of disallowing riparian revegetation action for particular reaches on the basis of its designated EVC thereby restricting the choice of actions to only SW2 or SW1, should not have been done. The reason is that there is uncertainty over the accuracy of EVC designation. In hindsight, it would have been preferable to allow all five actions to be considered, and then screened the results after Zonation analysis. This will be addressed in future work that MW undertakes as part of continuous improvement (see Section 4).

3.3 *Where* Should We Take Action as a Matter of Priority?

To recap, in coming up with our quantitative action prioritization, we want to take into account three considerations: a) what's valuable at *present* (i.e. under CURR conditions), b) what's predicted to be valuable under a business-as-usual-future (i.e. under BAUF conditions), and c) what's expected to produce the most cost-effective improvement in instream biodiversity (relative to BAUF). The intent is to ensure that the Zonation solution will capture high-quality areas that are good for instream biodiversity *both at present and at the future timepoint*. We seek to promote continuity of high instream biodiversity areas from now through to the future (*sensu* Thomson *et al*. 2009), and also prefer management gains that come off a high base or starting value than those that come off a low base/starting value.

We first describe the key ingredients required for a Zonation analysis before presenting the Zonation solution for action prioritisation within the MW region.

3.4 Zonation Settings

We opted to use the basic core area Zonation cell removal rule (often referred to as *CAZ* in the Zonation literature, see Box 3) in all our Zonation analyses. We chose to use the *CAZ* rule because it helps ensure that the core areas of individual taxa/species are retained even if they occur in species-poor regions (Moilanen *et al*. 2005). The rule prevents the early removal of core areas of even the initially widespread species. With *CAZ*, the last sites to be removed should be those sites containing strong habitat suitability of high weight taxa/species (see Section 3.4.1).

In the rest of this section, we describe other key inputs and settings required for our Zonation analysis, the role they play in Zonation, and the rationale and methods used in their construction. Specifically, we describe:

i) taxa/species weights, W_j

ii) designation of species-specific connectivity requirements, and

iii) 'condition-retention analysis with the management gain mode', and the 'tuning factor' used to adjust the relative emphasis between representation (CURR), condition (BAUF) and management gain as a result of action

3.4.1 Taxa/Species weights

The weighting of input features is an important, necessary and unavoidably subjective choice (there is no 'correct' answer!) in a Zonation analysis. The input features for our Zonation action prioritization analysis consists of 52 (non-weedy, non-invasive) macroinvertebrate families, 13 native fish species and 2 representations of platypus—one representing females-only (who have more stringent habitat requirements) and another representing all platypus (males and females). Weights given to features influence their balance in the priority ranking process. By default, Zonation allocates a weight of 1.0 to each input feature, so adopting the default would have given a very large weighting overall to macroinvertebrates as a group (52/67 = 77.6%).

We eschewed the default and instead devised a weighting scheme that aimed to balance at the first level, social preferences with respect to macroinvertebrates, native fish and platypus, and then at the next level (i.e. within each taxa group) considerations such as sensitivity to disturbance, conservation status and expected resilience under BAUF conditions.

Following Lehtomäki *et al*.'s (2016) suggestion, we adopt a top-down approach to weighting. We start with 100 weight points (an arbitrary choice), and we divided them between macroinvertebrates, fish, platypus in a 60:30:10 ratio.

To take into account potential impacts under BAUF conditions, we first characterised expected 'winners' and 'losers' under BAUF conditions. This was done (fairly coarsely) by computing for each taxa *j*, the difference in habitat suitability under CURR and BAUF conditions at each reach *i*, multiplying by stream reach length and summing the result across all reaches:

$$LossGainUnderBAUF_j = \sum_{i=1}^{8233}(BAUFHabSuit_i - CURRHabSuit_i) * StreamLen_i$$

Taxa with a net negative $LossGainUnderBAUF_j$ value were deemed 'losers' under BAUF conditions. Recall that our macroinvertebrate families were divided into sensitivity groups A, B, C, D, and weedy/invasive (Table 1). We categorised macroinvertebrate families by sensitivity group *and* expected BAUF impact as sensitivity group A 'losers', sensitivity group B 'losers', sensitivity group C 'losers', sensitivity group D 'losers', 'winners' regardless of sensitivity group and weedy/invasive (Table 10, column 1). These six categories were then assigned weights in the ratio 4 : 3 : 2 : 1 : 0.25 : 0 respectively (Table 10, column 4).

The weight applied in Zonation for individual macroinvertebrate families in each category, $ZonWt_k$, was then calculated as:

$$ZonWt_k = \frac{w_k}{\sum_{k=1}^{6} N_k * w_k} * 60 / N_k$$

where w_k is the category weight and N_k is the number of families in each category, k.

Table 10 Details of macroinvertebrate family sensitivity groups, the number of families in each group, the corresponding sensitivity group weight and the computed Zonation weight applied to an individual family in each given sensitivity group.

Category group (k)	Members of the category group by *code label	Number of families in category group k (N_k)	Category weight (w_k)	Zonation weight applied to individual families in category group k ($ZonWt_k$)
Sensitivity group A 'losers'	QT24, QT21, QT18, QT17, QT15, QT04, QT02, QP04, QP02, QP01, QO08, QM01, QE06, QE05, QE03, QDAD, QD35, QD22, QD06, QC39, QC20, QC10	22	4	1.7266
Sensitivity group B 'losers'	QT25, QT06, QT01, QP03, QE02, QDAE, QD10, QD09, QD01, QC37, QC34, OP03	12	3	1.2950
Sensitivity group C 'losers'	QT03, OT01, KG06	3	2	0.8633
Sensitivity group D 'losers'	QE08, QC13, QC11, QC09, OP06, OP02, KG07	7	1	0.4317
'winners' under BAUF conditions (regardless of sensitivity group)	QT23, QT08, QO12, QO07, QO05, QH65, QH56, QD07	8	0.25	0.1079
Weedy/invasive	QO16, QO02, QH67, LH01, KG08, KG05, IF61	7	0	0

* refer to Table 1 for details of the corresponding family name

As a taxonomic group, fish, were allocated 30 out of a total of 100 weight points. We divided our 13 native species into 3 weighting groups and allocated Zonation weights based on considerations such as conservation status, whether habitat suitability for the species is expected to be negatively affected under BAUF conditions and whether they are migratory (and hence have stronger capacity for dispersal and colonization). The Zonation weights for each native fish species and the rationale for the designated weight is summarized in Table 11.

Table 11 The three weighting groups applied to the 13 native fish species. Zonation weight is the weight applied to each species within the corresponding group.

Group	Species	Zonation weight	Comment
1	River blackfish (GADOMARM) Mountain galaxias (GALAORNA) Yarra pygmy perch (NANNOBSC) Australian grayling (PROTMARA)	5	Habitat suitability for these species is expected to be strongly negative under BAUF conditions. NANNOBSC and PROTMARA are also species of conservation concern
2	Pouched lamprey & Short-headed lamprey (LAMPREYS) Southern pygmy perch (NANNAUST) Flathead gudgeon (PHILGRAN)	1.667	Habitat suitability for these species is expected to improve under BAUF conditions, but these species are non-migratory
3	Short-finned eel (ANGUAUST) Broad-finned galaxias (GALABREV) Common galaxias (GALAMACU) Spotted galaxias (GALATRUT) Tupong (PSEUURVI) Australian smelt (RETSEMO)	0.833	Habitat suitability for these species is expected to improve under BAUF conditions, and these species are migratory (implying better capability for dispersal and colonization)

Platypus were allocated 10 out of a total of 100 weight points. To recap, platypus in the MW region are represented by an 'AllPlaty' HSM (based on male and female, sub-adult and adult data) and a 'FemPlaty' HSM based on just female sub-adult/adult data). Zonation weights of 4 and 6 were allocated to the 'AllPlaty' and 'FemPlaty HSMs respectively. A higher weighting was given to platypus given evidence of current rapid decline in the distribution and abundance of platypus across the region and predicted further decline with future urbanization and climate change.

3.4.2 Taxa/Species connectivity requirements

Connectivity is fundamentally important because it influences the ability of organisms to move between, disperse to, and colonise different sites—processes that affect population persistence.

In streams, the loss (severe degradation) of a reach results in a local loss as well as losses in the upstream and downstream neighbourhoods of that reach. In Zonation, the severity of upstream and downstream losses can be specified separately for each species. This capability allows us to accommodate the ecological and life-history requirements of different species—from species that have relatively small home ranges and only need to move a few hundred metres upstream and downstream, to diadromous species that need access to both freshwater and marine habitats at different stages of their life-cycle.

The first requirement for representing stream connectivity in a Zonation analysis is a 'directed connectivity definitions file' that encodes the directional (upstream-downstream) relationship between reaches in the MW region. A reach can have several upstream connections, but only one downstream connection (see Sect 3.3.3.3 in Moilanen *et al*. 2014 for details).

Following Moilanen *et al*. (2008), we define responses of species connectivity loss using two functions, one each for response to upstream and downstream loss. The overall loss for any species is then calculated as the product of the respective upstream and downstream losses. Please refer to Moilanen *et al*. (2008, 2014) for full details of the relevant equations used for incorporating species-specific connectivity responses into the (marginal loss value calculation used in Zonation's cell removal rule for) quantitative conservation prioritization. We used archetypal neighbourhood loss response functions to represent expected ecological responses to lost connectivity (Figure 7).

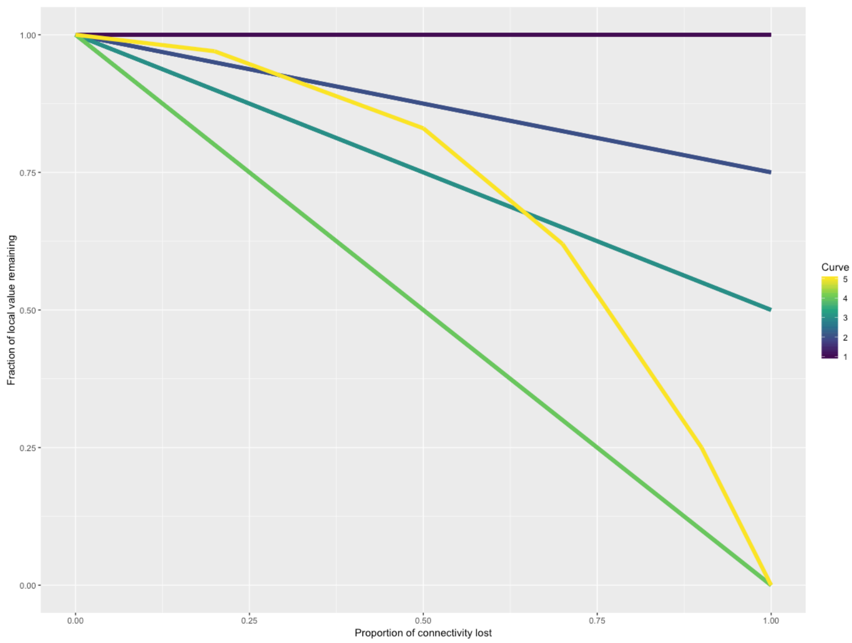


Figure 7. The archetypal neighbourhood loss response functions used in our Zonation set-up showing how the fraction of original local value (y-axis) changes as the proportion of connectivity lost (either upstream or downstream of a reach) increases. Each curve represents a different pattern of response to connectivity loss. Curve 1: No connectivity/neighbourhood loss response; Curve 2: Slight negative linear connectivity loss response; Curve 3: Moderate negative linear connectivity loss response; Curve 4: Strong negative linear connectivity loss response; Curve 5: Negative non-linear connectivity loss response; slight to begin with, then stronger as connectivity/neighbourhood habitat loss advances.

The designation of upstream and downstream connectivity/neighbourhood loss response for macroinvertebrates, native fish and platypus was based on expert knowledge and judgement of taxa requirements (Chris Walsh for macroinvertebrates; Rhys Coleman for fish and platypus).

In the case of macroinvertebrates, connectivity of upstream habitat was what was considered to be important. Archetypal loss response functions (Fig. 6) were assigned to connectivity loss in the upstream and downstream direction according to macroinvertebrate sensitivity group as shown in Table 12.

Table 12 Archetypal connectivity loss curves (Figure 7) in the upstream and downstream direction for each macroinvertebrate sensitivity group.

Sensitivity group	Total number of families	Upstream loss curve	Downstream loss curve
A	23	4	1
B	16	3	1
C	4	2	1
D	9	2	1

With respect to native fish species, the importance of connectivity of upstream and downstream habitats varied depending on the life-history requirements of each species. For instance, diadromous species in particular, are expected to have a strong negative response to the loss of downstream habitat connectivity, while species that have relatively small or localized home ranges are expected to be less affected by loss of upstream and downstream connectivity (Table 13).

Table 13 Archetypal connectivity loss curves (Figure 7) in the upstream and downstream direction for each native fish species.

Species	Upstream loss curve	Downstream loss curve	Comment
Short-finned eel (ANGUAUST)	2	4	Diadromous. Needs to be able move upstream-downstream to access different habitats, including marine environments.
River blackfish (GADOMARM)	2	2	Non-migratory. Small home range, territorial and needs upstream-downstream access for dispersal
Broad-finned galaxias (GALABREV)	3	4	Diadromous. Needs to be able move upstream-downstream to access different habitats, including marine environments.
Common galaxias (GALAMACU)	2	3	Diadromous. Needs to be able move upstream-downstream to access different habitats, including marine environments.
Ornate galaxias (GALAORNA)	4	2	Tends to occupy headwaters, so upstream habitats very important
Spotted galaxias (GALATRUT)	2	3	Diadromous. Needs to be able move upstream-downstream to access different habitats, including marine environments.
Pouched lamprey & Short-headed lamprey (LAMPREYS)	4	4	Diadromous; Needs to be able move upstream-downstream to access different habitats , including marine environments.
Southern pygmy perch (NANNAUST)	2	2	Non-migratory. Needs some upstream-downstream access to access different habitats

Yarra pygmy perch (NANNOBSC)	2	2	Non-migratory. Needs some upstream-downstream access to access different habitats
Flathead gudgeon (PHILGRAN)	2	2	Non-migratory. Needs some upstream-downstream access to access different habitats
Australian grayling (PROTMARA)	3	4	Diadromous; spawns in freshwater reaches of coastal rivers, larvae washed out to sea, juveniles return to freshwater for remainder of life cycle
Tupong (PSEUURVI)	4	4	Diadromous. Needs to be able move upstream-downstream to access different habitats, including marine environments.
Australian smelt (RETRSEMO)	2	2	Non-migratory. Needs some upstream-downstream access to access different habitats

Platypus need to be able to move upstream and downstream to access feeding areas. Platypus were assigned an upstream loss curve of 2 and a downstream loss curve of 3 (Figure 7). The rationale was that loss of downstream connectivity has a greater negative impact because waterways are larger in the downstream direction, and therefore loss of downstream connectivity implies a greater loss of habitat resources, including low flow refuges.

3.4.3 Zonation's 'condition-retention analysis with management gain mode' & choice of 'tuning factor' for relative emphasis between representation (CURR), condition (BAUF) & management gain via action

The final Zonation input we have to consider is what would be an appropriate balance between *representation*, expected *condition* under BAUF, and *management gain* as a result of action. Our approach closely follows that described in Moilanen *et al*. (2011, 2014). Specifically, we use a Zonation set-up referred to in Zonation terminology as 'condition-retention analysis with management gain mode' (Moilanen *et al*. 2014, pp 69-72).

In Zonation terminology, *representation* refers to the starting state of instream biodiversity patterns as represented by HSM predictions (for the 67 taxa) under CURR conditions. Using our HSMs we create 67 CURR (raster) input layers for use in Zonation. BAUF conditions will modify habitat suitability across the MW region for our 67 taxa. In Zonation terminology, we use our BAUF HSM predictions to create *condition-transformed* layers for each taxa *j* for use in Zonation:

$$IF\left(BAUFHabSuit_j - CURRHabSuit_j \geq 0\right),$$

$$COND_j = 1$$

$$ELSECOND_j = BAUFHabSuit_j / CURRHabSuit_j$$

And we create the *management gain* layers for each taxa *j* for use in Zonation:

$$IF(ACTIONHabSuit_j - BAUFHabSuit_j > 0),$$
$$MgtGain_j = ACTIONHabSuit_j / BAUFHabSuit_j$$
$$ELSE MgtGain_j = 1$$

In Zonation's condition-retention analysis with management gain mode, a tuning parameter, β, controls how much weight is given to *representation* versus *management gain*. If we wish to emphasize the expected gains as a result of management actions, we can weight that more strongly, by assigning a higher value to β. We would then expect the Zonation solution to spatially prioritise reaches where biota benefit proportionally most from management action. There is a risk however, with strongly weighting expected gains from management action, in that the gains may not materialise. This could be due to a number of reasons such as implementation failure or failure of critical assumptions underpinning actions and on-ground outcomes under particular conditions. For instance, riparian revegetation could fail to establish, or could be compromised by channel erosion, floods or fire; in certain locations, landscape constraints might mean that the management of stormwater runoff from existing impervious cover cannot meet the standards needed for effective stream protection.

As with the choice of taxa/species weights, there is no 'correct' answer or definitive method for determining what the β value should be. Rather, we seek a β value that reflects a sensible balance between *representation*, expected *condition* under BAUF, and *management gain* as a result of action. We experimented with a range of β values (5, 10 and 20) for our particular analysis set-up, in each case producing mapped prioritisation solutions for discussion and deliberation by the MW HWS leadership team. The higher the value of β, the more strongly the solution emphasised areas of *prospective* management gain (which included a number of currently degraded sites at which good gains from a 'low' starting base were predicted) and the lower the emphasis on existing areas of high instream biodiversity. On balance it was felt that it was important not to excessively downgrade focus and emphasis on existing areas of high biodiversity for the sake of pursuing prospective management gains. Hence, we settled on a β value of 5.

3.5 Zonation Action Prioritisation Solution

Using the various input layers and weight settings as described in Section 3.4, we ran the Zonation condition-retention analysis with management gain mode, and obtained the spatially explicit, continuous rank solution shown in Figure 8. As is evident from figure 8, there are highly ranked reaches in each of the major catchments (though there are comparatively few in the Dandenong catchment).

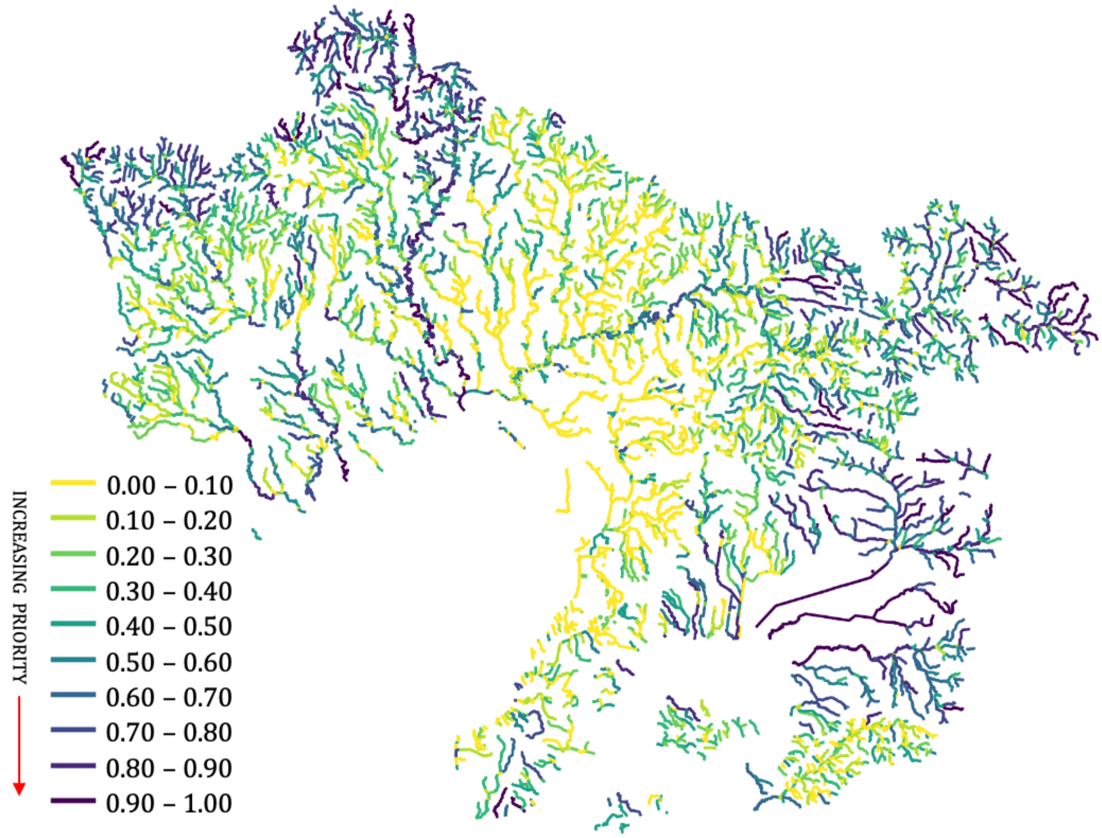
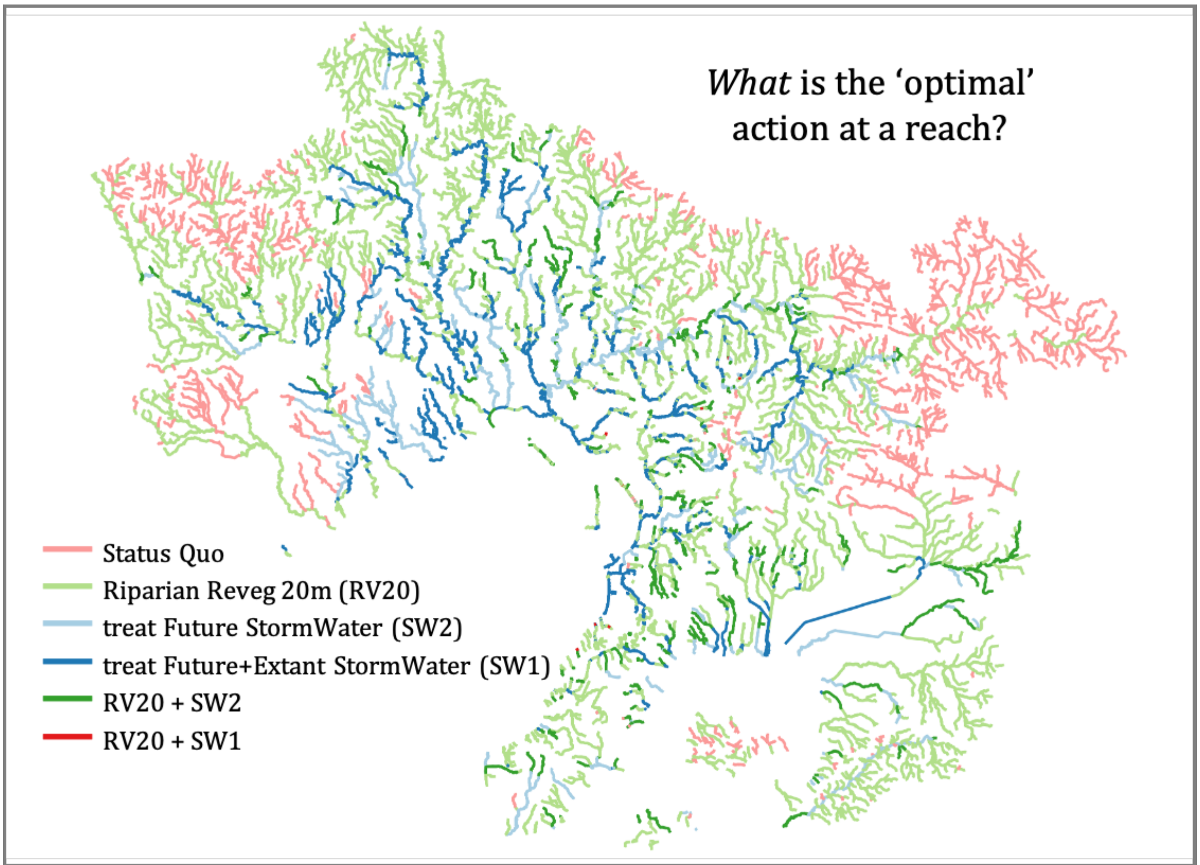


Figure 8. Map of the continuous ranking of spatial priorities (0-1) produced by the Zonation analysis in which the 'optimal' action was 'applied' at each reach in the MW region after identifying the most cost-effective action and including the various customisations.

In Figure 9, we bring together figures 6 and 8 to make the point that they need to be *used in conjunction* to identify for each reach, *what* the 'optimal' (cost-effective) action is (from the set we examined). And *where* across the landscape of greater Melbourne, action should first be focused.



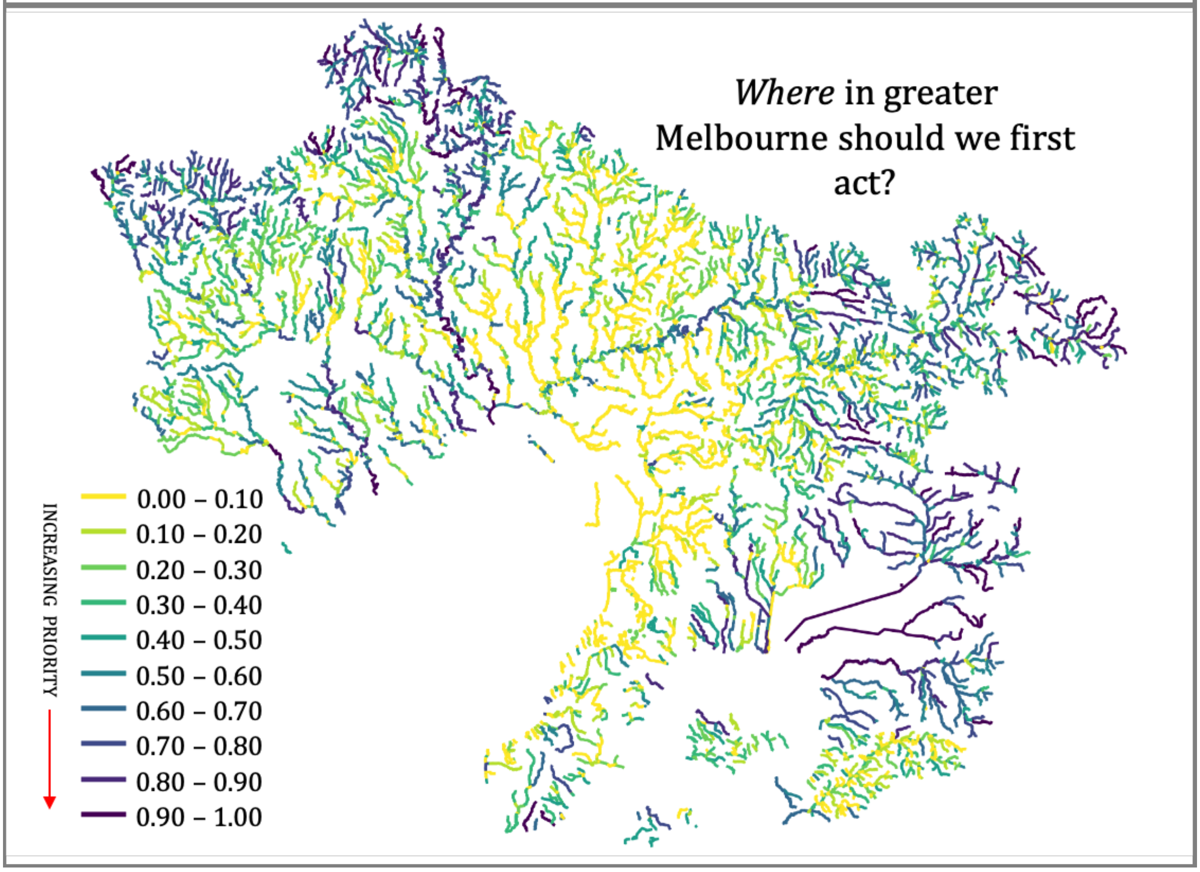


Figure 9 Juxtaposition of maps showing *what* the 'optimal' (most cost-effective) action is from the perspective of instream biodiversity (top), and *where* in greater Melbourne action should be first be undertaken as determined by our Zonation analysis (bottom).

The top-ranked reaches in Figure 8 represent the recommended priorities for implementing actions based on the Zonation analysis. However, this was not the endpoint of the action prioritization analysis and a process of 'sense-checking' was instituted. This was because there was additional contextual information, not included in the Zonation analysis, that was important to account for. Sense-checking involved reviewing the mapped spatial priorities with the following questions in mind:

i) is the reach dominated by a highly human-modified channel? e.g. a completely concrete-lined channel or underground pipe
ii) is the target action realistic/feasible? For reaches where RV20 is disallowed because of levee or EVC constraints, the only other permissible actions are SW2 and SW1—is the identified cost-effective action at the site actually realistic and/or feasible? Or should it be set to SQ?
iii) is there anything odd or unintuitive about the action and/or priority location?

This manual, qualitative process of sense-checking was carried out by senior analysts in the MW HWS team (Sharyn RossRakesh, Rhys Coleman, Andrew Grant) assisted by internal consultations with MW specialists and regional waterway officers. Findings and feedback from the checks process identified some technical issues which led to fixes, adjustments and re-iteration of the Zonation analysis run. The result shown in Figure 8 is the outcome of multiple rounds of iteration and refinement.

3.5.1 Usage of Zonation Quantitative Action Prioritisation in the Healthy Waterways Strategy 2018

As stated above, the Zonation ranking represented the quantitatively derived action priorities. But it is important to stress that Zonation ranks did ***not*** dictate HWS action planning and targets. Top-ranked reaches were reviewed via the checks process described above and where possible refinements were made and the analysis re-run. Any 'manual over-ride' decisions were also made at this point, justified and documented. For instance, for particular reaches riparian revegetation was disallowed due to risks to levees, leaving SW2/SW1 as the only two other options. But depending on the specific context, they might simply be infeasible (e.g. the amount of impervious area to be treated within the life of the strategy), and the choice might thus be to set the action to 'Status Quo' at those reaches.

After the MW-checks process, the revised list of designated action for each reach was compared against proposed actions captured independently during the community co-design workshops to identify 'matches' (where Zonation analysis priorities aligned with stakeholder priorities) and 'near-misses' (where stakeholder priorities were less highly ranked in comparison to the Zonation analysis process). Where feasible, 'near-miss' stakeholder-proposed actions were adopted into strategy priorities. Quantitative benefits predicted by the resultant collective set of actions then formed the basis of preliminary HWS targets relating to instream biota. Benefits were always estimated at the finest spatial scale used in modeling (i.e. the 8,233 reach-level), and then 'packaged' or aggregated to larger spatial units such as MW subcatchments (formerly called Management Units) for presentation, communication and so on.

Note that the quantitative habitat suitability modelling and action prioritisation described in this document relate only to *instream biota*. Other key values and conditions of importance to the Healthy Waterways Strategy, such as frogs, birds, water quality and environmental flow risks were accounted for in processes described in the 'Healthy Waterways Strategy 2018 Resource Document' (Melbourne Water 2020).

4 Achievements and Plans for Continuous Improvement

We successfully applied a novel and rigorous approach to management-action prioritisation using ecological model predictions, analyses and maps in stakeholder workshops that co-designed priority actions and 50-year targets for Melbourne's Healthy Waterways Strategy 2018.

In co-developing the Healthy Waterways Strategy with communities, MW needed to:

- account for climate and land use changes in strategic planning to optimise stream biodiversity and waterway health
- identify the most cost-effective action for supporting stream biodiversity at any given reach
- strategically prioritise investment in interventions across the region, given current spatial differences in stream biodiversity and expected conditions under climate and land use change

In partnership with the Waterway Ecosystem Research Group (University of Melbourne) and the Centre for Freshwater Ecosystems (La Trobe University), the Melbourne Waterway Research-Practice Partnership (MWRPP) co-developed and applied a suite of interlinked spatial and quantitative tools. Specifically, we

i) developed a GIS stream network, hydrologically-delineated watersheds for each reach, and ecologically-relevant environmental data to enable comprehensive, multiscale characterisation and modelling of stream conditions and biodiversity values across the region
ii) used ~20 years of georeferenced biological data and our environmental stream reach data to develop habitat suitability models (HSMs) for 59 macroinvertebrate families, 13 native fish species and platypus
iii) used the models to make spatially-explicit predictions of current and future habitat suitability across the full stream network, including impacts of climate change and urban growth
iv) used the models for scenario analyses—such as quantitative predictions of the benefits of key management actions, like riparian revegetation, stormwater management and removal of instream fish barriers, in any required combination
v) combined expected benefits of management actions for all modelled animals, along with associated costs, in order to prioritise actions (using the conservation planning software, Zonation)

These new tools provided powerful analytical capacity to explore strategic concerns for long-term planning and to conduct region-wide prioritisation analyses. Outputs of plausible future scenarios and mitigating actions were summarised, mapped and shared with stakeholders to support deliberations that ultimately informed priority actions and target-setting in the Healthy Waterways Strategy 2018. We believe they have proved their utility by enabling and successfully supporting an ambitious process that was more comprehensive, systematic, community-engaged and participatory than ever before.

It is acknowledged that the development of the Zonation action prioritization solution and the iterative expert review and refinement process was carried out under time pressures. This is being addressed by a commitment to, and concrete plans for continuous improvement. For example, a post-project debriefing of science collaborators and multiple MW teams was undertaken in June 2018. It identified a range of potential improvements such as better representation of headwater streams, accounting for highly-modified channels and refined costing of actions. A range of uncertainties that are important to unpack and probe more carefully was also identified. These identified areas for improvement are being actively addressed in multiple ways, such as in research programs, the 'Healthy Waterways Strategy - Monitoring, Evaluation, Reporting and Improvement (MERI) Framework' (Melbourne Water 2019), and the 'Monitoring and Evaluation Plans (MEPs) for Rivers, Wetlands and Estuaries' (Melbourne Water, *in prep*).

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Appendix A

Estimated costs of removing instream fish barriers by type (David Fisher, Melbourne Water)

Barrier type	Typical fishway type	Estimated capital cost for a fishway of height <1 m (Category 1)	1-2 m (Category 2)	2-3 m (Category 3)
Artificial rock		10,000	20,000	30,000
Concrete channel		80,000	150,000	220,000
Crossing	Culverts	30,000	45,000	
Dam	Cone Fishway	400,000	641,740	1,000,000
Drop structure	Rock Ramp	61,300	146,483	171,033
Estuary mouth	Dredging?	100,000	120,000	140,000
Farm dam	Baffle/Cone Fishway	200,000	300,000	500,000
Gauging station	Rock Ramp	61,300	146,483	171,033
Gauging weir	Rock Ramp	61,300	146,483	171,033
Natural rock	NA	10,000	20,000	30,000
Pipe	Baffle	30,000	45,000	
Retarding basin	Baffle	80,000	150,000	220,000
Stormwater wetland	Cone Fishway	400,000	641,740	1,000,000
Weir	Rock Ramp	61,300	146,483	171,033

Notes on costs for maintenance of fishways (Leigh Smith, Melbourne Water):

1. One-off Condition Assessment (detailed): $500 per asset (usually only completed once every few years)
2. Periodic (currently set at monthly for fishways) preventative maintenance: $500 per asset per visit ($6000 per year per asset)
3. Corrective/breakdown maintenance (cost obviously varies) however, a small allowance of $10,000 per asset has been made. We have assumed that as a minimum, 5% of the entire asset portfolio (60+ fishways) would require CM/BM in any one year = 3 assets.
4. If major repairs are required, this would most likely trigger a capital renewal project.