Re-running habitat suitability models with updated climate-impacted projections and other scenarios of interest

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Acknowledgment of Country

The University of Melbourne acknowledges the Traditional Owners of the unceded land on which we work, learn and live: the Wurundjeri Woi Wurrung and Bunurong peoples (Burnley, Parkville, Southbank and Werribee campuses), the Yorta Yorta Nation (Dookie and Shepparton campuses), and the Dja Dja Wurrung people (Creswick campus).

The University also acknowledges and is grateful to the Traditional Owners, Elders and Knowledge Holders of all Indigenous nations and clans who have been instrumental in our reconciliation journey.

We recognise the unique place held by Aboriginal and Torres Strait Islander peoples as the original owners and custodians of the lands and waterways across the Australian continent, with histories of continuous connection dating back more than 60,000 years. We also acknowledge their enduring cultural practices of caring for Country.

We pay respect to Elders past and present and acknowledge the importance of Indigenous knowledge in the Academy. As a community of researchers, teachers, professional staff and students we are privileged to work and learn every day with Indigenous colleagues and partners.

1 Introduction/Background

As part of the Healthy Waterway Strategy development process we developed habitat suitability models (HSMs) for stream macroinvertebrates, native fish and platypus. The input data, model development process and details of how the models were used for action prioritisation are described in Chee *et al*. (2020). Habitat Suitability Models (HSMs) analyse the relationships between the environmental characteristics at sites where a family/species is detected (and also at sites where the family/species is *not* detected) to develop a quantitative model that predicts how suitable any given stream reach is for the family/species. Higher habitat suitability implies higher probability of occurrence. However, it is important to note that while habitat may be suitable, there are a range of reasons for why animals may not occur at or use that habitat, such as fragmentation and relative isolation of suitable habitat, poor dispersal capability or barriers to dispersal and movement.

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. 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 set of environmental predictors therefore included variables such as catchment area, mean annual air temperature, mean annual runoff depth (an indicator of water availability 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) (Table 1). 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 1).

We used our 67 instream HSMs to estimate biodiversity values at 8,000+ stream reaches across the Port Philip and Westernport (PPWP) region, make predictions of how those values are likely to change under projected future scenarios of urban growth and climate change, and quantify expected benefits of specific management actions or combinations of actions (Chee *et al*. 2020). By considering expected benefit (computed for all modelled taxa) along with reach-specific costs associated with candidate actions, we identified the most cost-effective management action at any given reach. We then analysed this map of cost-effective actions with spatial conservation prioritisation software (Zonation) to rank all 8,000+ reaches showing where we should optimally act first to protect and improve stream biodiversity (Chee *et al*. 2020).

Table 1. Definition/description and units of environmental variables used in the development of the macroinvertebrate, fish, and platypus habitat suitability models. (Adapted from Chee et al. 2020).

	Environmental Predictor	Definition/Description	Units	Macro-invertebrates	Fish	Platypus
1	CatIgneous	Percentage of catchment overlying igneous rocks (e.g. granites, basalts, grandiorite, rhyolite and gabbro).	%	✓	✓	✓
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	✓	✓	✓
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 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	NA	✓	✓	✓
5	Instream Full Barriers (at multiple timepoints)	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	--	✓	--
6	Instream Part Barriers (at multiple timepoints)	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	NA		✓	

		to features, generally <5 m in height that have the potential to permit fish passage on occasion, such as during high flow events.				
7	Mean Annual Air Temperature [mnAnnAirTm_deg]	Average annual mean (monthly) air temperature for the reach and immediate environs.	^{0}C	✓	✓	✓
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	✓	✓	
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 $\leq$ 10m from the stream, and exponentially weighted upstream with a half-decay distance of 1000 m. Range = 0-1.	NA			✓
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	✓	✓	--
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 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.	NA	--	--	✓
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	✓	--	--

2 Projections for exploring climate warming and drying

Assessing the likely impacts of climate change on aquatic biota in rivers and wetlands is important from a comprehensive whole-of-system strategic planning perspective. The instream HSMs—developed as part of the Healthy Waterway Strategy 2018—predicted changes in the habitat suitability of instream biota in the face of combined climatic warming and drying. However, the means by which we represented warming and drying for scenario predictions did not consider a range of plausible future climates projected by various Global Climatic Models or more recently developed climate projections. An important question to answer is whether that approach is adequate and/or sufficiently robust. For instance, do we get very different predictions using more sophisticated and detailed climate change data and/or methods of modelling drying patterns and intensity? And importantly, are our priority actions robust under a range of plausible climate futures?

Scenario analyses of in-stream HSMs used to inform HWS 2018 were undertaken in late-2017 and climate change impacts (of warming and drying) were expressed using simple methods. Warming was represented by a 1.5°C increase in mean annual temperature from 2016 values, capped at a maximum of 15.8°C. 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). These options were chosen to be broadly consistent with DELWP (2016), and still largely *within* the 'experience' of the training data used to develop our HSMs.

Australia's climate is, however, changing with temperatures increasing over land and sea, precipitation patterns shifting, and sea levels rising as described in the State of the Climate 2020 (CSIRO and BoM, 2020) and State of the Climate 2022 (CSIRO and BoM, 2022). On average, Australia has warmed by 1.47 ± 0.24 °C since national records began in 1910 (CSIRO and BoM 2022) and streamflow has changed across the country, broadly increasing in the north and decreasing in the south (Srikanthan et al. 2022). In south-east Australia, precipitation started to decline around 1990, and the average April to October precipitation from 2000 to 2021 is ~10% less than that of the 1900-1999 period (CSIRO and BoM, 2022). Along with this observed decline in precipitation, streamflow has declined substantially in both the south-west and south-east, where changes in streamflow are typically disproportionally larger than changes in precipitation (Chiew, 2006; Wasko et al., 2021).

In 2019, updated projections for temperature became available from CSIRO and in 2022, updated projections of runoff became available from the Bureau of Meteorology. We describe these datasets below.

2.1 Air temperature

There are multiple sources of climate change projection data. However, taking into account lessons learnt in 'Assessing Climate Change Projections for Catchment Water Quality and Ecosystem Modelling of Port Phillip and Western Port Catchments' (Cetin *et al*. 2021), we have decided to update our representation of warming using application-ready mean annual temperature projections from CSIRO (also known as Victorian Climate Projections 2019 or VCP19 projections). This consists of a dynamically downscaled set of simulations based on CSIRO's Conformal Cubic Atmospheric Model (CCAM). For these simulations, six global climate models (GCMs) recommended by Climate Change in Australia (CCIA) as representative of the range of projected changes in temperature and rainfall as well as other climate variables were downscaled to 5 km resolution over Victoria.

This subset of six GCMs (Table 2) comes from a larger pool of >40 candidate GCMs. GCMs typically have a grid resolution of 100-200+ km^2. This means mountains, coastlines, urban areas and certain atmospheric phenomena (e.g. storms) may not be well resolved. In general, downscaling attempts to interpret regional changes in climate that are poorly resolved in the GCM simulations (see e.g. Figure 1). (Downscaling, bias-correction and output evaluation are large topics and the reader is referred to Clarke et al. 2019 and references therein.)

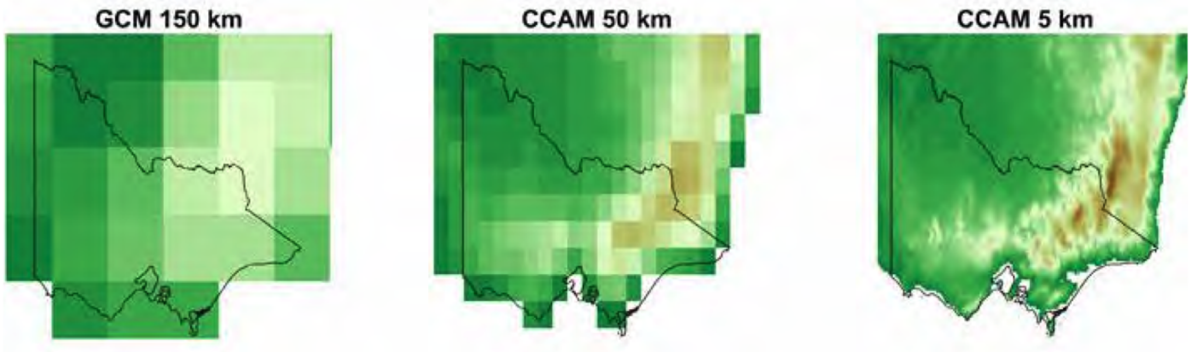


Figure 1. Topography of southeast Australia in a typical GCM resolution (~150 km), intermediate downscaling using CCAM (50 km grid) and high-resolution downscaling using CCAM (5 km grid). Height scale extends to 2000 m above sea level. Source (figure and caption): Clarke et al. (2019).

The six models were chosen

- to represent a range of climate impacts that was consistent with the range of projections made by the CMIP5 (Coupled Model Intercomparison Project Phase 5) ensemble of GCMs, including both drier and wetter future climates
- as having realistic representations of large-scale drivers of the Australian climate (e.g. ENSO, monsoons, etc.)

According to Clarke *et al*. (2019), the six models downscaled can be considered a combination of higher quality GCMs as well as a sufficient cross-section to represent the broad range of GCM projections for Australia. Table 2 lists details of VCP19's six GCM host models and their relevance for VCP19 projections.

Table 2. VCP19's six GCM host models, their institute and country of origin, spatial resolution and relevance for VCP19 projections. (Compiled from: https://www.climatechangeinaustralia.gov.au/en/overview/methodology/list-models/ and Clarke et al. (2019)).

CMIP5 Model ID	Institute & Country of Origin	Atmosphere resolution at equator Latitude (km)	Atmosphere resolution at equator Longitude (km)	Relevance for VCP19
ACCESS-1.0	CSIRO-BoM, Australia	210	130	Maximum consensus for many regions. A hot, dry model in the south of Victoria.

				Representative of the consensus of GCM projections in northern Victoria
CNRM-CM5	CNRM-CERFACS, France	155	155	Hot/wet end of range in Southern Australia. Representative of the consensus of GCM projections over Victoria, particularly in the north.
GFDL-ESM2M	NOAA, GFDL, USA	275	220	Hotter and drier model for many clusters. Often, a hot, dry model for Victoria.
HadGEM2-CC	MOHC, UK	210	130	Maximum consensus for many regions. Often, a hot, dry model for Victoria.
MIROC5	JAMSTEC, Japan	155	155	Low warming, wetter model. Often a low warming, wet model for Australia and Victoria.
NorESM1-M	NCC, Norway	120	120	Low warming, wettest representative model. Often a low warming, wet model for Victoria, especially in the south.

Due to limitations on modern supercomputing resources, VCP19 modelling focused on a medium (RCP4.5) and a high (RCP8.5) emissions scenario out of a possible set of RCP2.6, RCP4.5, RCP6 and RCP8.5. The number after RCP (Representative Concentration Pathway) indicates the increased rate of energy (e.g. stored as heat) trapped in the Earth system by the increased concentrations of greenhouse gases. According to Clarke et al. (2019), RCP2.6 is the greenhouse gas emission scenario used by the GCM development teams that is the closest to that required to meet the Paris Agreement targets.

The climate of Victoria has been getting warmer, with the mean annual temperature rising by over 1°C between 1910 and 2018 (Clarke et al. 2018). Beyond the next couple of decades, the projected change in temperature depends strongly on the greenhouse gas emissions pathway that the world follows. Here we focus on 2070 as the time point of interest as that roughly coincides with the 50-year horizon of HWS 2018.

All climate models and downscaling techniques include different assumptions in their design, no single model should be considered a definitive, or even a most probable, likely or plausible prediction of the future climate. It is important to consider and plan for the range of projections.

The application-ready mean annual temperature CC projections for 2070 were downloaded, processed from netCDF to R and GIS readable grid format, interpolated to ensure coverage of the entire PPWP region and calculated for every stream reach (subwatershed) in the stream network used for HWS 2018. The VCP19 mean annual temperature CC projection data for 2070 are 30-year aggregates centred on 2070 (to adequately reflect climate variability). Figures 2 and 3 show the spatial distribution of gridded mean annual temperature projections across the PPWP region for each of the six VCP19 models at 2070 under the moderate and the high emission pathways, respectively.

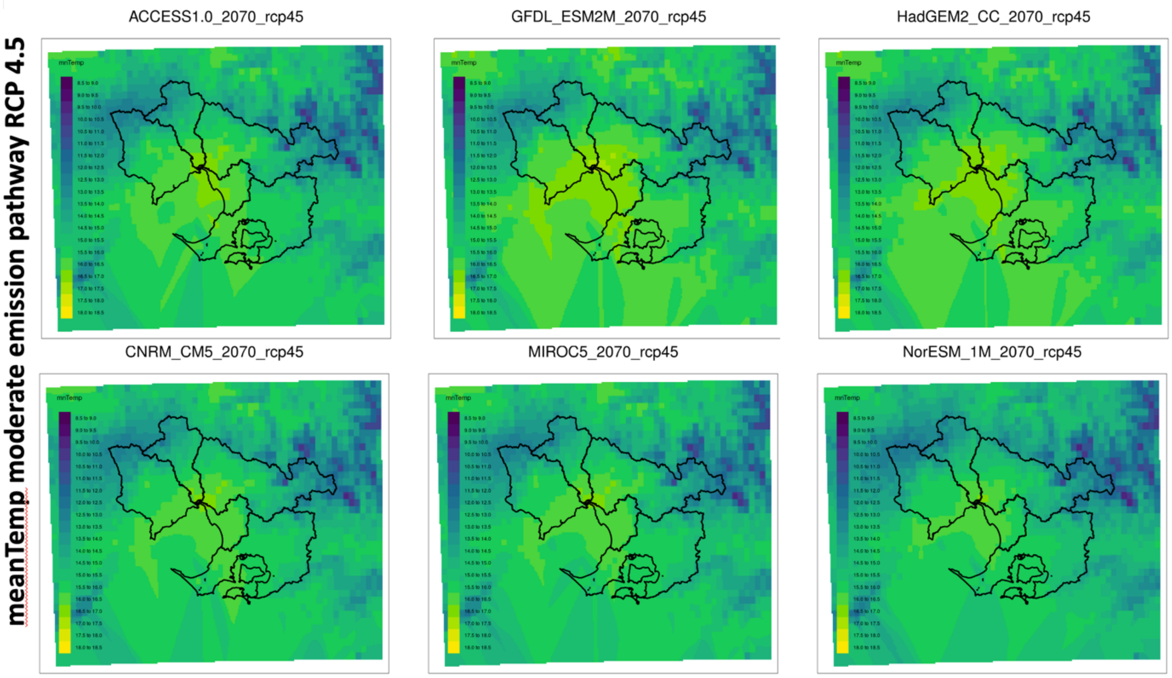


Figure 2. Gridded projections (5 km by 5km) of mean annual temperature across the PPWP region, for the six VCP19 models at 2070, given the moderate emission pathway scenario represented by RCP 4.5. Darker blues denote lower temperatures and lighter colours denote warmer temperatures.

The most pronounced warming is expected to occur around the areas with greatest urban development. This is particularly noticeable in the high emission scenario pathway (Figure 3). For this high emission scenario of RCP 8.5, the HadGEM2_CC model seems to produce the warmest mean annual temperature projections for the PPWP region.

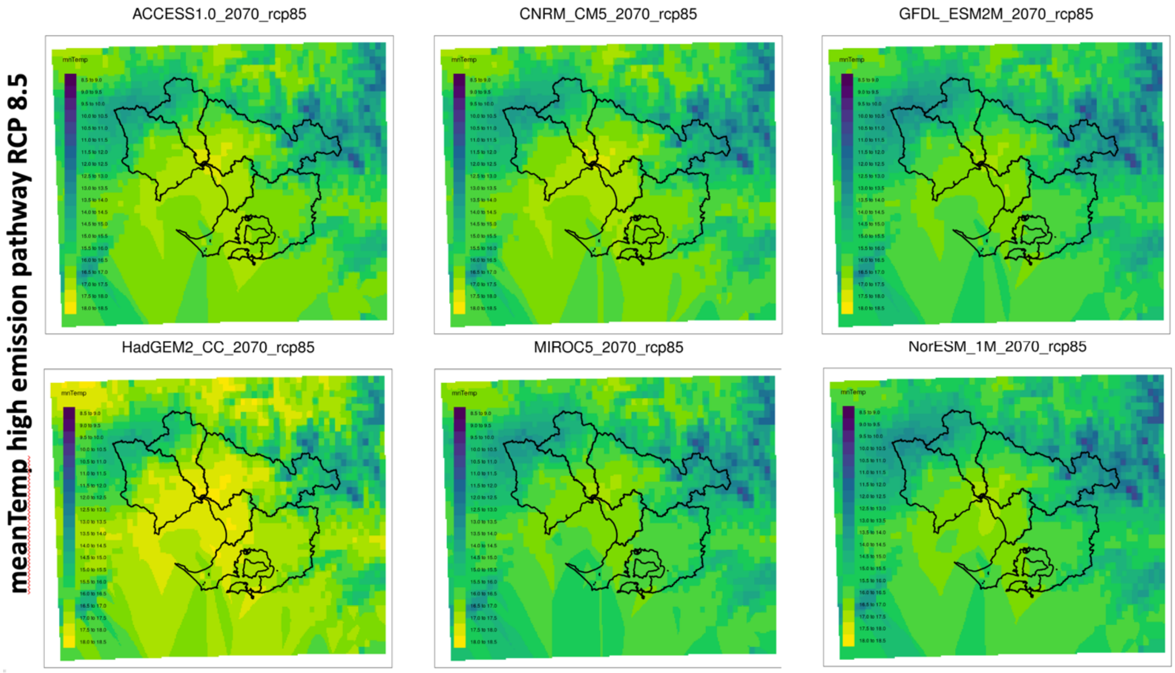


Figure 3. Gridded projections (5km by 5km) of mean annual temperature across the PPWP region, for the six VCP19 models at 2070, given the high emission pathway scenario represented by RCP 8.5. Darker blues denote lower temperatures and lighter colours denote warmer temperatures.

Figure 4 summarises the various mean annual temperature projections of interest as violin plots that show the entire distribution of data (for the PPWP region) across the mean annual temperature range. Under the moderate emission pathway RCP 4.5, GFDL_ESM2M and HadGEM2_CC predicted higher temperatures at 2070 than the other four host models, whilst NorESM_1M predicted the coolest set of temperatures (Figure 4). For the high emission pathway RCP 8.5, HadGEM2_CC and ACCESS1.0 predicted higher temperatures than the other four host models. For both emission scenarios RCP 4.5 and RCP 8.5 though, all six VCP19 models predict warmer temperatures than 'mnAnnAirTm_Warmer' that was used for modelling climate warming impact for HWS 2018 (Figure 4).

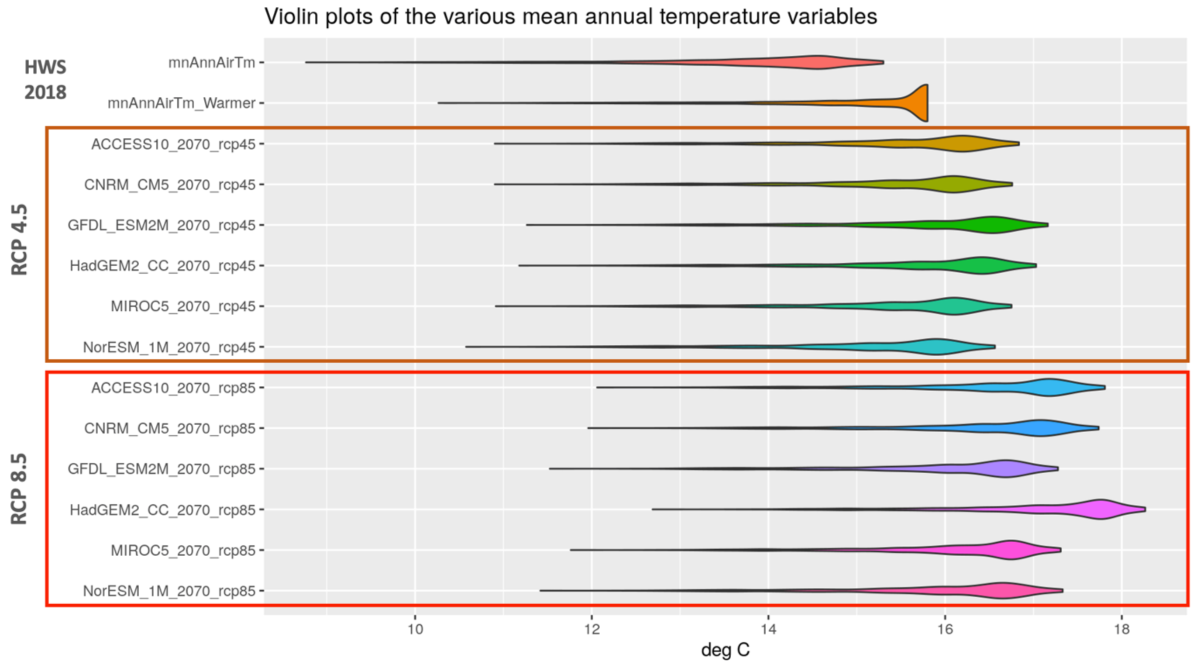


Figure 4. Violin plots of the various mean annual temperature projections of interest across the PPWP region. The top two, mnAnnAirTm and mnAnnAirTm_Warmer, are the mean temperature variables used in our HSMs to represent CURR (current, nominally ~2016) and warmer business-as-usual-future (BAUF, circa 2070) conditions respectively, in the development process of the HWS 2018. The brown rectangle groups projections from the six VCP19 models, given a moderate emission pathway of RCP 4.5. The red rectangle groups projections from the six VCP19 models, given a high emission pathway of RCP 8.5.

In Figure 5, we summarise how much warmer VCP19 model projections for RCP 4.5 and RCP 8.5 are in violin plots of the difference between each VCP19 model-emission scenario and the HWS 2018 'mnAnnAirTm_Warmer' variable. As noted above, for the bulk of projections across the region all six VCP19 models project warmer temperatures than 'mnAnnAirTm_Warmer' and under the high emission pathway, median projected warming ranges from 0.84 °C to 1.96 °C above 'mnAnnAirTm_Warmer'.

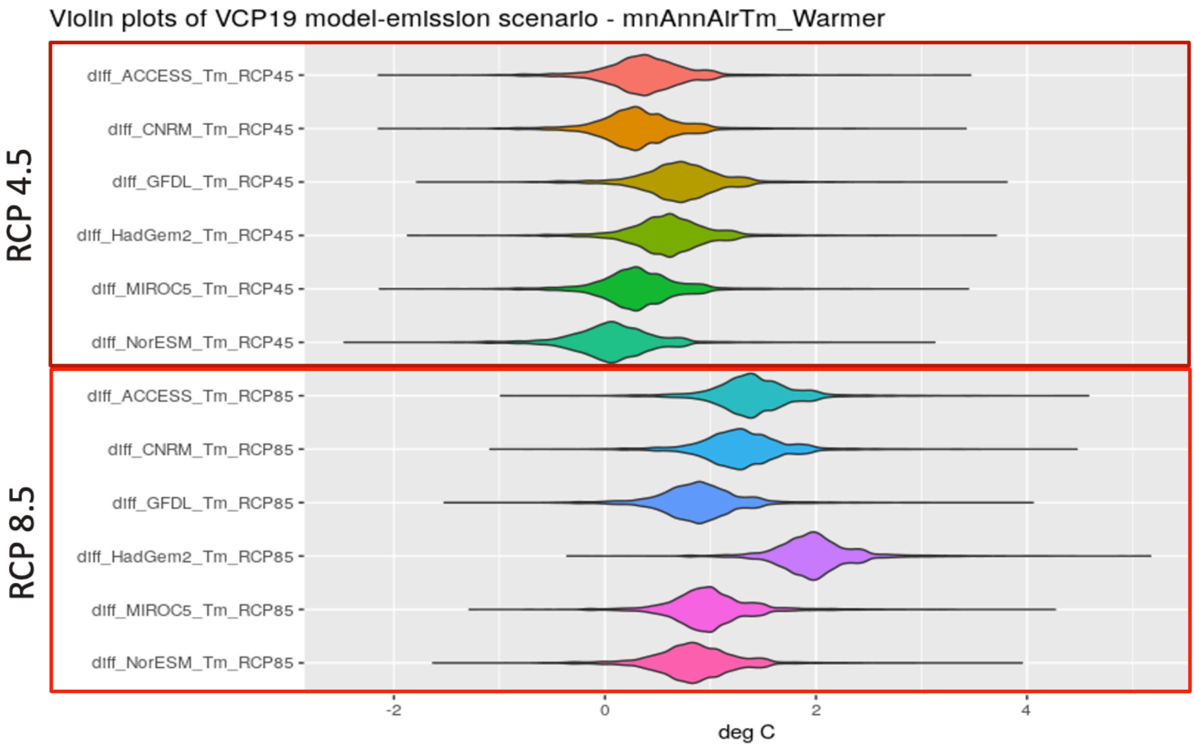


Figure 5. Violin plots of the difference between each VCP19 model-emission scenario and the HWS 2018 'mnAnnAirTm_Warmer' variable across the PPWP region. The brown rectangle groups projections from the six VCP19 models, given a moderate emission pathway of RCP 4.5. The red rectangle groups projections from the six VCP19 models, given a high emission pathway of RCP 8.5.

To see what this looks like spatially across the PPWP region, Figure 6 shows the 'difference' maps of how temperature projections from each of the six VCP19 models differs from 'mnAnnAirTm_Warmer' under the moderate emission pathway RCP 4.5. On the diverging colour scale, darker reds indicate temperatures higher than 'mnAnnAirTm_Warmer', white indicates little temperature difference, and blue indicates temperatures lower than 'mnAnnAirTm_Warmer'. For all six VCP19 models, temperature in the inner urban areas of Melbourne are projected to be higher than 'mnAnnAirTm_Warmer'. In the upper Yarra catchment, there are distinct areas that are projected to be warmer and cooler than 'mnAnnAirTm_Warmer' across all six VCP19 models (Figure 6).

The 'difference' maps under high emission pathway RCP 8.5 show much more pronounced projected warming relative to 'mnAnnAirTm_Warmer' with few patches showing white or light blue across the region (Figure 7).

For subsequent scenarios of interest in this report, we used ACCESS1.0 RCP 4.5 and HadGEM2_CC RCP 8.5 (Table 2) to represent "book-end" mean annual air temperature inputs for HSM predictions.

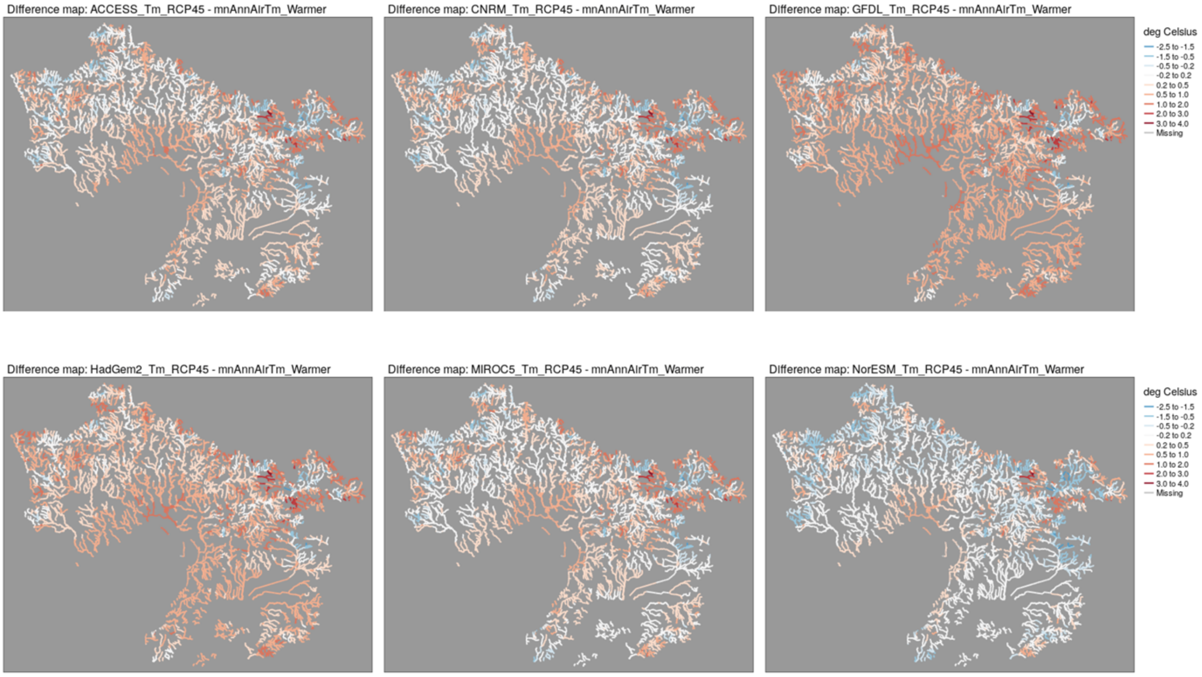


Figure 6. 'Difference' maps showing where temperatures projected by each of the six VCP19 models differs from that of 'mnAnnAirTm_Warmer' under the moderate emission pathway RCP 4.5. Diverging colour scale where darker reds indicate temperatures that are much warmer than 'mnAnnAirtm_Warmer', white indicates little temperature difference and deeper blues indicate temperatures much cooler than 'mnAnnAirTm_Warmer'.

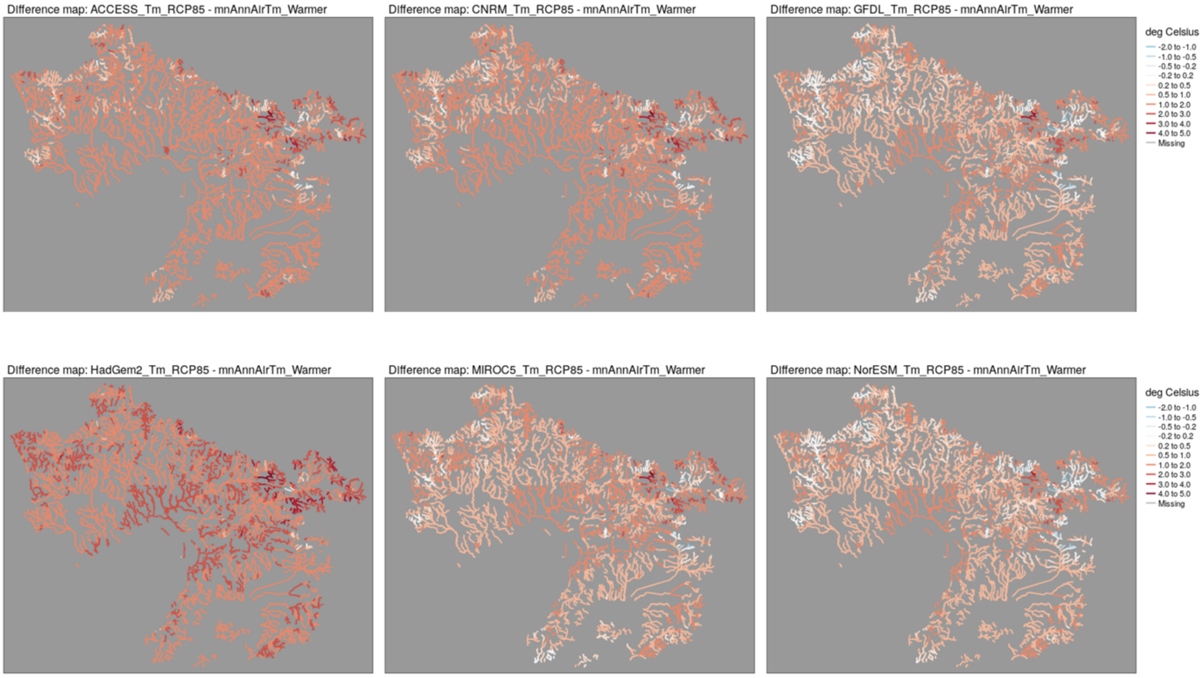


Figure 7. 'Difference' maps showing where temperatures projected by each of the six VCP19 models differs from that of 'mnAnnAirTm_Warmer' under the high emission pathway RCP 8.5. Diverging colour scale where darker reds indicate temperatures that are much warmer than 'mnAnnAirtm_Warmer', white indicates little temperature difference and deeper blues indicate temperatures much cooler than 'mnAnnAirTm_Warmer'.

2.2 Runoff depth

In 2022, climate-impacted runoff projections driven by the Australian Water Resource Assessment Landscape (AWRA-L v6) model (Frost *et al*. 2018) using the CSIRO application-ready climate data became available from the Bureau of Meteorology hydrological projections service, Australian Water Outlook.

The AWRA-L model is a daily timestep, gridded, spatially-distributed water balance model (Figure 8). It simulates the flow of water through the landscape with precipitation entering the grid cell, interception by vegetation, infiltration, movement and storage in various soil layer moisture stores, and movement out of the grid cell as evapotranspiration, runoff or deep drainage to groundwater (Figure 9).

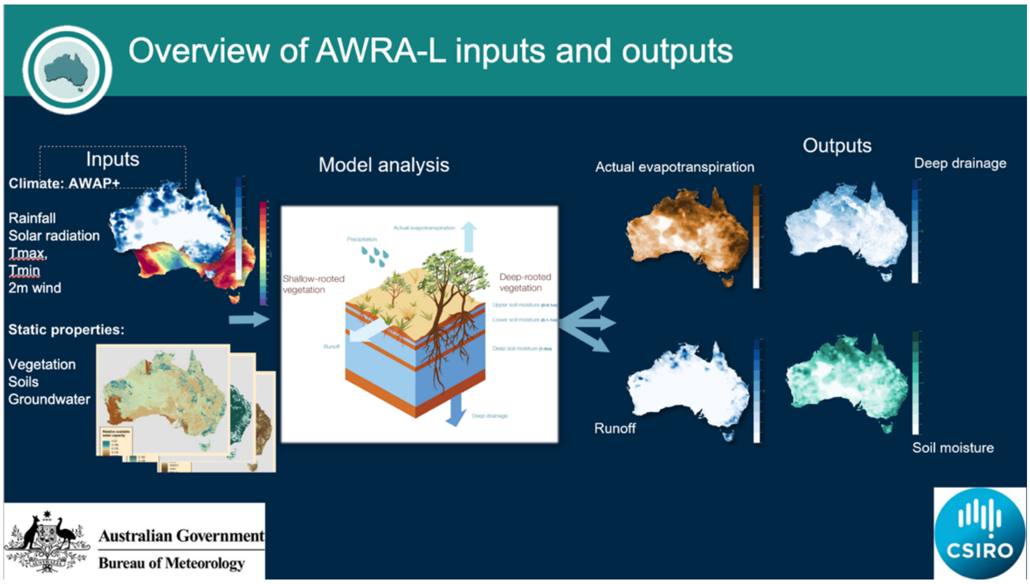


Figure 8. Visual overview of the Australian Water Resource Assessment Landscape (AWRA-L v6) model and its inputs and outputs.

The AWRA-L model is calibrated continentally to simulate hydrology over a range of climate, geological and vegetation conditions, while simultaneously providing realistic simulations of soil moisture and evapotranspiration (Frost et al. 2018; Srikanthan et al. 2022).

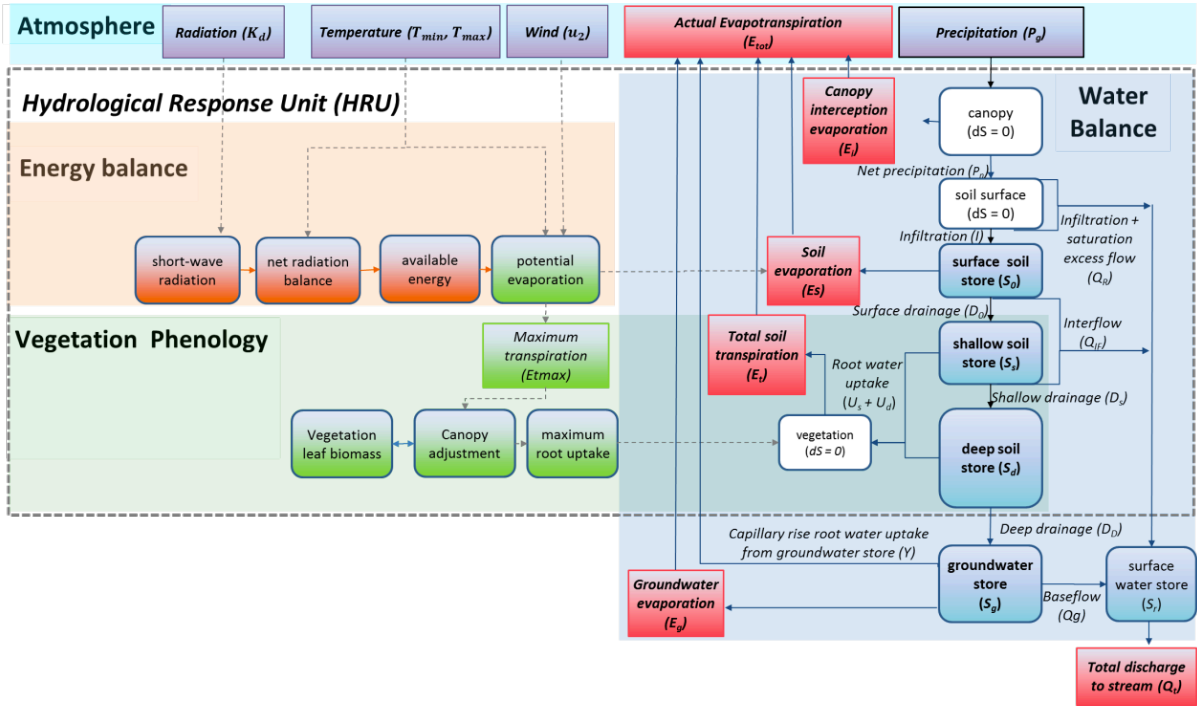


Figure 9. Visual summary of AWRA-L's conceptual structure. Purple denotes climate inputs. Blue rounded boxes denote water stores. Red boxes denote water flux outputs. Orange-brown rounded boxes denote energy balance. Green rounded boxes indicate vegetation processes. Dotted line indicates hydrological response unit processes. Source: Frost et al. (2018).

To adequately simulate the impacts of climate change on hydrological fields, the AWRA-L model is forced by an ensemble of climate scenarios, which is a combination of RCPs, GCMs, downscaling and bias-correction approaches (Figure 10, Srikanthan et al. 2022). The resulting impacts of climate change are analysed together with expert interpretation of the methodologies used along the modelling chain to provide the key messages and reports related to future changes of critical water balance components (Srikanthan et al. 2022).

In addition to the two criteria used to select a subset of GCMs for VCP19 described above, two additional criteria were required to select GCMs for BoM's hydrological projections. Namely, the GCMs had to (Srikanthan et al. 2022):

- model key cloud features known to be important for the Southern Hemisphere
- have the following required data fields made available by the modelling centre that produced them: near-surface air temperature, wind, precipitation and solar radiation

Of the six VCP19 models, only four (ACCESS1.0, CNRM-CM5, GFDL-ESM2M and MIROC5) satisfied the four criteria and had the full complement of data outputs required to drive AWRA-L (Figure 10).

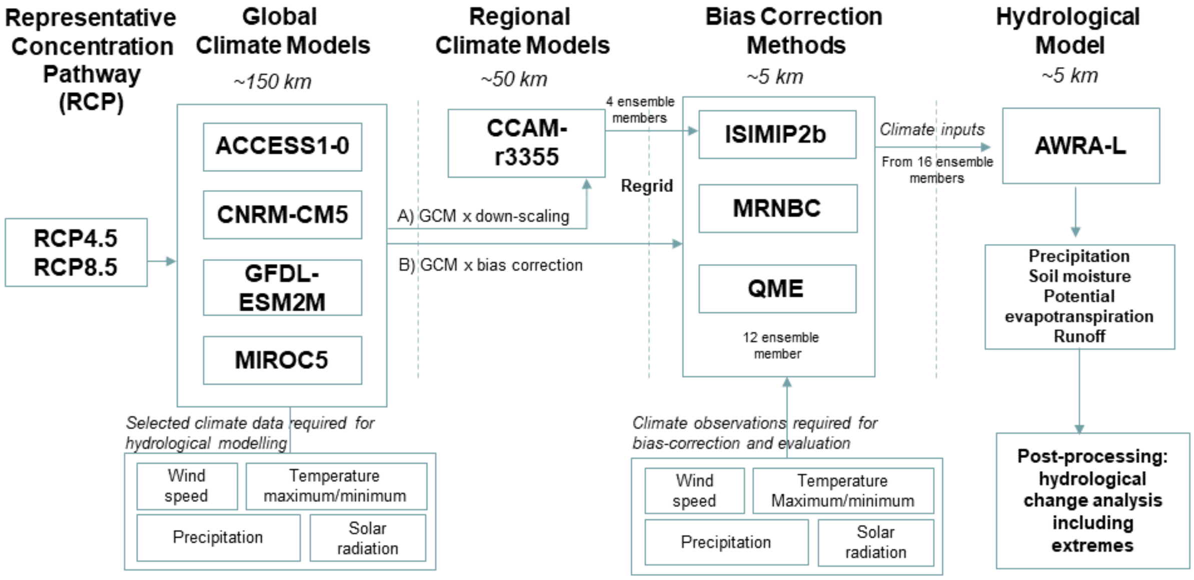


Figure 10. Schematic of the Bureau of Meteorology's climate-change impacted hydrological projections processing and modelling workflow. Source: Srikanthan et al. (2022).

We acquired the historical and climate-impacted projection gridded runoff time-series data, processed it from netCDF to R and GIS readable grid format, interpolated to ensure coverage of the entire PPWP region, and derived climate-impacted runoff projections for 2070 for every stream reach (subwatershed) in the stream network used for HWS 2018.

The distribution of four mean annual runoff variables of interest for this report are shown in Figure 11. The frequency distribution in the 0-50 mm and 50-100 mm bins of 'dryAnnQ' is notably different to that of 'meanAnnQ', 'annQ_RCP45_2070' and 'annQ_RCP85_2070'. Specifically, the "drying" in the 0-50 mm and 50-100 mm bins of the latter three runoff variables is less severe than that of 'dryMeanQ'.

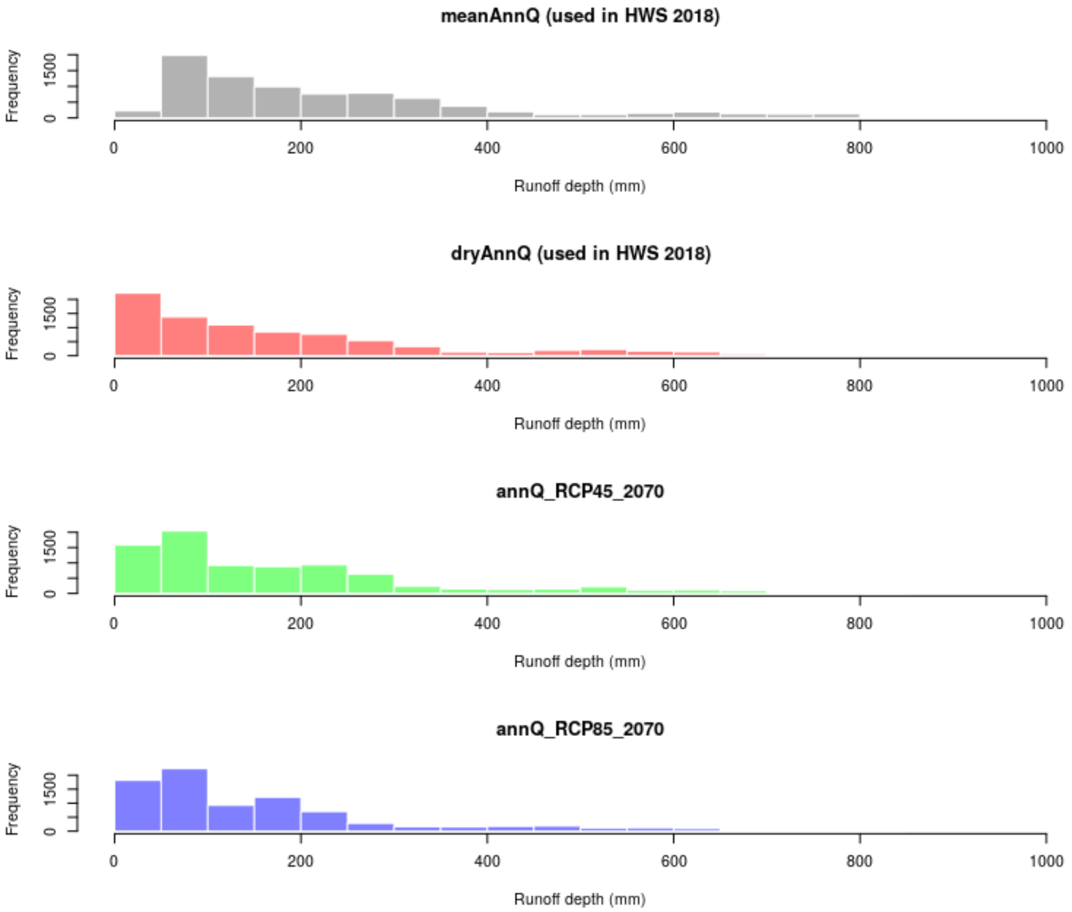


Figure 11. Histograms of the four mean annual runoff depth variables of interest for the PPWP region. From top to bottom: 'meanAnnQ' (grey) – representing mean annual runoff for CURR (current, nominally ~2016) conditions; 'dryAnnQ' (red) – representing climate change-impacted drier BAUF (business-as-usual-future, circa 2070) conditions; 'annQ_RCP45_2070' (green) – mean annual runoff projection under moderate emission pathway RCP 4.5; 'annQ_RCP85_2070' (blue) – mean annual runoff projection under high emission pathway RCP 8.5.

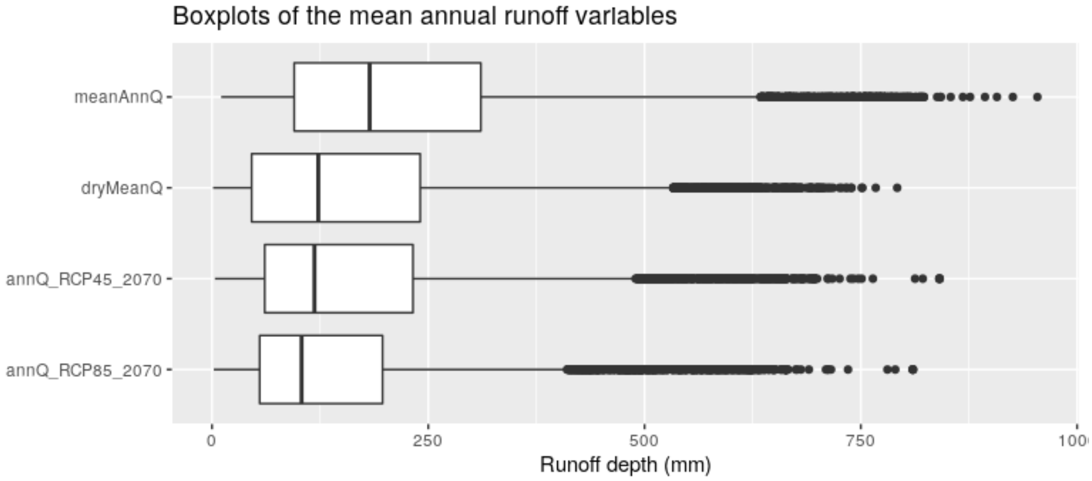


Figure 12. Boxplots of the four mean annual runoff variables of interest for the PPWP region.

Across the PPWP region, the spatial pattern of the four mean annual runoff variables of interest are illustrated in Figure 13.

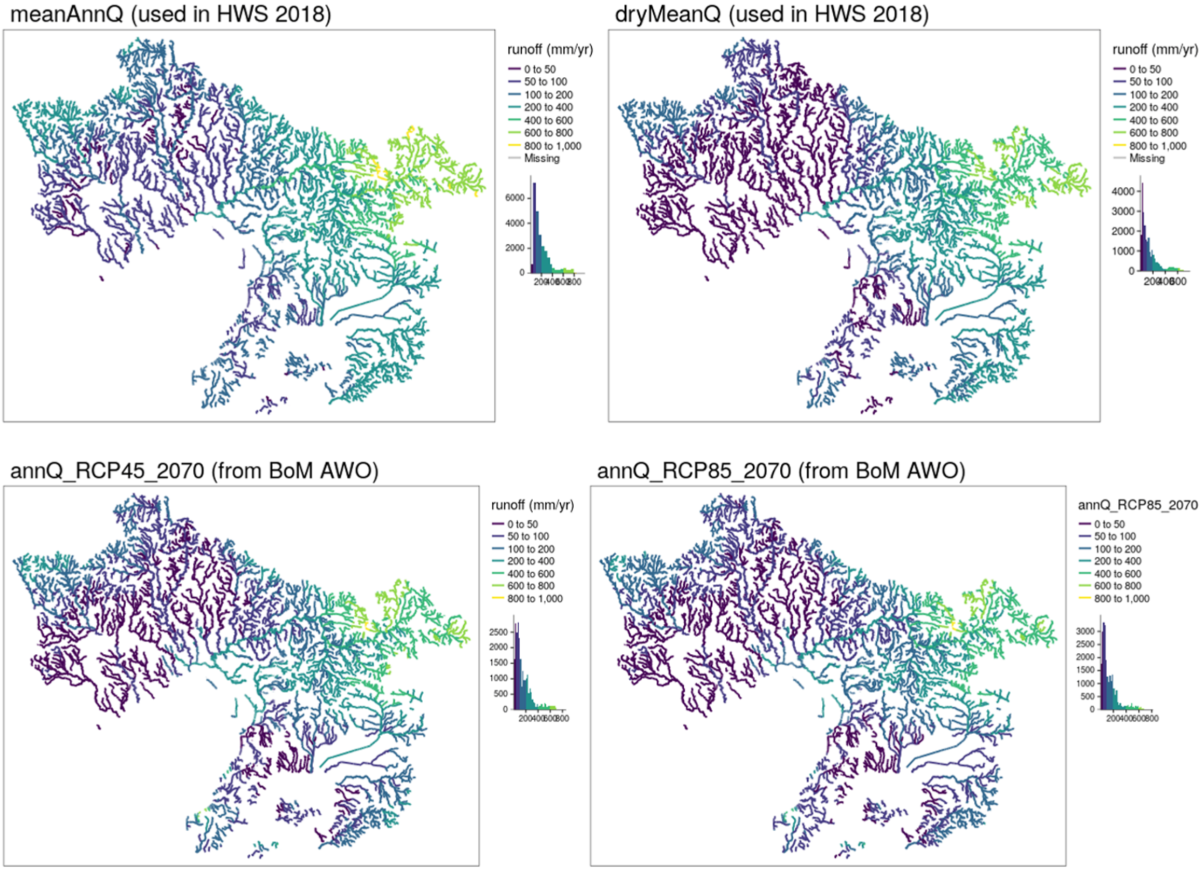


Figure 13. Mean annual runoff variables mapped for the PPWP region. 'meanAnnQ' was used to represent mean annual runoff for CURR (current, nominally ~2016) conditions in HWS 2018; 'dryAnnQ' was used to represent climate change-impacted drier BAUF (business-as-usual-future, circa 2070)conditions; 'annQ_RCP45_2070' is mean annual runoff projection under moderate emission pathway RCP 4.5; 'annQ_RCP85_2070' is mean annual runoff projection under high emission pathway RCP 8.5. Darker purples and blues represent lower runoff values and lighter greens and yellow represent higher runoff values.

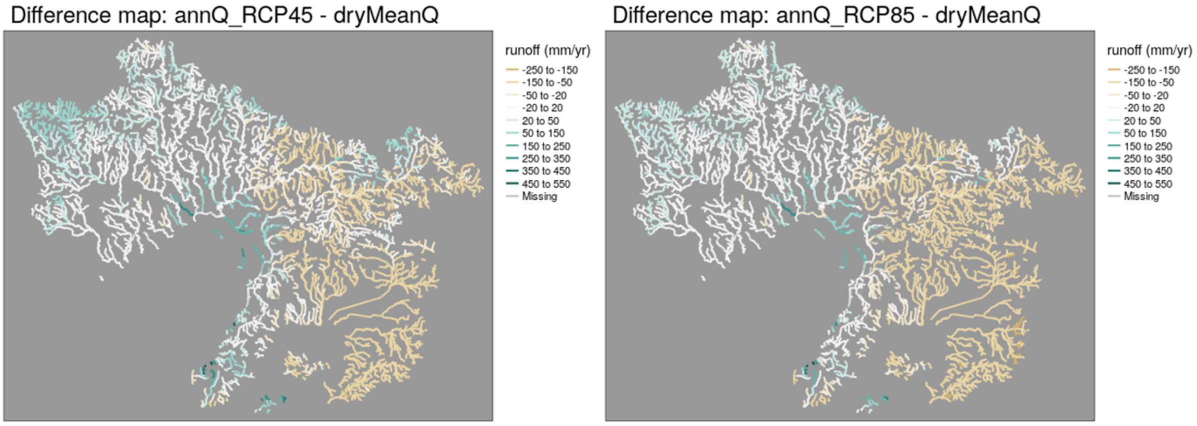


Figure 14. 'Difference' maps showing where projected mean annual runoff under the moderate emission pathway RCP 4.5 (left) and the high emission pathway RCP 8.5 (right) differs from that of 'dryMeanQ'. On this diverging colour scale darker browns indicate runoff that is much lower than 'dryMeanQ', white indicates little runoff difference and deeper blue-greens indicate runoff much higher than 'dryMeanQ'.

3 Scenarios of interest

Scenarios of interest were used to explore the impacts of different combinations of temperature and runoff projections and mitigating actions operating on their own or in particular combinations.

The current (CURR) scenario reflects estimates of various environmental measures as at 2016 (Table 3). 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). As mentioned above, warming was represented by a 1.5°C increase in mean annual temperature, capped at a maximum of 15.8°C. 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 3). These values for temperature increase and reduction in runoff 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 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).

The new scenarios of interest for the HWS mid-term review are listed and described in Table 4. We can think of the ACCESS 1.0 RCP 4.5, HadGEM2_CC RCP 4.5, ACCESS1.0 RCP 8.5 and HadGEM2_CC RCP 8.5 scenarios as alternatives to BAUF (used in HWS 2018). These scenarios differ from BAUF **only** with regard to **mean annual temperature** and **mean annual runoff**. The Attenuated Forest and Attenuated Imperviousness estimates are identical to that used in BAUF (Table 4).

In the following sections, we present the predicted impact of the various scenarios of interest on macroinvertebrates, native fish species and platypus. We provide results in three main formats given our interest in making comparisons across multiple scenarios:

a) Stacked barplots summarising the lengths of stream in each predicted lumar (**L**and **U**se **Ma**croinvertebrate **R**esponse index or LUMaR – referred to as 'lumar' in this report) rating category (for macroinvertebrates) or predicted habitat suitability category (for native fish and platypus) by scenario
b) Mapped predictions of lumar rating categories or predicted habitat suitability across the Port Philip Westernport (PPWP) region by scenario
c) 'Difference' maps showing where and how scenario predictions differ relative to a specified scenario of interest

Table 3. Details of the CURR (current) and BAUF (business-as-usual-future) scenarios used in the development process of the HWS 2018.

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, capped at 15.8 ^{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 when all parcels within the PPWP 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

Table 4. List and description of climate change-impacted temperature and runoff scenarios under moderate and high emission pathways, action scenarios, and CC-impacted and action scenario combinations explored in this report.

	Scenario Code	Description
Climate change-impacted temperature and runoff projections		
1	ACCESS_RCP4.5	Like BAUF, but with ACCESS 1.0 projected mean annual temperature AND mean annual runoff projection under moderate emission pathway RCP 4.5 (annQ_RCP45_2070)
2	HadGEM_RCP4.5	Like BAUF, but with HadGEM2_CC projected mean annual temperature AND mean annual runoff projection under moderate emission pathway RCP 4.5 (annQ_RCP45_2070)
3	ACCESS_RCP8.5	Like BAUF, but with ACCESS 1.0 projected mean annual temperature AND mean annual runoff projection under high emission pathway RCP 8.5 (annQ_RCP85_2070)
4	HadGEM_RCP8.5	Like BAUF, but with HadGEM2_CC projected mean annual temperature AND mean annual runoff projection under high emission pathway RCP 8.5 (annQ_RCP85_2070)
Mitigating actions		
5	RV20	Like BAUF, but revegetate riparian zones on both stream sides, to 20m width along all streams in the PPWP region
6	RV20_SW3	Like BAUF, but revegetate riparian zones on both stream sides, to 20m width along all streams in the PPWP 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.
5	ACCESS_RCP4.5 HadGEM_RCP4.5 ACCESS_RCP8.5 HadGEM_RCP8.5 _RV20	Climate change-impacted temperature from ACCESS 1.0 OR HadGEM2_CC AND mean annual runoff under RCP 4.5 OR RCP 8.5 AND revegetate riparian zones on both stream sides, to 20m width along all streams in the PPWP region
6	ACCESS_RCP4.5 HadGEM_RCP4.5 ACCESS_RCP8.5 HadGEM_RCP8.5 _RV20_SW3	Climate change-impacted temperature from ACCESS 1.0 OR HadGEM2_CC AND mean annual runoff under RCP 4.5 OR RCP 8.5 AND revegetate riparian zones on both stream sides, to 20m width along all streams in the PPWP 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.

4 Macroinvertebrates

The stacked barplots of stream lengths in each lumar rating category allows us to compare the predicted impact of scenarios against one another, across an aggregate PPWP region-wide scale (Figure 15). The predicted outcome under the ACCESS 1.0 and HadGEM2_CC high emission (RCP 8.5) pathways are slightly worse than the predicted outcome under the ACCESS 1.0 and HadGEM2_CC moderate emission (RCP 4.5) pathways. Somewhat surprisingly, however, the predicted (summary) outcomes with respect to macroinvertebrates (as characterised by lumar scores) under the updated climate change-impacted runoff and temperature scenarios are very similar (Figure 15).

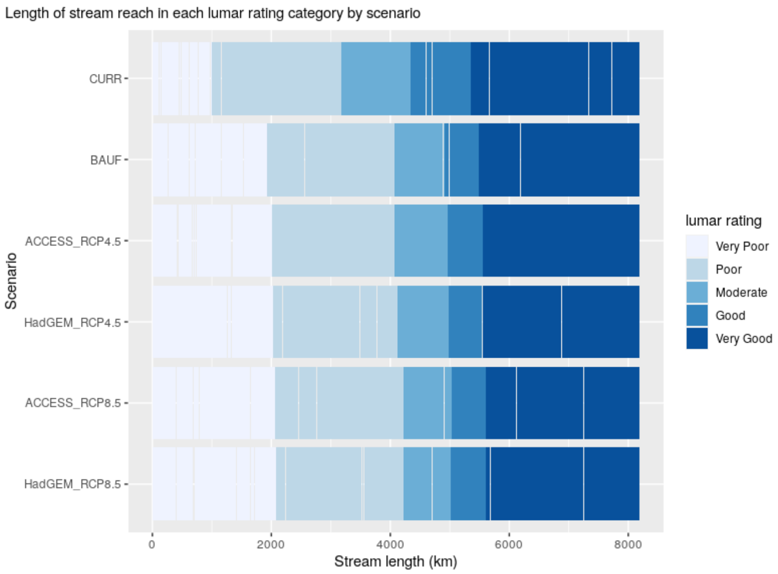


Figure 15. Stacked barplots of stream lengths in each lumar rating category by scenario (see Table 4). Deeper blues indicate better lumar ratings. The intervals for the lumar rating categories are: Very Poor -0.3 - 0.05, Poor 0.05 - 0.35, Moderate 0.35 - 0.5, Good 0.5 - 0.65, Very Good 0.65 - 1.0.

The spatial distribution of lumar ratings under the various scenarios are shown in the upper four images in Figure 16. The bottom two images in Figure 16 are 'difference' maps that highlight the particular areas within the PPWP region where the 'bookend' scenario predictions differ from (i.e. is higher or lower than and by how much) the BAUF scenario used in HWS 2018.

For the ACCESS 1.0 RCP 4.5 scenario, there are pockets through the sub-catchments (a management boundary used by Melbourne Water and the HWS and is not necessarily a hydrologically delineated drainage boundary), Boyd Creek, Deep Creek Upper, Plenty River Lower, Diamond Creek (Rural), Andersons and Jumping Creek in Yarra River Lower, Mornington Peninsula Western Creeks, Dalmore Outfalls, Cardinia, Toomuc, Deep and Ararat Creeks, King Parrot and Musk Creeks, Lang Lang River and Bass River where predicted lumar values are higher than under BAUF (blue-green stream reaches in bottom-left image, Figure 16). For the ACCESS 1.0 RCP 4.5 scenario, there are also pockets scattered throughout the PPWP region, such as in the sub-catchments of Werribee River Upper, Werribee River Lower, Maribyrnong River, Yarra River Upper (Rural), Little Yarra River and Hoddles Creek, Woori Yallock Creek, Bunyip River Middle and Upper, Tarago River, Lang Lang River and Bass River, where predicted lumar values are lower than under BAUF (brown stream reaches in bottom-left image, Figure 16). For the HadGEM2 CC RCP 8.5 scenario, there is some overlap in the 'difference' map pattern with the ACCESS 1.0 RCP 4.5 scenario, particularly with respect to higher lumar values relative to BAUF (blue-green stream reaches in bottom-right image, Figure 16), but there are also notable areas of variation in the sub-catchments of Boyd Creek, Deep Creek Upper, Emu Creek, Jacksons Creek, Werribee River Upper and Woori Yallock Creek (brown stream reaches in bottom-right image, Figure 16).

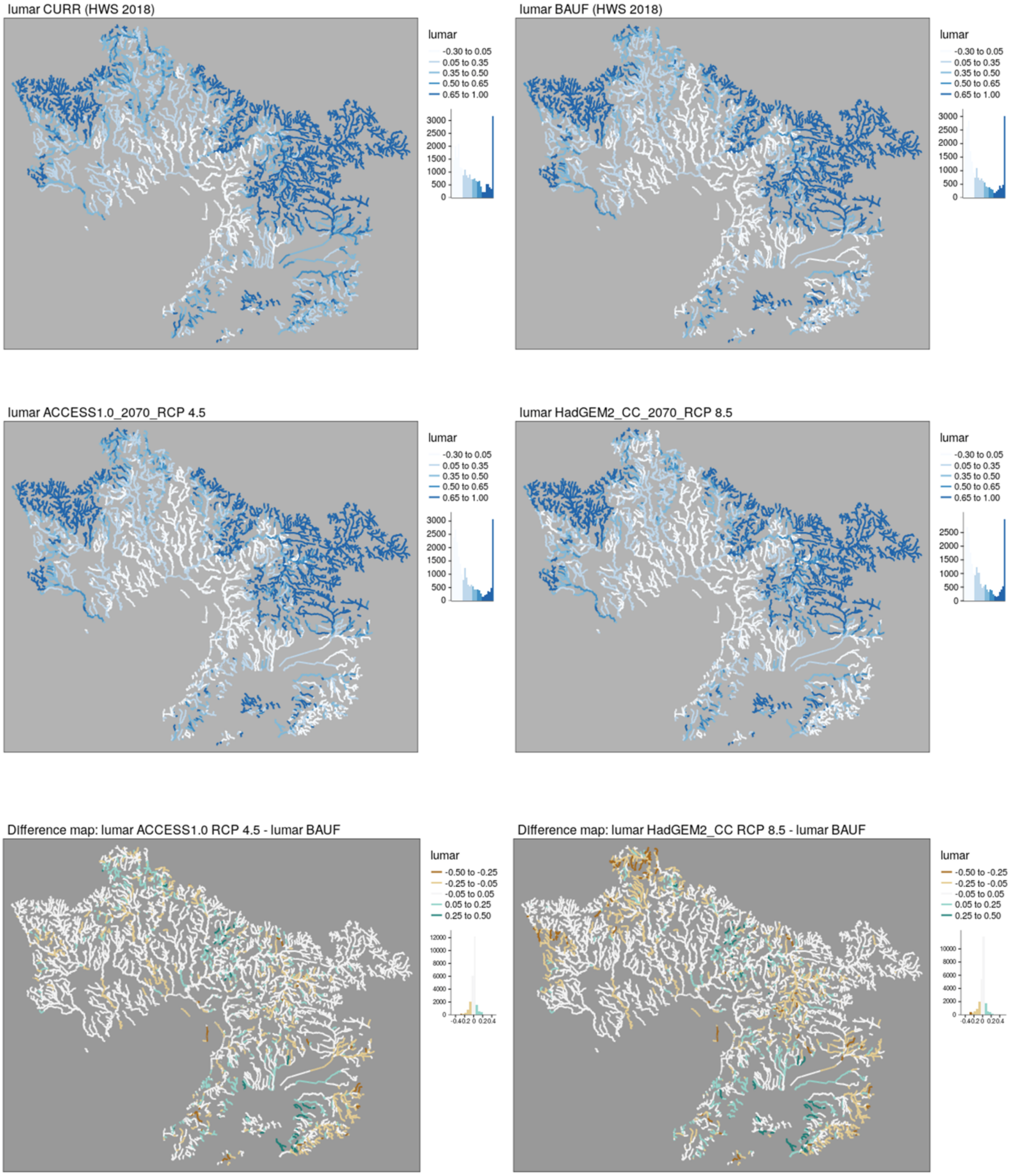


Figure 16. Mapped predictions of lumar scores across the PPWP region under the CURR scenario used in HWS 2018 (top-left), the BAUF scenario used in HWS 2018 (top-right), ACCESS 1.0 RCP4.5 (middle-left) and HadGEM2_CC RCP8.5 (middle-right). Deeper blues indicate higher lumar values. 'Difference' maps show where predicted lumar under ACCESS 1.0 RCP4.5 (bottom-left) and under HadGEM2_CC RCP8.5 differs from that of the BAUF scenario used in HWS 2018. On this diverging colour scale darker browns indicate lower lumar values relative to BAUF, white indicates little difference and deeper blue-greens indicate higher lumar values relative to BAUF.

4.1 What is the mitigating impact of actions?

The three stacked barplot summaries of stream lengths in each lumar rating category (Figure 17) allows us to compare climate-change-impacted scenarios *without* (i.e. ACCESS 1.0 RCP 4.5, HadGEM2_CC RCP4.5, ACCESS 1.0 RCP8.5 and HadGEM2_CC RCP 8.5) and *with* the two main mitigating actions, namely, revegetating both stream sides to a 20m riparian buffer on its own (RV20) and revegetation together with treatment of all future *and* some existing impervious cover such that attenuated imperviousness in existing urban areas is reduced to 75% of 2016 levels (RV20_SW3).

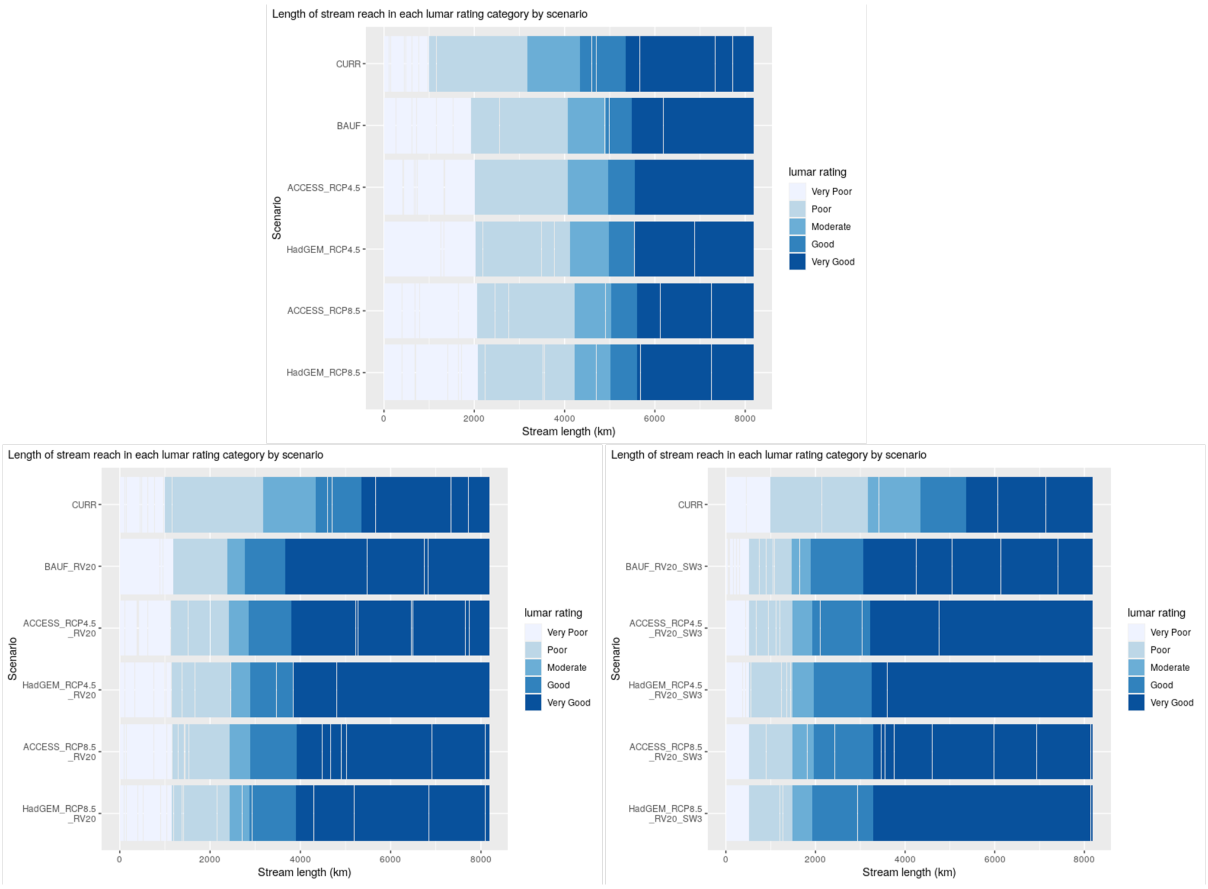


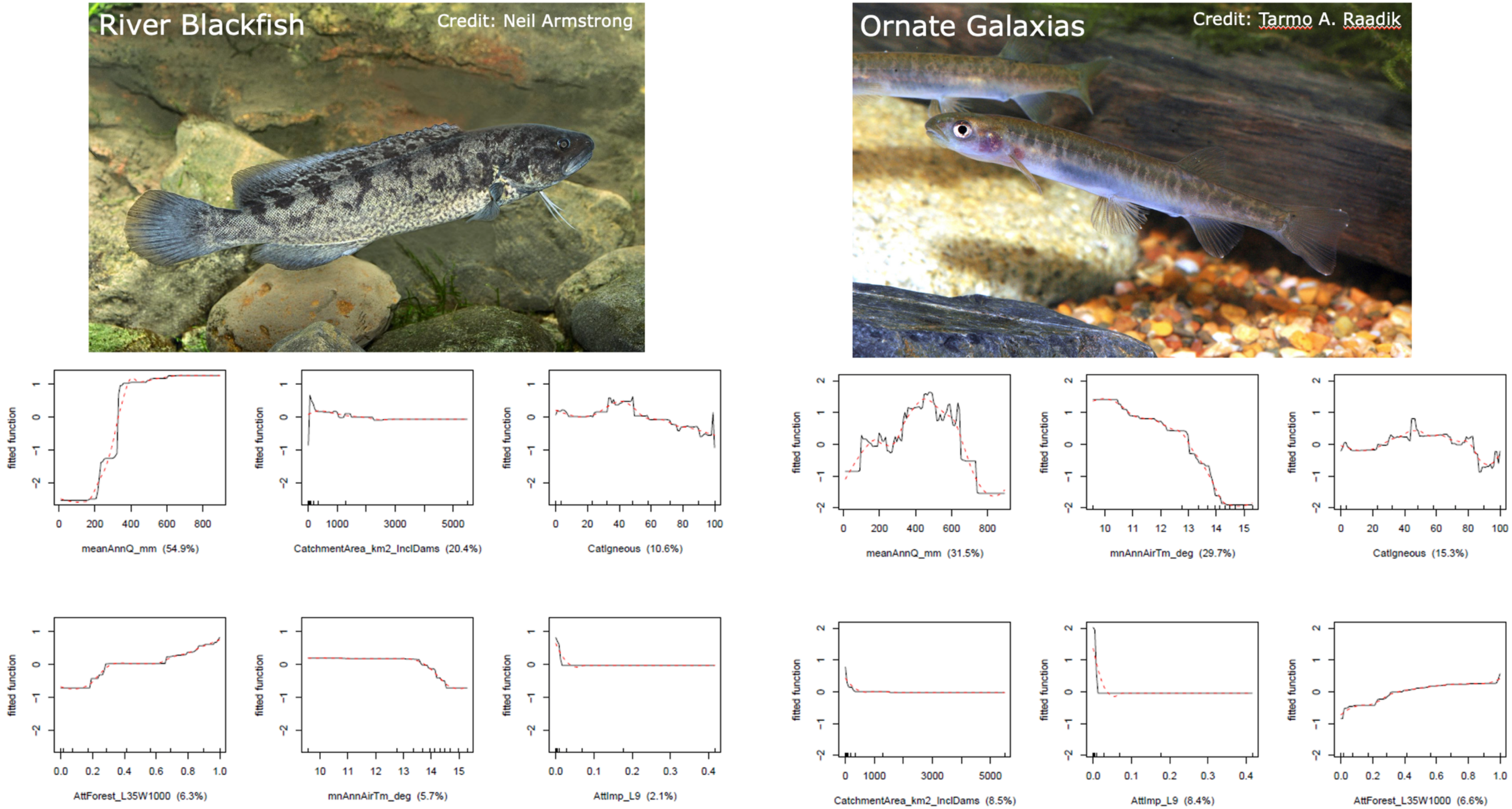
Figure 17. Summary stacked barplots of stream lengths in each lumar rating category by scenario for climate change-impacted scenarios with no mitigation action (top), for CC-impacted scenarios with RV20 (bottom-left) and for CC-impacted scenarios with RV20_SW3 (see Table 4 for full description of each scenario). The intervals for the lumar rating categories are: Very Poor -0.3 - 0.05, Poor 0.05 - 0.35, Moderate 0.35 - 0.5, Good 0.5 - 0.65, Very Good 0.65 - 1.0.

For macroinvertebrates, RV20 is a highly effective mitigating action under both RCP 4.5 and RCP 8.5 scenarios with ACCESS 1.0 and HadGEM2_CC, as judged by the increased lengths of stream in the 'Good' and 'Very Good' lumar rating categories (last four rows in bottom-left image compared to last four rows in top image in Figure 17). RV20_SW3 is predicted to be an even more effective mitigating action, as judged by further increases in lengths of stream in the 'Good' and 'Very Good' lumar rating categories, and this applies even under the high emission pathway scenarios (last four rows in bottom-right image compared to last four rows in bottom-left image in Figure 17).

5 Native Fish

In the HWS development process, we considered 13 native fish species for which we had sufficient data to develop HSMs. A number of the 13 native fish species are widely distributed across south-east Australia and a number of them have positive associations with mean annual air temperature. For this report, we focus on two native fish species that are expected to be at-risk under climate change, namely, River Blackfish (‘gadomarm’) and Ornate Galaxias (‘galaorna’) (top images in Figure 18). The bottom images in Figure 18 show the environmental predictors included in the HSM for each respective species, and the shape of each fitted response curve. River Blackfish as a positive (stepped) relationship with mean annual runoff, while Ornate Galaxias has a more variable but unimodal relationship showing a peak in the range between 380-650 mm. The fitted curve for River Blackfish shows a negative relationship with mean annual air temperature between 13.7-15.0 °C but the relative percentage contribution of the mean annual air temperature in the River Blackfish HSM is only ~5.7%. In comparison, the fitted curve for Ornate Galaxias shows a negative relationship with mean annual air temperature beginning between 10.8-14.2 °C and its relative percentage contribution in the HSM is much greater at ~29.7%.

The stacked barplots of stream lengths in each predicted habitat suitability category allows us to compare for each species, the predicted impact of scenarios against one another, across an aggregate PPWP region-wide scale (Figure 19). For River Blackfish, the predicted outcome under the ACCESS 1.0 and HadGEM2_CC moderate emission (RCP 4.5) pathways are slightly worse, but not too dissimilar to that under BAUF. Under the high emission (RCP 8.5) pathways, however, the predicted outcome under HadGEM2_CC is noticeably worse than under ACCESS 1.0 (left image, Figure 19). For Ornate Galaxias, the predicted outcome under ACCESS 1.0 RCP 4.5 is poorer relative to BAUF and poorer still, under HadGEM2_CC RCP 4.5. When we get to RCP 8.5, there are no longer any lengths of stream in the highest predicted habitat suitability category of 0.75-1.0 and only very small lengths of stream in the category of 0.60-0.75 (right image, Figure 19).


River Blackfish Credit: Neil Armstrong

Ornate Galaxias Credit: Tarmo A. Raadik

Figure 18. The two native fish species expected to be at-risk under climate change: River Blackfish (top-left) and the fitted response curves for the environmental predictors in its (boosted regression tree) habitat suitability model (bottom-left) and Ornate Galaxias (top-right) and the fitted response curves for environmental predictors in its (boosted regression tree) habitat suitability model (bottom-right). For each species, the predictors are set out in order of relative percentage contribution (a measure of 'importance'). See Table 1for detailed descriptions of predictors.

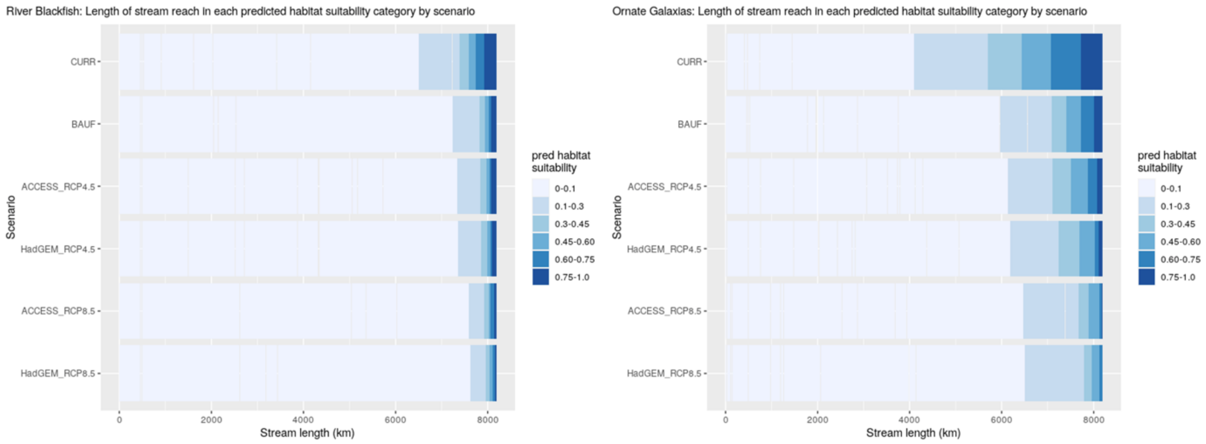


Figure 19. Summary stacked barplots of stream lengths in each habitat suitability category by climate change-impacted scenario for River Blackfish (left) and Ornate Galaxias (right). The intervals for the predicted habitat suitability categories are: 0 - 0.10, 0.10 - 0.30, 0.30 - 0.45, 0.45 - 0.60, 0.60 - 0.75 and 0.75 - 1.0.

The spatial distribution of predicted habitat suitability of River Blackfish under the various scenarios are shown in the upper four images in Figure 20. The bottom two images in Figure 20 are ‘difference’ maps that highlight the particular areas within the PPWP region where the ‘bookend’ scenario predictions differ from (i.e. is higher or lower than and by how much) the BAUF scenario used in HWS 2018.

The mapped habitat suitability of River Blackfish under the CURR scenario shows a relatively restricted distribution within the PPWP region with high predicted habitat suitability areas concentrated in reaches in the sub-catchments of Lerderderg River, Woori Yallock Creek, Little Yarra River and Hoddles Creek, Watts River (Rural), Watts River (Source), Yarra River Upper (Rural), Yarra River Upper (Source) and Bunyip River Middle and Upper (top-left image, Figure 20). Under the BAUF scenario, the high predicted habitat suitability areas shrink to reaches in the sub-catchments of Yarra River Upper (Rural) and Yarra River Upper (Source), with pockets of moderate predicted habitat suitability in the sub-catchments of Watts River (Source) and Woori Yallock Creek (top-right image, Figure 20).

The spatial pattern of predicted habitat suitability for River Blackfish under the ACCESS 1.0 RCP 4.5 scenario is very similar to that under the BAUF scenario (middle-left image, Figure 20). However, under the HadGEM2_CC RCP 8.5 scenario, we see further contraction of predicted habitat suitability to a small number of reaches in the stronghold sub-catchments of Yarra River Upper (Rural) and Yarra River Upper (Source) (middle-right image, Figure 20).

Under the ACCESS 1.0 RCP 4.5 scenario, there are a small number of streams with increased predicted habitat suitability relative to BAUF in the sub-catchments of Lerderderg River, Watts River (Rural), Watts River (Source) and Yarra River Upper (Rural) (bottom-left image, Figure 20). There are, however, many more streams with decreased predicted habitat suitability relative to BAUF in the sub-catchments of Watts River (Rural), Watts River (Source), Yarra River Upper (Rural), Little Yarra River and Hoddles Creek, Woori Yallock Creek, Cardinia, Toomuc, Deep and Ararat Creeks, Bunyip River Middle and Upper and Tarago River. Under the HadGEM2_CC RCP 8.5 scenario, the only notable reach showing increased predicted habitat suitability relative to BAUF is in the management unit of Watts River (Rural). The rest of the “difference” consists of decreases in predicted habitat suitability, and these decreases are in reaches spread across the sub-catchments of Lerderderg River, Yarra River Middle, Watts River (Rural), Watts River (Source), Yarra River Upper (Rural), Little Yarra River and Hoddles Creek, Woori Yallock Creek, Cardinia, Toomuc, Deep and Ararat Creeks, Bunyip River Middle and Upper and Tarago River (bottom-right image, Figure 20).

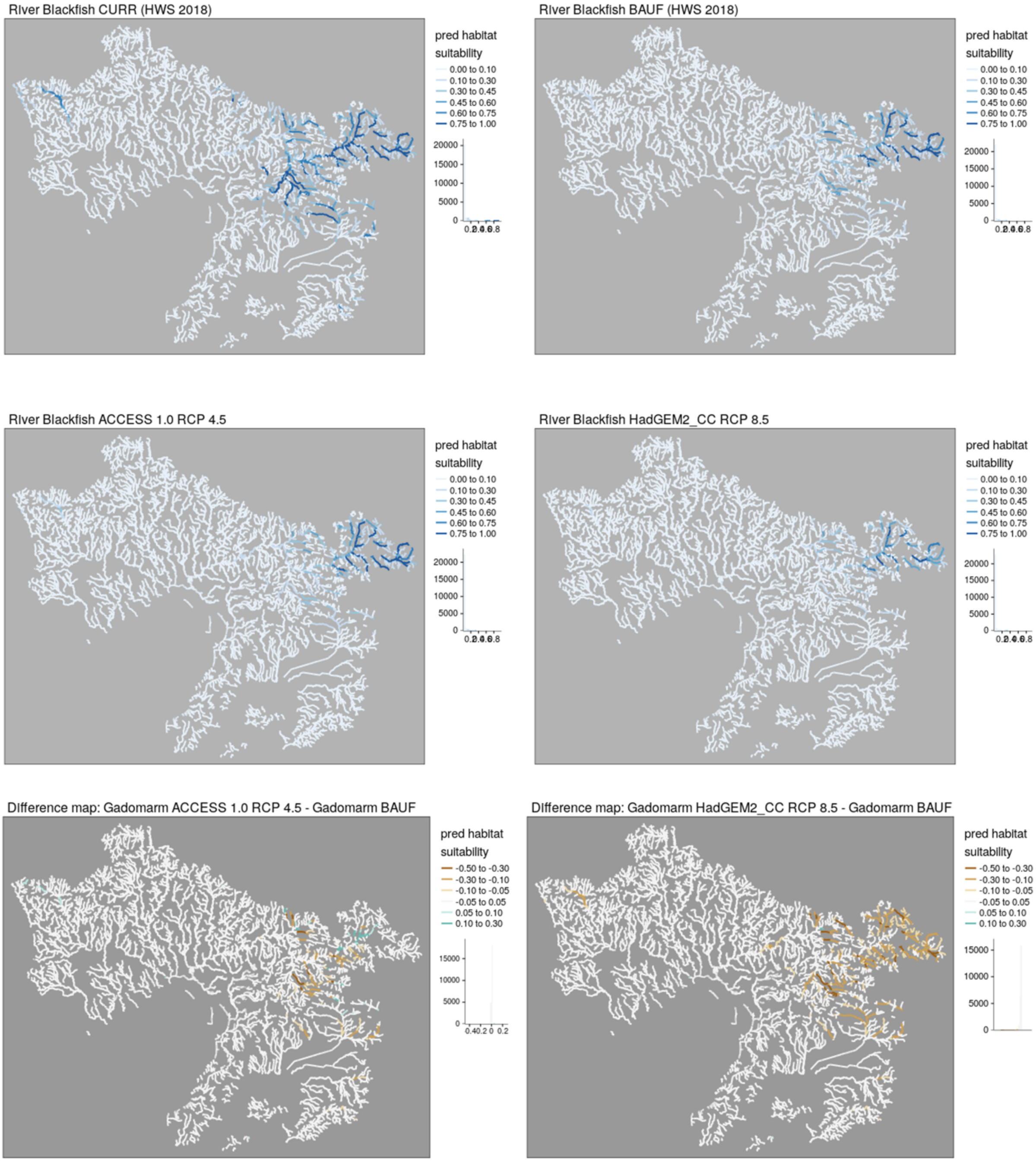


Figure 20. Mapped predictions of River Blackfish habitat suitability across the PPWP region under the CURR scenario used in HWS 2018 (top-left), the BAUF scenario used in HWS 2018 (top-right), ACCESS1.0 RCP4.5 (middle-left) and HadGEM2_CC RCP8.5 (middle-right). Deeper blues indicate higher predicted habitat suitability. 'Difference' maps show where predicted habitat suitability under ACCESS 1.0 RCP4.5 (bottom-left) and under HadGEM2_CC RCP8.5 differs from that of the BAUF scenario used in HWS 2018. On this diverging colour scale darker browns indicate lower predicted habitat suitability relative to BAUF, white indicates little difference and deeper blue-greens indicate higher predicted habitat suitability relative to BAUF.

The spatial distribution of predicted habitat suitability of Ornate Galaxias under the various scenarios are shown in the upper four images in Figure 21. The bottom two images in Figure 21 are ‘difference’ maps that highlight the particular areas within the PPWP region where the ‘bookend’ scenario predictions differ from (i.e. is higher or lower than and by how much) the BAUF scenario used in HWS 2018.

The mapped habitat suitability of Ornate Galaxias under the CURR scenario shows a relatively broad distribution right across the PPWP region. Ornate Galaxias high predicted habitat suitability areas are concentrated in stream reaches in the sub-catchments of Werribee River Upper, Lerderderg River, Jacksons Creek, Emu Creek, Deep Creek Upper, Boyd Creek, Plenty River Upper, Plenty River (Source), Diamond Creek (Source), Steels and Pauls Creek (Source), Watts River (Rural), Watts River (Source), Yarra River Upper (Source), Yarra River Upper (Rural), Little Yarra River and Hoddles Creek, Woori Yallock Creek, Bunyip River Middle and Upper and Tarago River (top-left image, Figure 21).

Under the BAUF scenario the high predicted habitat suitability areas contract to reaches in the sub-catchments of Werribee River Upper, Lerderderg River, Jacksons Creek, Plenty River Upper, Watts River (Rural), Watts River (Source), Yarra River Upper (Source), Yarra River Upper (Rural), Little Yarra River and Hoddles Creek, with pockets of moderate predicted habitat suitability in the sub-catchments of Deep Creek Upper, Plenty River Upper, Plenty River (Source), Diamond Creek (Source) and Steels and Pauls Creek (Source) (top-right image, Figure 21).

The spatial pattern of predicted habitat suitability for Ornate Galaxias under the ACCESS 1.0 RCP 4.5 scenario is very similar to that under the BAUF scenario, except that predictions in the western portion of the PPWP region are somewhat more favourable whilst those in the eastern portion of the region are slightly poorer (middle-left image, Figure 21). Under the HadGEM2_CC RCP 8.5 scenario however, we see pronounced contraction of high predicted habitat suitability areas to just the reaches in the sub-catchments of Yarra River Upper (Rural) and Yarra River Upper (Source), with other areas of moderate to high predicted habitat suitability under BAUF downgraded to much lower predicted habitat suitability (middle-right image, Figure 21).

Under the ACCESS 1.0 RCP 4.5 scenario, there are areas of streams with increased predicted habitat suitability relative to BAUF in the sub-catchments of Werribee River Upper, Lerderderg River, Jacksons Creek, Emu Creek, Deep Creek Upper, Boyd Creek, Yarra River Upper (Rural), Yarra River Upper (Source), Little Yarra River and Hoddles Creek, Bunyip River Middle and Upper and Mornington Peninsula South-Eastern Creeks (bottom-left image, Figure 21). There are, however, also areas of streams with decreased predicted habitat suitability relative to BAUF in all the above-mentioned sub-catchments, as well as Plenty River Upper, Steels and Pauls Creek, Yarra River Middle, Lang Lang River and French and Phillip Islands (bottom-left image, Figure 21).

Under the HadGEM2_CC RCP 8.5 scenario, the most notable area showing increased predicted habitat suitability relative to BAUF is in the management unit of Yarra River Upper (Source). The rest of the “difference” consists of decreases in predicted habitat suitability, and these decreases are in reaches spread across the sub-catchments of Werribee River Upper, Lerderderg River, Jacksons Creek, Deep Creek Upper, Plenty River Upper, Watts River (Rural), Watts River (Source), Yarra River Upper (Source), Yarra River Upper (Rural), Little Yarra River and Hoddles Creek, Bunyip River Middle and Upper, Tarago River, Lang Lang River and French and Phillip Islands (bottom-right image, Figure 21).

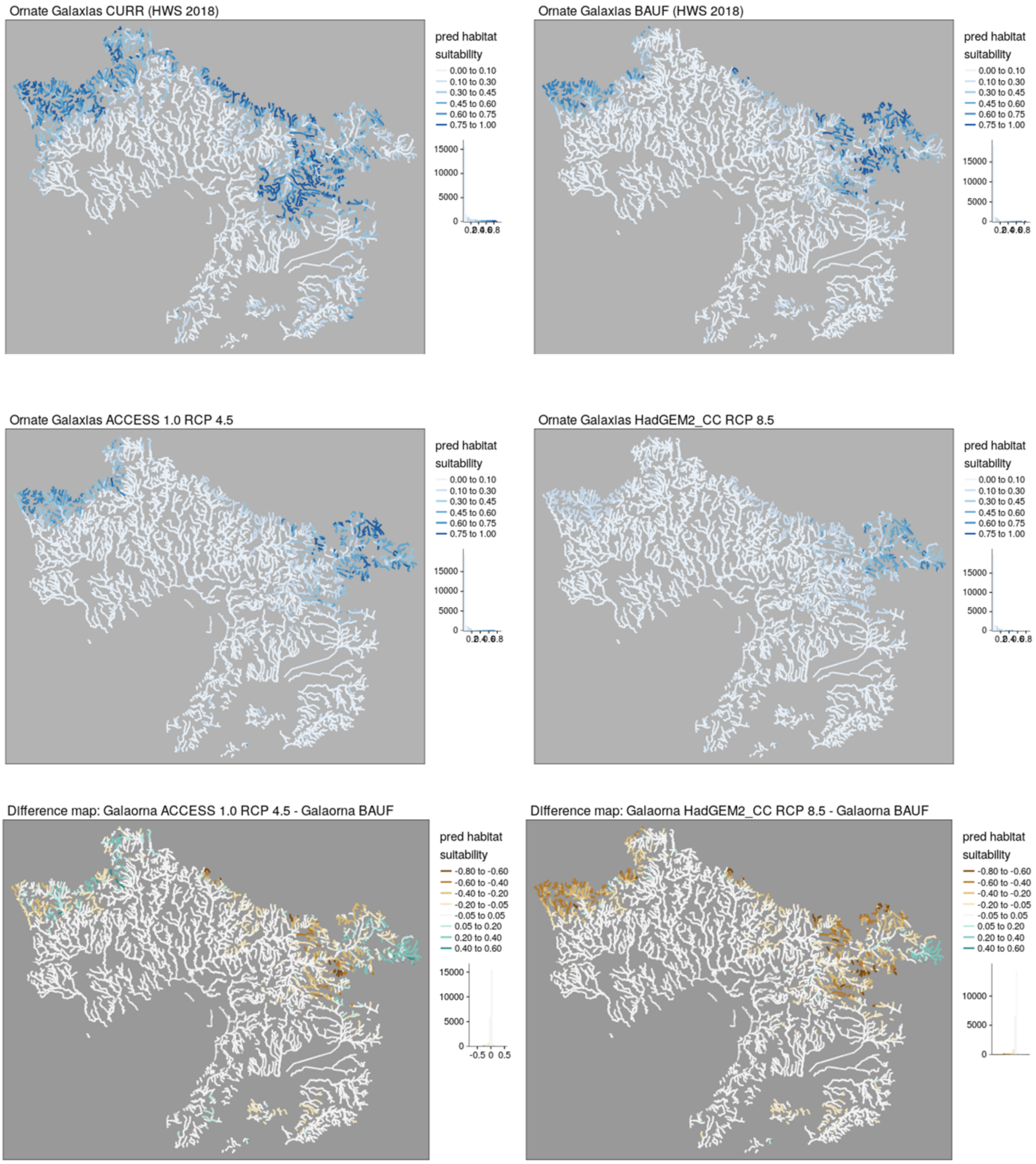


Figure 21. Mapped predictions of Ornate Galaxias habitat suitability across the PPWP region under the CURR scenario used in HWS 2018 (top-left), the BAUF scenario used in HWS 2018 (top-right), ACCESS1.0 RCP4.5 (middle-left) and HadGEM2_CC RCP8.5 (middle-right). Deeper blues indicate higher predicted habitat suitability. 'Difference' maps show where predicted habitat suitability under ACCESS 1.0 RCP4.5 (bottom-left) and under HadGEM2_CC RCP8.5 differs from that of the BAUF scenario used in HWS 2018. On this diverging colour scale darker browns indicate lower predicted habitat suitability relative to BAUF, white indicates little difference and deeper blue-greens indicate higher predicted habitat suitability relative to BAUF.

5.1 What is the mitigating impact of actions?

The three stacked barplot summaries of stream lengths in each predicted habitat suitability category (Figure 22) allows us to compare climate-change-impacted scenarios *without* (i.e. ACCESS 1.0 RCP 4.5, HadGEM2_CC RCP4.5, ACCESS 1.0 RCP8.5 and HadGEM2_CC RCP 8.5) and *with* the two main mitigating actions, namely, revegetating both stream sides to a 20m riparian buffer on its own (RV20) and revegetation together with treatment of all future *and* some existing impervious cover such that attenuated imperviousness in existing urban areas is reduced to 75% of 2016 levels (RV20_SW3).

For River Blackfish, RV20 is predicted to make very little difference at all as a mitigating action under both RCP 4.5 and RCP 8.5 scenarios with ACCESS 1.0 and HadGEM2_CC, as judged by the lengths of stream in the various habitat suitability categories (last four rows in bottom-left image compared to last four rows in top image in Figure 22). RV20_SW3 is similarly predicted to make very little difference as a mitigating action, as judged by the lengths of stream in the various habitat suitability categories (last four rows in bottom-right image compared to last four rows in bottom-left image in Figure 22).

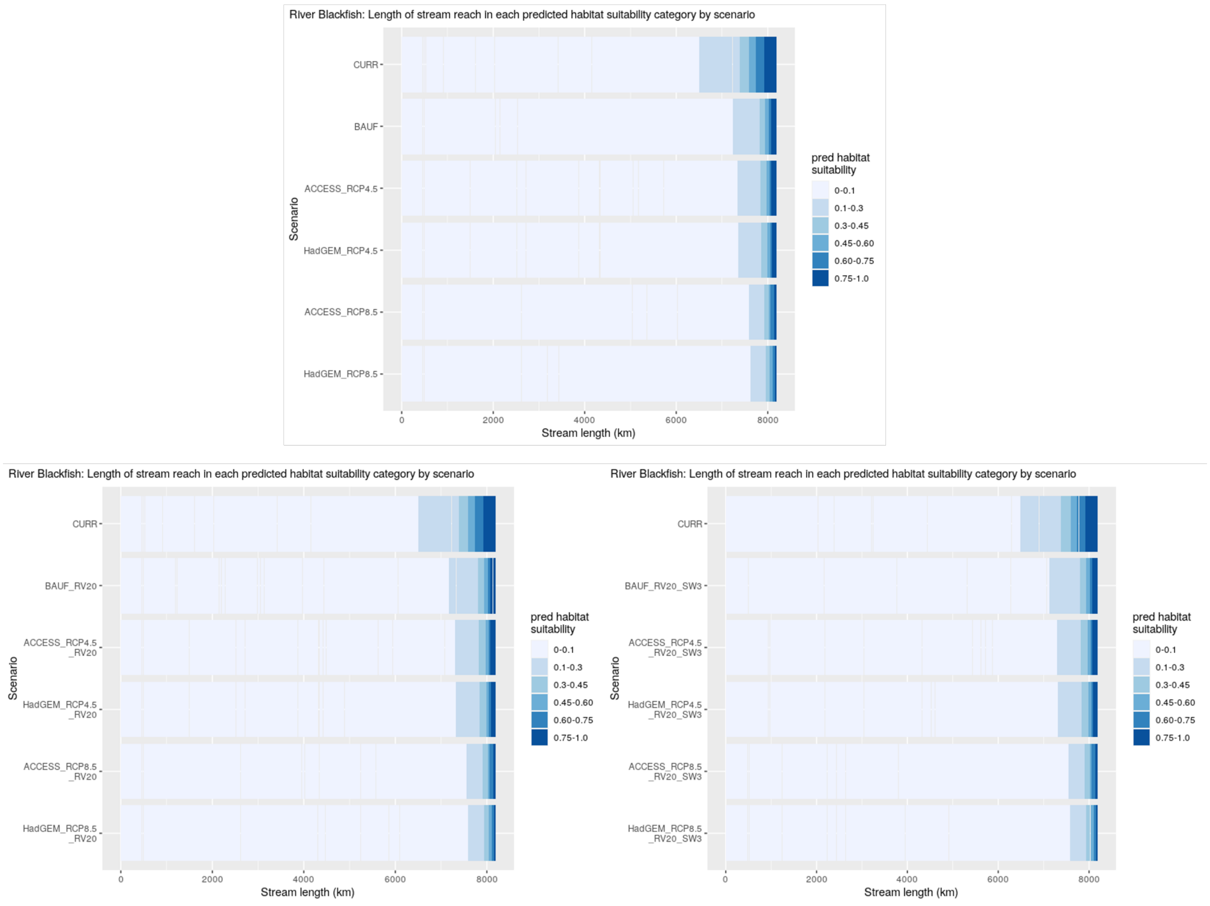


Figure 22. Summary stacked barplots for River Blackfish of stream lengths in each predicted habitat suitability category by scenario for climate change-impacted scenarios with no mitigation action (top), for CC-impacted scenarios with RV20 (bottom-left) and for CC-impacted scenarios with RV20_SW3 (see Table 4 for full description of each scenario). The intervals for the predicted habitat suitability categories are: 0 - 0.10, 0.10 - 0.30, 0.30 - 0.45, 0.45 - 0.60, 0.60 – 0.75 and 0.75 - 1.0.

The three stacked barplot summaries of stream lengths in each predicted habitat suitability category (Figure 23) allows us to compare climate-change-impacted scenarios *without* (i.e. ACCESS 1.0 RCP

4.5, HadGEM2_CC RCP4.5, ACCESS 1.0 RCP8.5 and HadGEM2_CC RCP 8.5) and *with* the two main mitigating actions, namely, revegetating both stream sides to a 20m riparian buffer on its own (RV20) and revegetation together with treatment of all future *and* some existing impervious cover such that attenuated imperviousness in existing urban areas is reduced to 75% of 2016 levels (RV20_SW3).

For Ornate Galaxias, RV20 is predicted to make some positive difference as a mitigating action under both RCP 4.5 and RCP 8.5 scenarios with ACCESS 1.0 and HadGEM2_CC. However, this is mainly manifest as increases in lengths of stream in the 0.1-0.3 habitat suitability category, with little change in the lengths of stream in the higher suitability categories (last four rows in bottom-left image compared to last four rows in top image in Figure 23). RV20_SW3 is similarly predicted to make some positive difference as a mitigating action, and it produces a larger quantum of benefit than RV20 on its own. But again, the benefit is mainly manifest as increases in lengths of stream in the 0.1-0.3 habitat suitability category, with little change in the lengths of stream in the higher suitability categories (last four rows in bottom-right image compared to last four rows in bottom-left image in Figure 23).

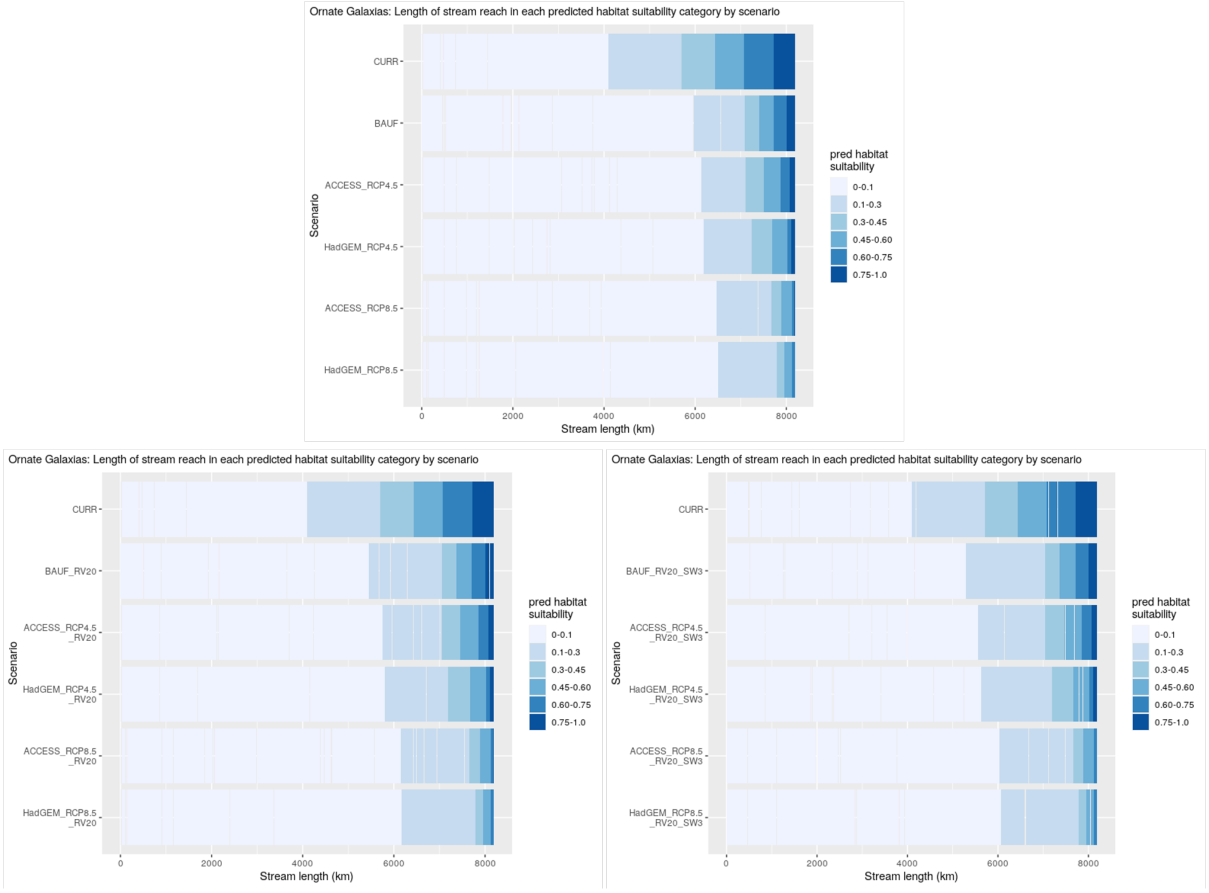


Figure 23. Summary stacked barplots for Ornate Galaxias of stream lengths in each predicted habitat suitability category by scenario for climate change-impacted scenarios with no mitigation action (top), for CC-impacted scenarios with RV20 (bottom-left) and for CC-impacted scenarios with RV20_SW3 (see Table 4 for full description of each scenario). The intervals for the predicted habitat suitability categories are: 0 - 0.10, 0.10 - 0.30, 0.30 - 0.45, 0.45 - 0.60, 0.60 – 0.75 and 0.75 - 1.0.

6 Platypus

In the HWS development process, we considered two separate platypus HSMs. One HSM developed with male and female platypus data (‘AllPlatyHWS’) and another HSM developed with only female platypus data (‘FemPlaty’). We quantified female-only habitat relationships separately because female platypus have more stringent habitat requirements for nesting sites and for foraging to support lactation (Serena & Grant 2017). Figures 24 and 25 show the environmental predictors included in AllPlatyHWS and FemPlaty, respectively, including the shape of each fitted response curve. Of particular note from a climate change perspective, are the particularly strong relative percent contributions to the model for mean annual discharge, mean annual temperature and antecedent runoff in both platypus HSMs. For the AllPlatyHWS model, percent values for these predictors were 20.6%, 11.3% and 9.7%, respectively. For the FemPlaty model, percent values for these predictors were 33%, 20.2% and 13.1%, respectively. In both models, increased habitat suitability was related to higher values of mean annual discharge and antecedent runoff, and lower values of mean annual air temperature.

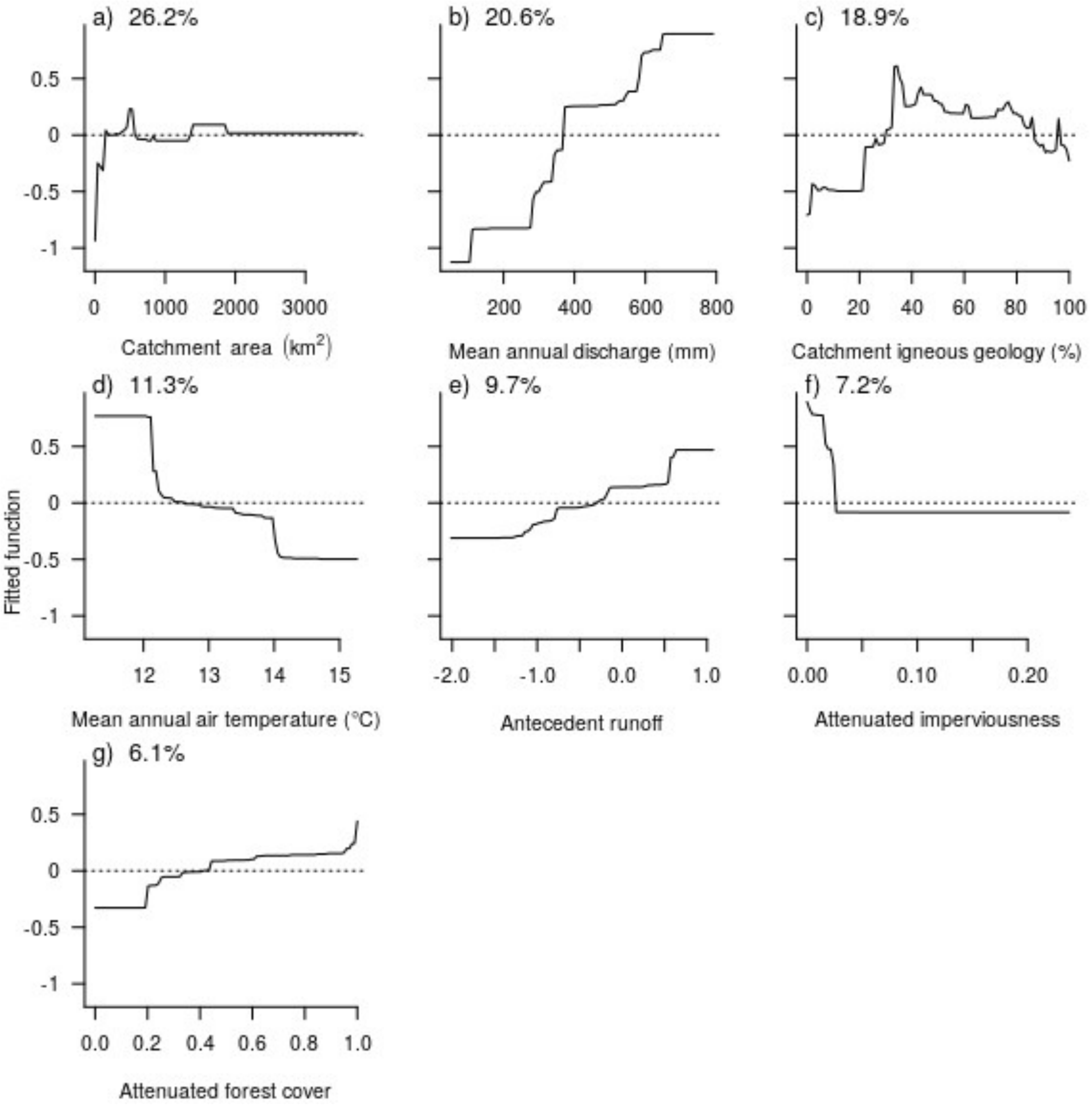


Figure 24. Fitted response curves for the predictors in the male-female platypus 'AllPlatyHWS' (boosted regression tree) habitat suitability model, in order of relative percentage contribution to the model: a) catchment area, b) mean annual discharge, c) catchment igneous geology, d) mean annual air temperature, e) antecedent runoff, f) attenuated imperviousness and g) attenuated forest cover.

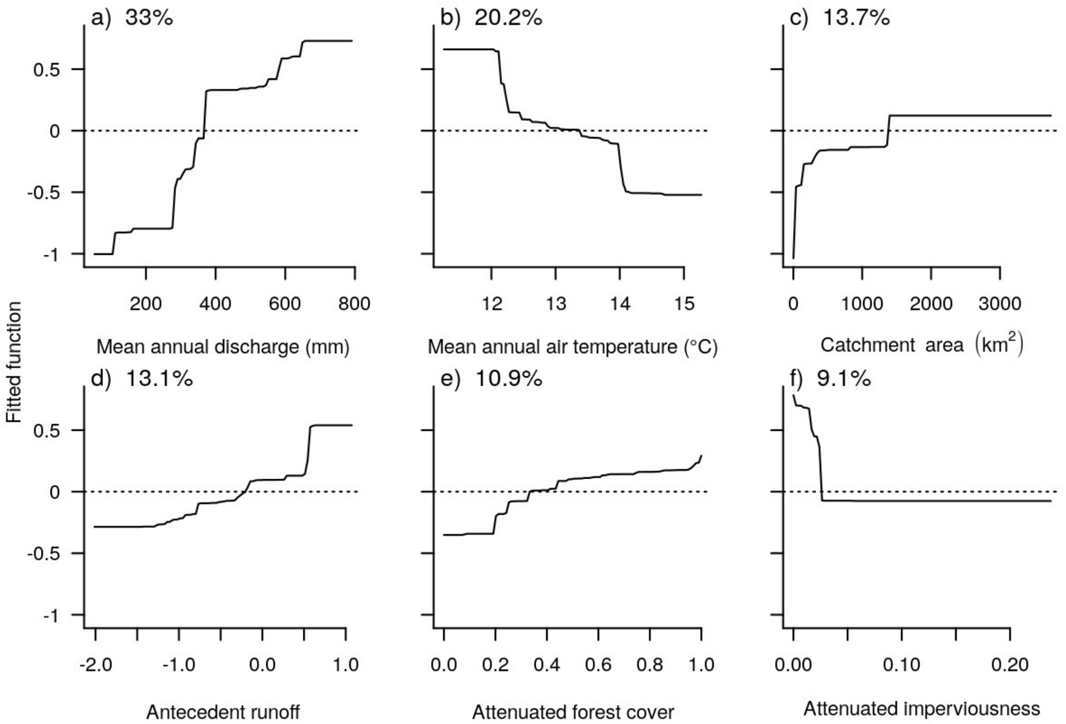


Figure 25. Fitted response curves for the predictors in the female-only platypus 'FemPlaty' (boosted regression tree) habitat suitability model, in order of relative percentage contribution to the model: a) mean annual runoff, b) mean annual air temperature, c) catchment area, d) antecedent runoff, e) attenuated forest cover and f) attenuated imperviousness.

The stacked barplots of stream lengths in each predicted habitat suitability category allows us to compare for each platypus model, the predicted impact of scenarios against one another, across an aggregate PPWP region-wide scale (Figure 26). For AllPlatyHWS, the predicted outcome under the ACCESS 1.0 and HadGEM2_CC moderate emission (RCP 4.5) pathways are clearly worse than that under BAUF, and the predicted outcome under the high emission (RCP 8.5) pathways are even worse still (left image, Figure 26). The AllPlatyHWS pattern of predicted outcome under the various scenarios also holds for FemPlaty, with poorer outcomes for RCP 4.5 under both ACCESS 1.0 and HadGEM2_CC, and severe declines given RCP 8.5 (right image, Figure 26). Under HadGEM2_CC RCP 8.5, there are no longer any lengths of stream in the 'Very High' predicted habitat suitability category for FemPlaty (right image, Figure 26).

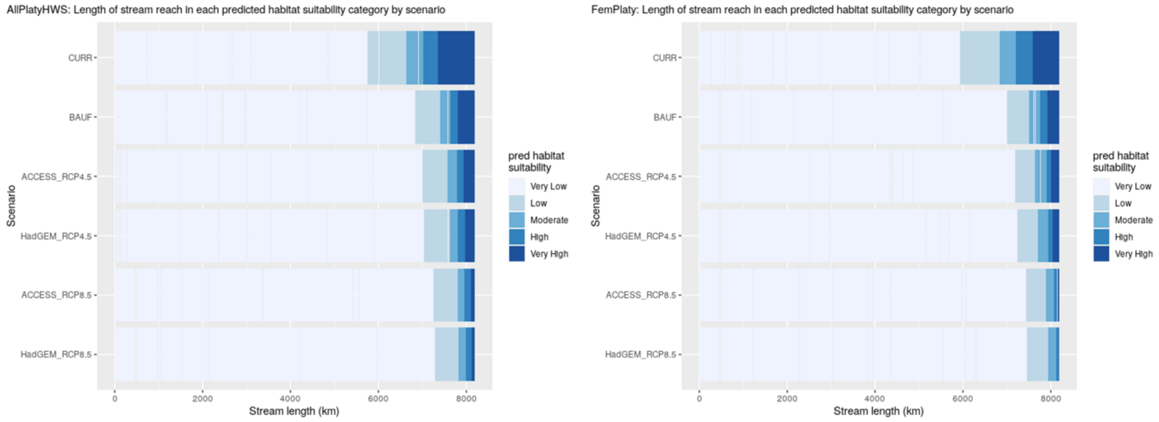


Figure 26. Summary stacked barplots of stream lengths in each habitat suitability category by climate change-impacted scenario for male-female platypus ('AllPlatyHWS', left) and female-only platypus ('FemPlaty', right). The intervals for the predicted habitat suitability categories are: Very Low 0 - 0.10, Low 0.10 - 0.20, Moderate 0.20 - 0.30, High 0.30 - 0.40, Very High 0.40 – 1.0.

The spatial distribution of predicted habitat suitability of male-female platypus as predicted by the AllPlatyHWS model under the various scenarios are shown in the upper four images in Figure 27. The bottom two images in Figure 27 are 'difference' maps that highlight the particular areas within the PPWP region where the 'bookend' scenario predictions differ from (i.e. is higher or lower than and by how much) the BAUF scenario used in HWS 2018.

The mapped habitat suitability of AllPlatyHWS under the CURR scenario shows a distribution largely concentrated in the north-east portion of the PPWP region with high predicted habitat suitability areas mainly in reaches in the sub-catchments of Yarra River Middle, Watts River (Rural), Watts River (Source), Yarra River Upper (Rural), Yarra River Upper (Source), Little Yarra River and Hoddles Creek, Woori Yallock Creek, Bunyip River Middle and Upper and Tarago River (top-left image, Figure 27). In the west of the region, there are a small number of scattered streams of moderate to high predicted habitat suitability in the sub-catchments of Werribee River Lower, Werribee River Middle, Werribee River Upper, Lerderderg River, Jacksons Creek, Emu Creek, Deep Creek Upper and Deep Creek Lower (top-left image, Figure 27).

Under the BAUF scenario the high predicted habitat suitability areas shrink quite considerably to mainly reaches in the sub-catchments of Yarra River Middle, Watts River (Source), Yarra River Upper (Rural) and Yarra River Upper (Source), with small pockets of moderate predicted habitat suitability in the sub-catchments of Watts River (Rural), Little Yarra River and Hoddles Creek, Woori Yallock Creek, Bunyip River Middle and Upper and Tarago River (top-right image, Figure 27). The areas of high predicted habitat suitability also become fragmented.

The spatial pattern of areas of high predicted habitat suitability for AllPlatyHWS under the ACCESS 1.0 RCP 4.5 scenario is very similar to that under the BAUF scenario but is even sparser still (middle-left image, Figure 27). Under the HadGEM2_CC RCP 8.5 scenario, we see even more pronounced contraction of areas of high predicted habitat suitability to a small number of reaches in the stronghold sub-catchments of Yarra River Middle, Watts River (Source), Yarra River Upper (Rural) and Yarra River Upper (Source) (middle-right image, Figure 27).

Under the ACCESS 1.0 RCP 4.5 scenario, there are a small number of streams with increased predicted habitat suitability relative to BAUF in the sub-catchments of Jacksons Creek, Yarra River Upper (Rural), Yarra River Upper (Source), Little Yarra River and Hoddles Creek and Bunyip River Middle and Upper (bottom-left image, Figure 27). There are, however, many more streams with decreased predicted habitat suitability relative to BAUF in the sub-catchments of Werribee River Upper, Watts River (Rural), Watts River (Source), Yarra River Upper (Rural), Yarra River Upper (Source), Little Yarra River and Hoddles Creek, Woori Yallock Creek, Bunyip River Middle and Upper and Tarago River (bottom-left image, Figure 27).

Under the HadGEM2_CC RCP 8.5 scenario, there is just one reach showing increased predicted habitat suitability relative to BAUF in the management unit of Watts River (Rural). The rest of the "difference" consists of decreases in predicted habitat suitability, and these decreases are in reaches spread across the sub-catchments of Werribee River Upper, Emu Creek, Deep Creek Upper, Yarra River Middle, Watts River (Rural), Watts River (Source), Yarra River Upper (Rural), Little Yarra River and Hoddles Creek, Woori Yallock Creek, Bunyip River Middle and Upper and Tarago River (bottom-right image, Figure 27).

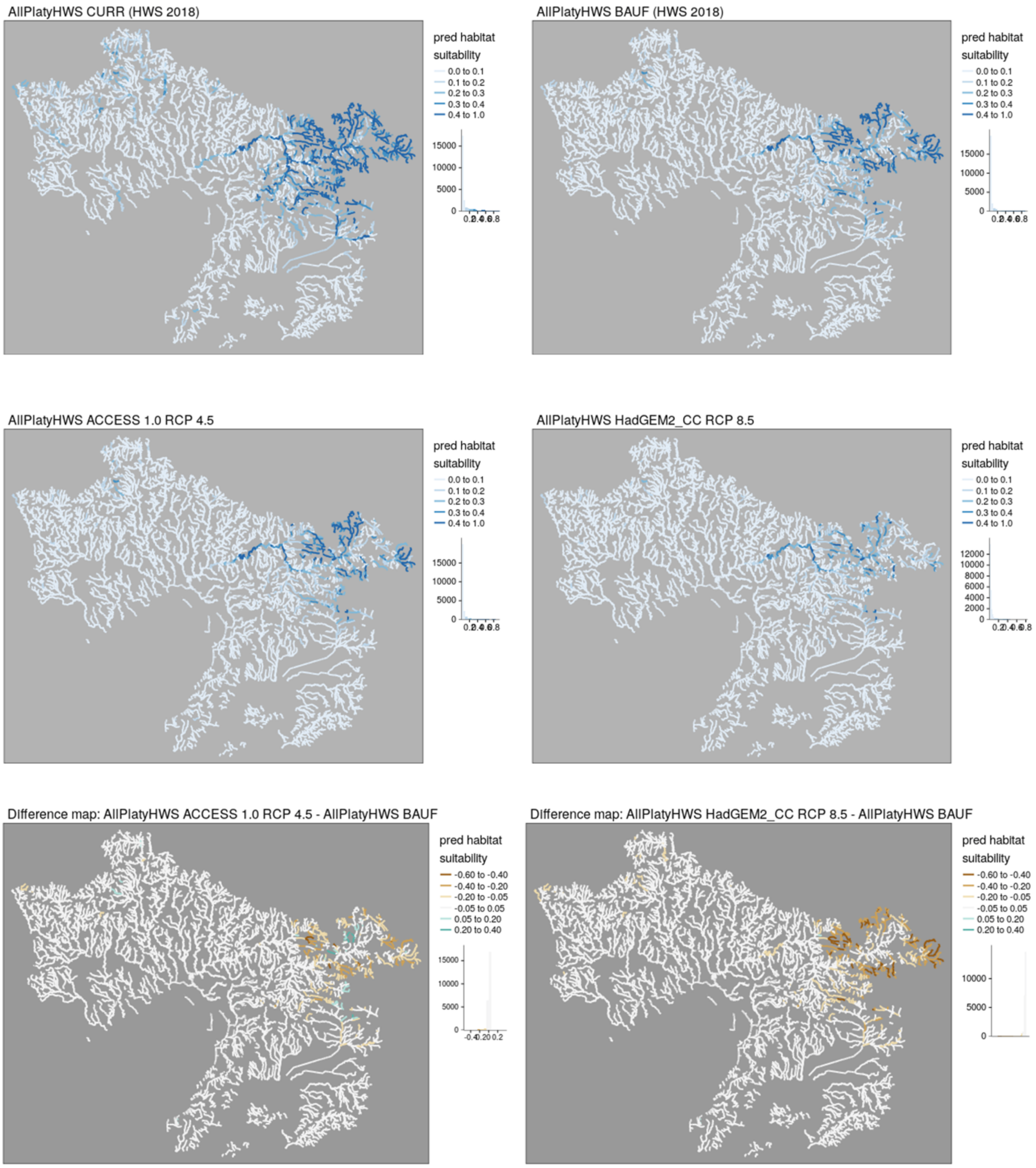


Figure 27. Mapped predictions of male-female platypus ('AllPlatyHWS') habitat suitability across the PPWP region under the CURR scenario used in HWS 2018 (top-left), the BAUF scenario used in HWS 2018 (top-right), ACCESS1.0 RCP4.5 (middle-left) and HadGEM2_CC RCP8.5 (middle-right). Deeper blues indicate higher predicted habitat suitability. 'Difference' maps show where predicted habitat suitability under ACCESS 1.0 RCP4.5 (bottom-left) and under HadGEM2_CC RCP8.5 differs from that of the BAUF scenario used in HWS 2018. On this diverging colour scale darker browns indicate lower predicted habitat suitability relative to BAUF, white indicates little difference and deeper blue-greens indicate higher predicted habitat suitability relative to BAUF.

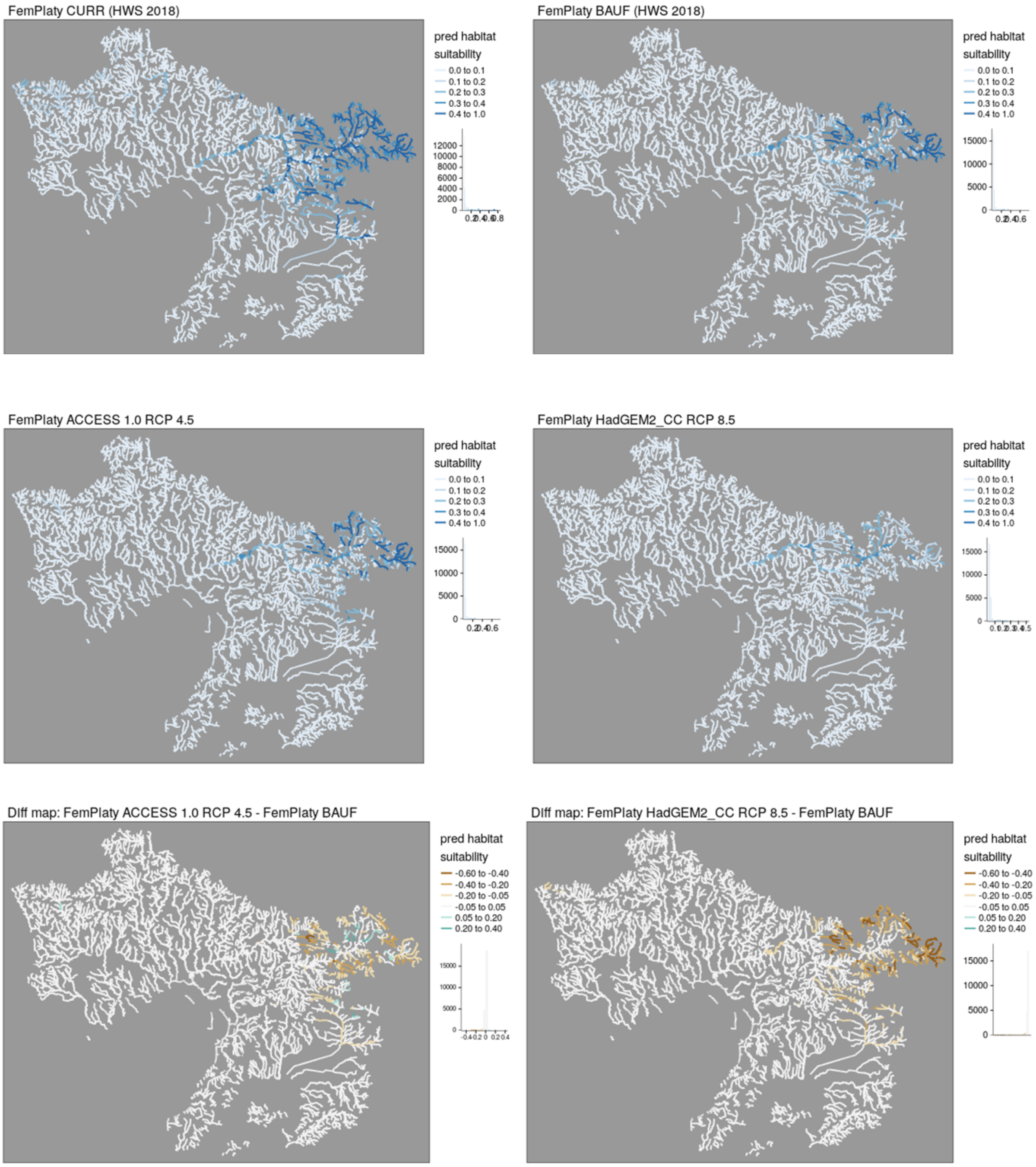
The spatial distribution of predicted habitat suitability of female-only platypus as predicted by the FemPlaty model under the various scenarios are shown in the upper four images in Figure 28. The bottom two images in Figure 28 are 'difference' maps that highlight the particular areas within the

PPWP region where the ‘bookend’ scenario predictions differ from (i.e. is higher or lower than and by how much) the BAUF scenario used in HWS 2018.

The mapped habitat suitability of FemPlaty under the CURR scenario is quite similar to that of AllPlatyHWS and consist of a distribution largely concentrated in the north-eastern portion of the PPWP region with high predicted habitat suitability areas mainly in reaches in the sub-catchments of Yarra River Middle, Watts River (Rural), Watts River (Source), Yarra River Upper (Rural), Yarra River Upper (Source), Little Yarra River and Hoddles Creek, Woori Yallock Creek, Bunyip River Middle and Upper and Tarago River (top-left image, Figure 28). In the west of the region, there are a small number of scattered streams of moderate predicted habitat suitability in the sub-catchments of Werribee River Lower, Werribee River Middle, Werribee River Upper, Lerderderg River, Jacksons Creek and Deep Creek Lower (top-left image, Figure 28).

Under the BAUF scenario the high predicted habitat suitability areas of FemPlaty (similar to that of AllPlatyHWS) contract considerably to mainly reaches in the sub-catchments of Yarra River Middle, Watts River (Source), Yarra River Upper (Rural) and Yarra River Upper (Source), with small pockets of moderate predicted habitat suitability in the sub-catchments of Watts River (Rural), Little Yarra River and Hoddles Creek, Woori Yallock Creek, Bunyip River Middle and Upper and Tarago River (top-right image, Figure 28). The areas of high predicted habitat suitability also become fragmented.

The spatial pattern of areas of high predicted habitat suitability for FemPlaty under the ACCESS 1.0 RCP 4.5 scenario is very similar to that under the BAUF scenario but is even sparser still (middle-left image, Figure 28). Under the HadGEM2_CC RCP 8.5 scenario, we see even more drastic contraction of areas of predicted habitat suitability. There are virtually no reaches of high predicted habitat suitability. Instead what remains are reaches of moderate predicted habitat suitability in the stronghold sub-catchments of Yarra River Middle, Watts River (Source), Yarra River Upper (Rural) and Yarra River Upper (Source) (middle-right image, Figure 28).


FemPlaty CURR (HWS 2018)

FemPlaty BAUF (HWS 2018)

FemPlaty ACCESS 1.0 RCP 4.5

FemPlaty HadGEM2_CC RCP 8.5

Diff map: FemPlaty ACCESS 1.0 RCP 4.5 - FemPlaty BAUF

Diff map: FemPlaty HadGEM2_CC RCP 8.5 - FemPlaty BAUF

Figure 28. Mapped predictions of female-only platypus ('FemPlaty') habitat suitability across the PPWP region under the CURR scenario used in HWS 2018 (top-left), the BAUF scenario used in HWS 2018 (top-right), ACCESS1.0 RCP4.5 (middle-left) and HadGEM2_CC RCP8.5 (middle-right). Deeper blues indicate higher predicted habitat suitability. 'Difference' maps show where predicted habitat suitability under ACCESS 1.0 RCP4.5 (bottom-left) and under HadGEM2_CC RCP8.5 differs from that of the BAUF scenario used in HWS 2018. On this diverging colour scale darker browns indicate lower predicted habitat suitability relative to BAUF, white indicates little difference and deeper blue-greens indicate higher predicted habitat suitability relative to BAUF.

Under the ACCESS 1.0 RCP 4.5 scenario, there are a small number of streams with increased FemPlaty predicted habitat suitability relative to BAUF in the sub-catchments of Lerderderg River, Yarra River Upper (Rural), Yarra River Upper (Source), Little Yarra River and Hoddles Creek and Bunyip River Middle and Upper (bottom-left image, Figure 28). There are, however, many more streams with decreased predicted habitat suitability relative to BAUF in the sub-catchments of Watts River (Rural), Watts River (Source), Yarra River Upper (Rural), Yarra River Upper (Source), Little Yarra

River and Hoddles Creek, Woori Yallock Creek, Bunyip River Middle and Upper and Tarago River (bottom-left image, Figure 28).

Under the HadGEM2_CC RCP 8.5 scenario, there are virtually no reaches showing increased FemPlaty predicted habitat suitability relative to BAUF. The rest of the "difference" consists of decreases in predicted habitat suitability, and these decreases are in reaches spread across the sub-catchments of Werribee River Upper, Yarra River Middle, Watts River (Rural), Watts River (Source), Yarra River Upper (Rural), Little Yarra River and Hoddles Creek, Woori Yallock Creek, Bunyip River Middle and Upper and Tarago River (bottom-right image, Figure 28).

6.1 What is the mitigating impact of actions?

The three stacked barplot summaries of stream lengths in each predicted habitat suitability category (Figure 29) allows us to compare climate-change-impacted scenarios for AllPlatyHWS *without* (i.e. ACCESS 1.0 RCP 4.5, HadGEM2_CC RCP4.5, ACCESS 1.0 RCP8.5 and HadGEM2_CC RCP 8.5) and *with* the two main mitigating actions, namely, revegetating both stream sides to a 20m riparian buffer on its own (RV20) and revegetation together with treatment of all future *and* some existing impervious cover such that attenuated imperviousness in existing urban areas is reduced to 75% of 2016 levels (RV20_SW3).

For AllPlatyHWS, RV20 is predicted to be quite effective as a mitigating action under both RCP 4.5 and RCP 8.5 scenarios with ACCESS 1.0 and HadGEM2_CC with predicted increases in lengths of stream in the 'Low', 'Moderate' and 'Very High' habitat suitability categories (last four rows in bottom-left image compared to last four rows in top image in Figure 29). RV20_SW3 is likewise predicted to be quite effective as a mitigating action, and it produces a larger quantum of benefit than RV20 on its own. Again, the benefit is mainly manifest as predicted increases in lengths of stream in the 'Low', 'Moderate' and 'Very High' habitat suitability categories (last four rows in bottom-right image compared to last four rows in bottom-left image in Figure 29).

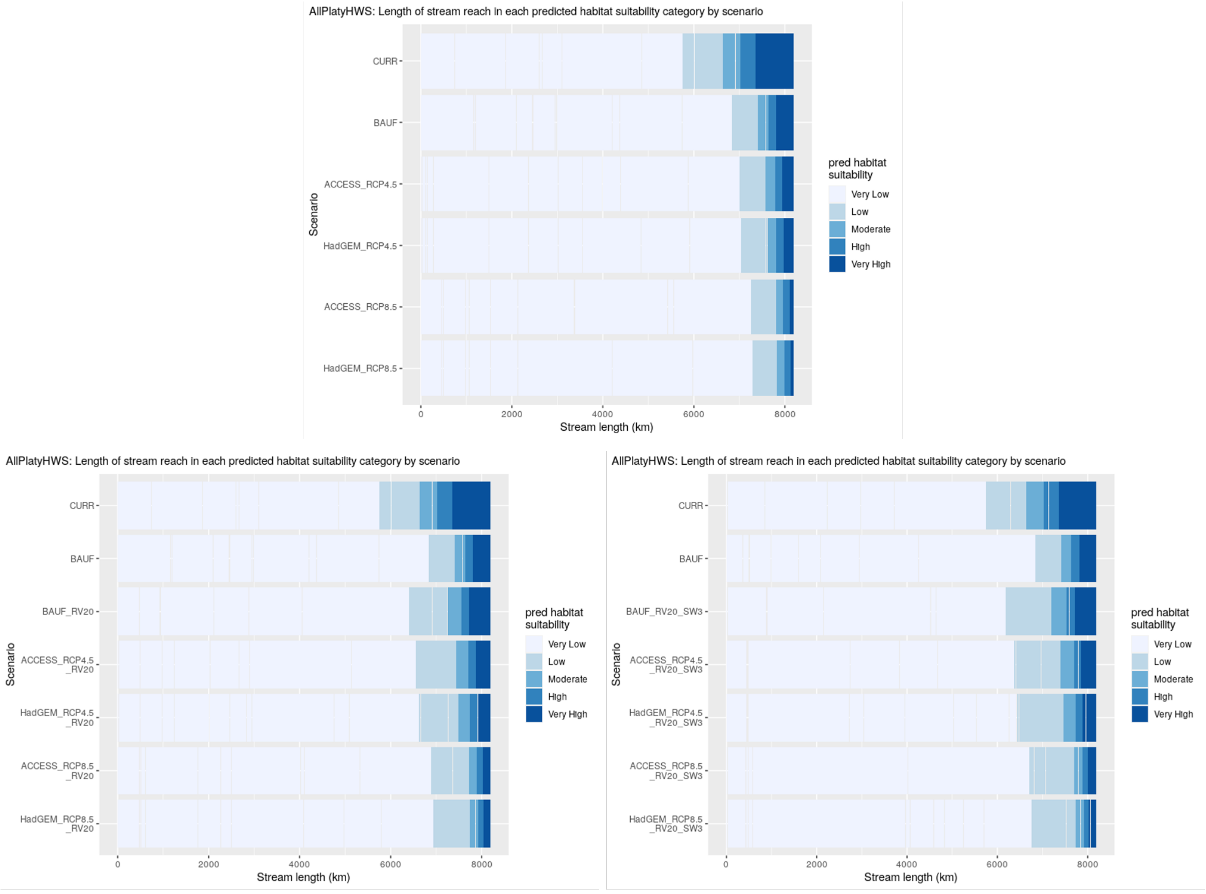


Figure 29. Summary stacked barplots for male-female platypus ('AllPlatyHWS') of stream lengths in each predicted habitat suitability category by scenario for climate change-impacted scenarios with no mitigation action (top), for CC-impacted scenarios with RV20 (bottom-left) and for CC-impacted scenarios with RV20_SW3 (see Table 4 for full description of each scenario). The intervals for the predicted habitat suitability categories are: Very Low 0 - 0.10, Low 0.10 - 0.20, Moderate 0.20 - 0.30, High 0.30 - 0.40, Very High 0.40 – 1.0.

The three stacked barplot summaries of stream lengths in each predicted habitat suitability category (Figure 30) allows us to climate-change-impacted scenarios for FemPlaty, climate-change-impacted scenarios *without* (i.e. ACCESS 1.0 RCP 4.5, HadGEM2_CC RCP4.5, ACCESS 1.0 RCP8.5 and HadGEM2_CC RCP 8.5) and *with* the two main mitigating actions, namely, revegetating both stream sides to a 20m riparian buffer on its own (RV20) and revegetation together with treatment of all future *and* some existing impervious cover such that attenuated imperviousness in existing urban areas is reduced to 75% of 2016 levels (RV20_SW3).

For FemPlaty, RV20 is predicted to have some positive benefit as a mitigating action under both RCP 4.5 and RCP 8.5 scenarios with ACCESS 1.0 and HadGEM2_CC. This is manifest mainly as predicted increases in lengths of stream in the 'High' habitat suitability category (last four rows in bottom-left image compared to last four rows in top image in Figure 30). RV20_SW3 is likewise predicted to have some benefit as a mitigating action, and it produces a slightly larger quantum of benefit than RV20 on its own. Again, the benefit is mainly manifest as predicted increases in lengths of stream in the 'High' habitat suitability category (last four rows in bottom-right image compared to last four rows in bottom-left image in Figure 30).

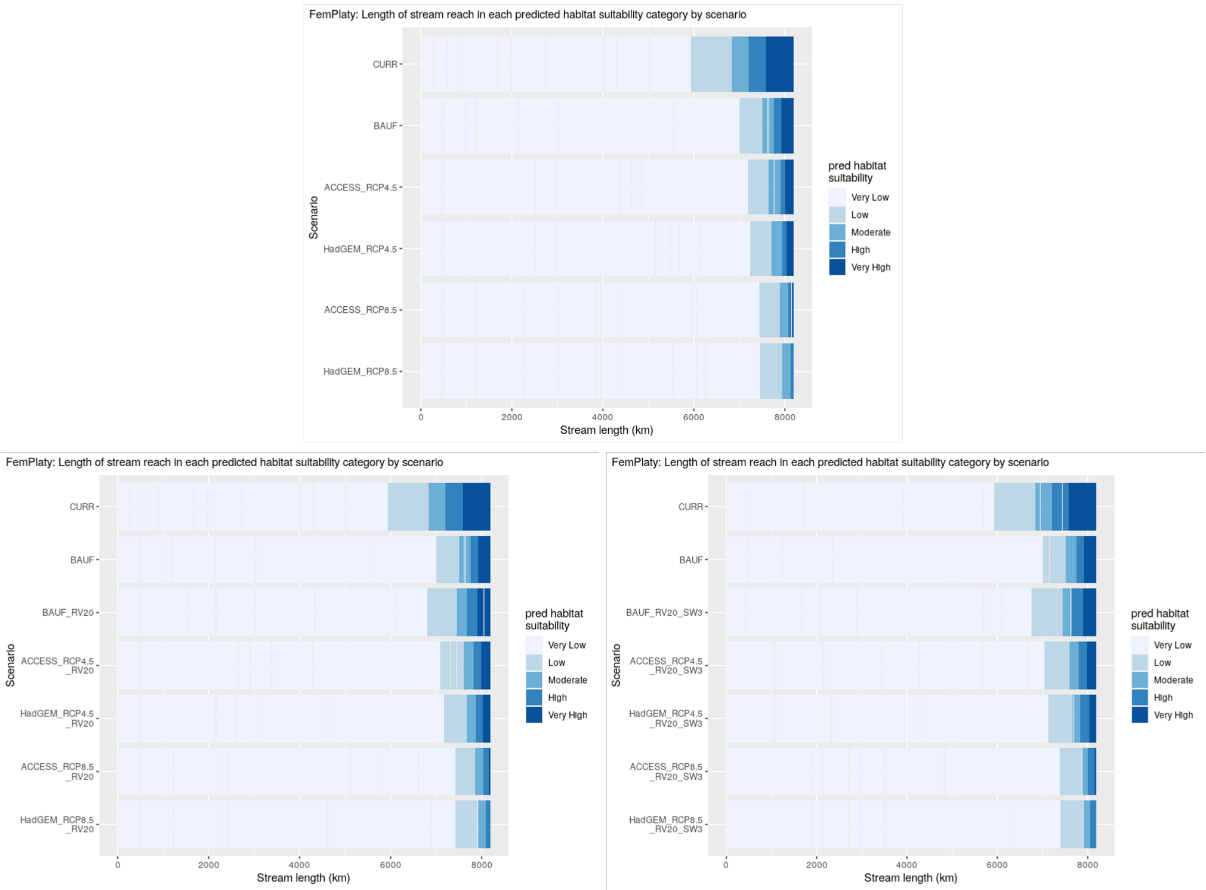


Figure 30. Summary stacked barplots for female-only platypus ('FemPlaty') of stream lengths in each predicted habitat suitability category by scenario for climate change-impacted scenarios with no mitigation action (top), for CC-impacted scenarios with RV20 (bottom-left) and for CC-impacted scenarios with RV20_SW3 (see Table 4 for full description of each scenario). The intervals for the predicted habitat suitability categories are: Very Low 0 - 0.10, Low 0.10 - 0.20, Moderate 0.20 - 0.30, High 0.30 - 0.40, Very High 0.40 – 1.0.

6.2 Results for alternative male-female platypus model ('AllPlatyColeman')

Post-HWS 2018, an alternative male-female platypus HSM (hereafter 'AllPlatyColeman') was developed in the course of writing the platypus modelling work up for publication. On reflection and in the course of considering reviewer comments on the manuscript, inclusion of the 'catchment igneous' predictor was difficult to justify. Therefore, for the 'AllPlatyColeman' model we dropped the 'catchment Igneous' predictor (that was in the 'AllPlatyHWS' model), and re-fit the model using the same input biological and environmental predictor dataset. The fitted response curves for the predictors, in order of relative contribution to the model, is shown in Figure 31). As you can see, whilst there is a slight difference in the relative contribution ordering of predictors, the shape of the fitted response curves are quite similar to and consistent with those of the 'AllPlatyHWS' (Figure 24).

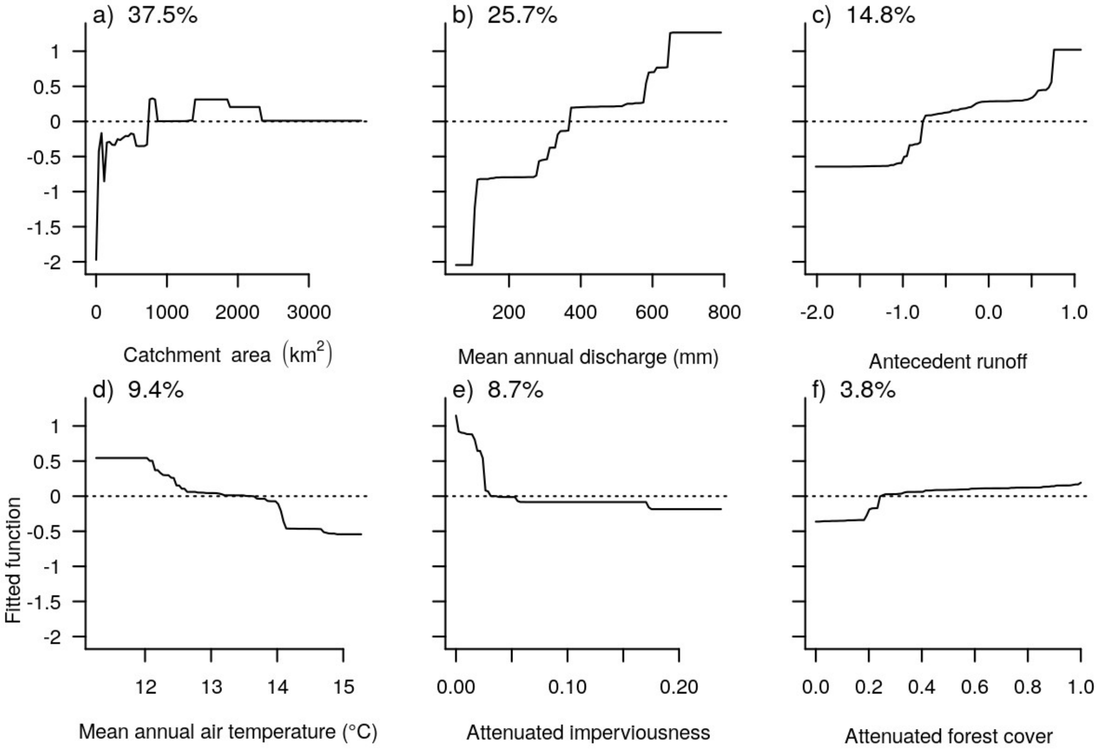


Figure 31. Fitted response curves for the predictors in the alternative male-female platypus 'AllPlatyColeman' (boosted regression tree) habitat suitability model, in order of relative percentage contribution to the model: a) catchment area, b) mean annual runoff, c) antecedent runoff, d) mean annual air temperature, e) attenuated imperviousness and f) attenuated forest cover.

The first point to note is that the 'AllPlatyColeman' model differs from the 'AllPlatyHWS' model, in that the 'AllPlatyHWS' model predicts greater lengths of streams in the 'Low', relative to the 'Moderate', 'High' and 'Very High' predicted habitat suitability categories, irrespective of the scenario being considered (Figure 32).

For AllPlatyColeman, the predicted outcome under the ACCESS 1.0 and HadGEM2_CC moderate emission (RCP 4.5) pathways are slightly but not greatly, worse than that under BAUF. The predicted outcomes under the high emission (RCP 8.5) pathways are, however, notably worse still than that under BAUF (left image, Figure 32).

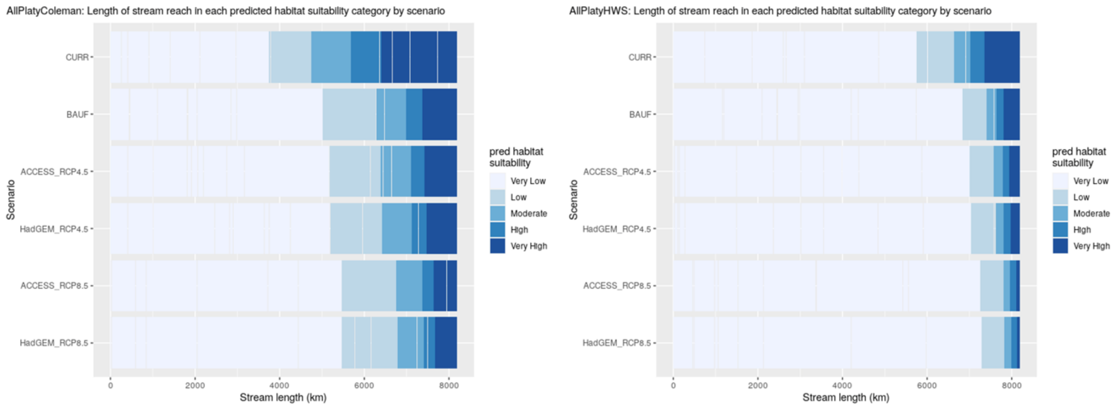


Figure 32. Summary stacked barplots of stream lengths in each habitat suitability category by climate change-impacted scenario for alternative male-female platypus ('AllPlatyColeman', left) and male-female platypus ('AllPlatyHWS', right). The intervals for the predicted habitat suitability categories are: Very Low 0 - 0.10, Low 0.10 - 0.20, Moderate 0.20 - 0.30, High 0.30 - 0.40, Very High 0.40 – 1.0.

The spatial distribution of predicted habitat suitability of male-female platypus as predicted by the AllPlatyColeman model under the various scenarios are shown in the upper four images in Figure 33. The bottom two images in Figure 33 are 'difference' maps that highlight the particular areas within the PPWP region where the 'bookend' scenario predictions differ from (i.e. is higher or lower than and by how much) the BAUF scenario used in HWS 2018.

The mapped habitat suitability of AllPlatyColeman under the CURR scenario shows a distribution that is much broader than that of AllPlatyHWS across the PPWP region (*cf* top-left images in Figure 27 and Figure 33). There is much overlap in streams of high predicted habitat suitability in the north-eastern portion of the region. The greatest differences in distribution of high predicted habitat suitability areas are in the western and south-eastern portions of the region. For AllPlatyColeman, there are notable areas with high predicted habitat suitability reaches in the western sub-catchments of Werribee River Lower, Werribee River Middle, Werribee River Upper, Lerderderg River, Jacksons Creek, Emu Creek, Deep Creek Upper and Deep Creek Lower (top-left image, Figure 33). In the north, there are also a smattering of high predicted habitat suitability reaches in the sub-catchments of Plenty River Upper, Plenty River (Source) and Diamond Creek (Source). In the south-east, there are high predicted habitat suitability reaches in the sub-catchments of Cardinia, Toomuc, Deep and Ararat Creeks, Bunyip Lower, King Parrot and Musk Creeks, Lang Lang River and Mornington Peninsula South-Eastern Creeks (top-left image, Figure 33).

Under the BAUF scenario the high predicted habitat suitability areas of AllPlatyColeman contract considerably. In the west, they contract to the upper reaches in the sub-catchments of Werribee River Upper, Lerderderg River, Jacksons Creek and Emu Creek (top-right image, Figure 33). In the north-east, they contract to reaches in the stronghold sub-catchments of Yarra River Middle, Watts River (Source), Yarra River Upper (Rural) and Yarra River Upper (Source), Little Yarra River and Hoddles Creek, Woori Yallock Creek, Bunyip River Middle and Upper and Tarago River (top-right image, Figure 33). The areas of high predicted habitat suitability in the west become highly fragmented. The situation is better in the north-east region, but there is still some degree of fragmentation of high predicted habitat suitability streams.

The spatial pattern of areas of high predicted habitat suitability for AllPlatyHWS under the ACCESS 1.0 RCP 4.5 scenario is essentially very similar to that under the BAUF scenario (middle-left image, Figure 33). Under the HadGEM2_CC RCP 8.5 scenario, the spatial pattern of areas of high predicted habitat suitability are quite similar to that under the ACCESS 1.0 RCP 4.5 scenario but there is more pronounced contraction of areas of high predicted habitat suitability, particularly in the west (middle-right image, Figure 33).

Under the ACCESS 1.0 RCP 4.5 scenario, there are a number of streams with increased predicted habitat suitability relative to BAUF in the sub-catchments of Werribee River Middle, Werribee River Upper, Lerderderg River, Jacksons Creek, Emu Creek, Deep Creek Upper, Boyd Creek, Yarra River Upper (Rural), Yarra River Upper (Source), Bunyip River Middle and Upper and Mornington Peninsula South-Eastern Creeks (bottom-left image, Figure 33). There are also many streams throughout the eastern portion of PPWP with decreased predicted habitat suitability relative to BAUF, including reaches in the stronghold sub-catchments of Watts River (Rural), Watts River (Source), Yarra River Upper (Rural), Yarra River Upper (Source), Little Yarra River and Hoddles Creek, Woori Yallock Creek, Bunyip River Middle and Upper, Tarago River and Lang Lang River (bottom-left image, Figure 33).

Under the HadGEM2_CC RCP 8.5 scenario, there are a small number of reaches, mainly in the western portion of PPWP showing increased predicted habitat suitability relative to BAUF. These occur in the management unit of Werribee River Middle, Werribee River Upper, Lerderderg River, Deep Creek Upper and Boyd Creek (bottom-right image, Figure 33). The rest of the “difference” consists of decreases in predicted habitat suitability, and these decreases are in reaches spread across the sub-catchments of Werribee River Upper, Lerderderg River, Jacksons Creek, Deep Creek Upper, Yarra River Lower, Yarra River Middle, Watts River (Rural), Watts River (Source), Yarra River Upper (Rural), Little Yarra River and Hoddles Creek, Woori Yallock Creek, Bunyip River Middle and Upper, Tarago River, King Parrot and Musk Creeks, Lang Lang River, and Mornington Peninsula South-Eastern Creeks (bottom-right image, Figure 33).

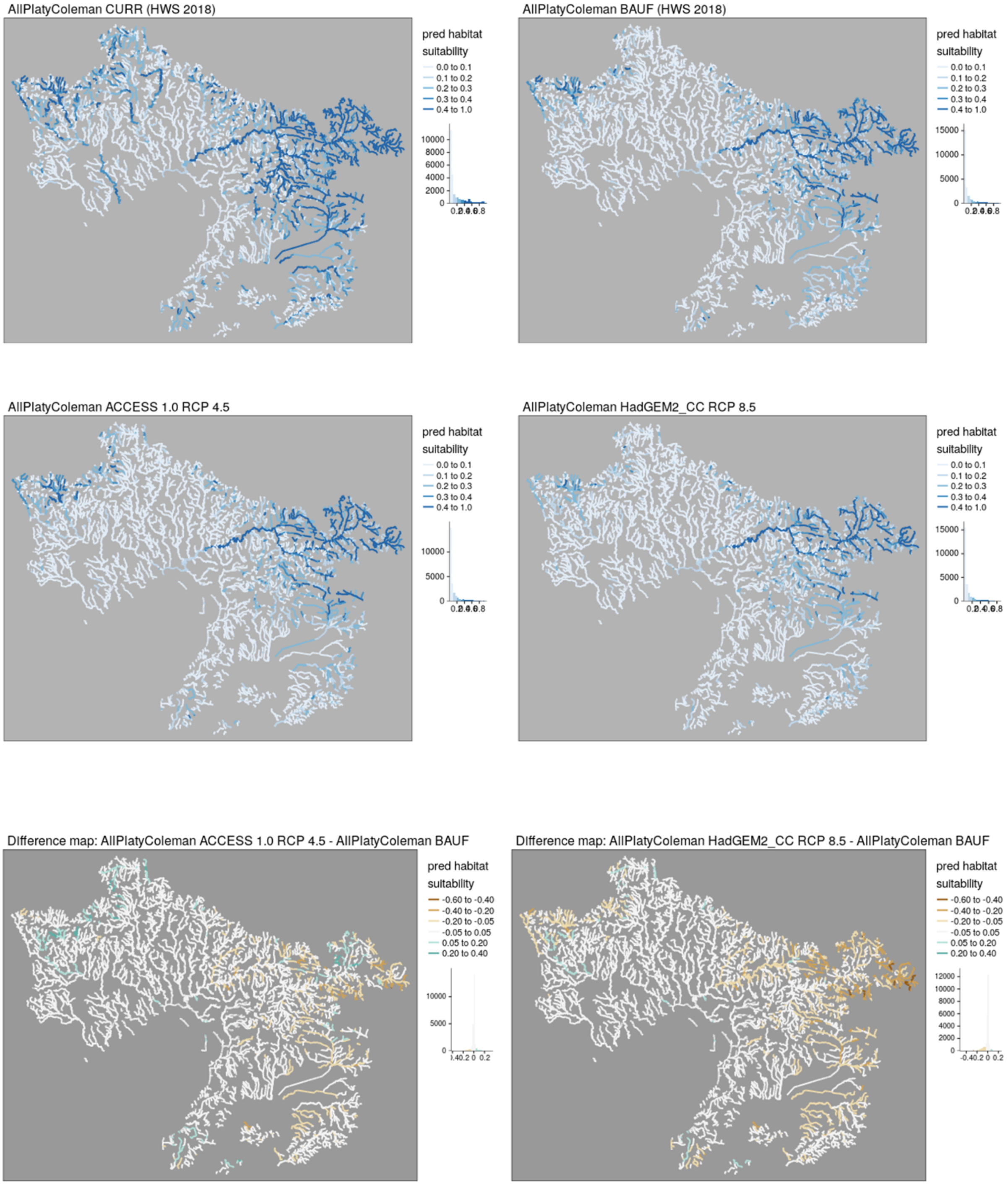


Figure 33. Mapped predictions of alternative male-female platypus ('AllPlatyColeman') habitat suitability across the PPWP region under the CURR scenario used in HWS 2018 (top-left), the BAUF scenario used in HWS 2018 (top-right), ACCESS1.0 RCP4.5 (middle-left) and HadGEM2_CC RCP8.5 (middle-right). Deeper blues indicate higher predicted habitat suitability. 'Difference' maps show where predicted habitat suitability under ACCESS 1.0 RCP4.5 (bottom-left) and under HadGEM2_CC RCP8.5 differs from that of the BAUF scenario used in HWS 2018. On this diverging colour scale darker browns indicate lower predicted habitat suitability relative to BAUF, white indicates little difference and deeper blue-greens indicate higher predicted habitat suitability relative to BAUF.

The three stacked barplot summaries of stream lengths in each predicted habitat suitability category (Figure 34) allows us to compare climate-change-impacted scenarios for AllPlatyColeman *without* (i.e. ACCESS 1.0 RCP 4.5, HadGEM2_CC RCP4.5, ACCESS 1.0 RCP8.5 and HadGEM2_CC RCP 8.5) and *with* the two main mitigating actions, namely, revegetating both stream sides to a 20m riparian buffer on its own (RV20) and revegetation together with treatment of all future *and* some existing impervious cover such that attenuated imperviousness in existing urban areas is reduced to 75% of 2016 levels (RV20_SW3).

For AllPlatyColeman, RV20 is predicted to be quite effective as a mitigating action under RCP 4.5 with ACCESS 1.0 and HadGEM2_CC, with predicted increases in lengths of stream in the 'Moderate', 'High' and 'Very High' habitat suitability categories (rows 4 and 5 in bottom-left image compared to rows 3 and 4 in top image in Figure 34). Under RCP 8.5 with ACCESS 1.0 and HadGEM2_CC however, the positive benefit of RV20 is more subdued with a smaller quantum of predicted increases in lengths of stream in the 'Moderate', 'High' and 'Very High' habitat suitability categories (rows 6 and 7 in bottom-left image compared to rows 5 and 6 in top image in Figure 34).

RV20_SW3 is likewise predicted to be quite effective as a mitigating action under RCP 4.5 with ACCESS 1.0 and HadGEM2_CC, with sizeable predicted increases in lengths of stream in the 'Moderate', 'High' and 'Very High' habitat suitability categories (rows 4 and 5 in bottom-right image compared to rows 3 and 4 in top image in Figure 34). Under RCP 8.5 with ACCESS 1.0 and HadGEM2_CC, however, the positive benefit of RV20_SW3 is more subdued with a smaller quantum of predicted increases in lengths of stream in the 'Moderate', 'High' and 'Very High' habitat suitability categories (rows 6 and 7 in bottom-left image compared to rows 5 and 6 in top image in Figure 34). Under both moderate and high emission scenarios however, RV20_SW3 produces a larger quantum of benefit than RV20 on its own.

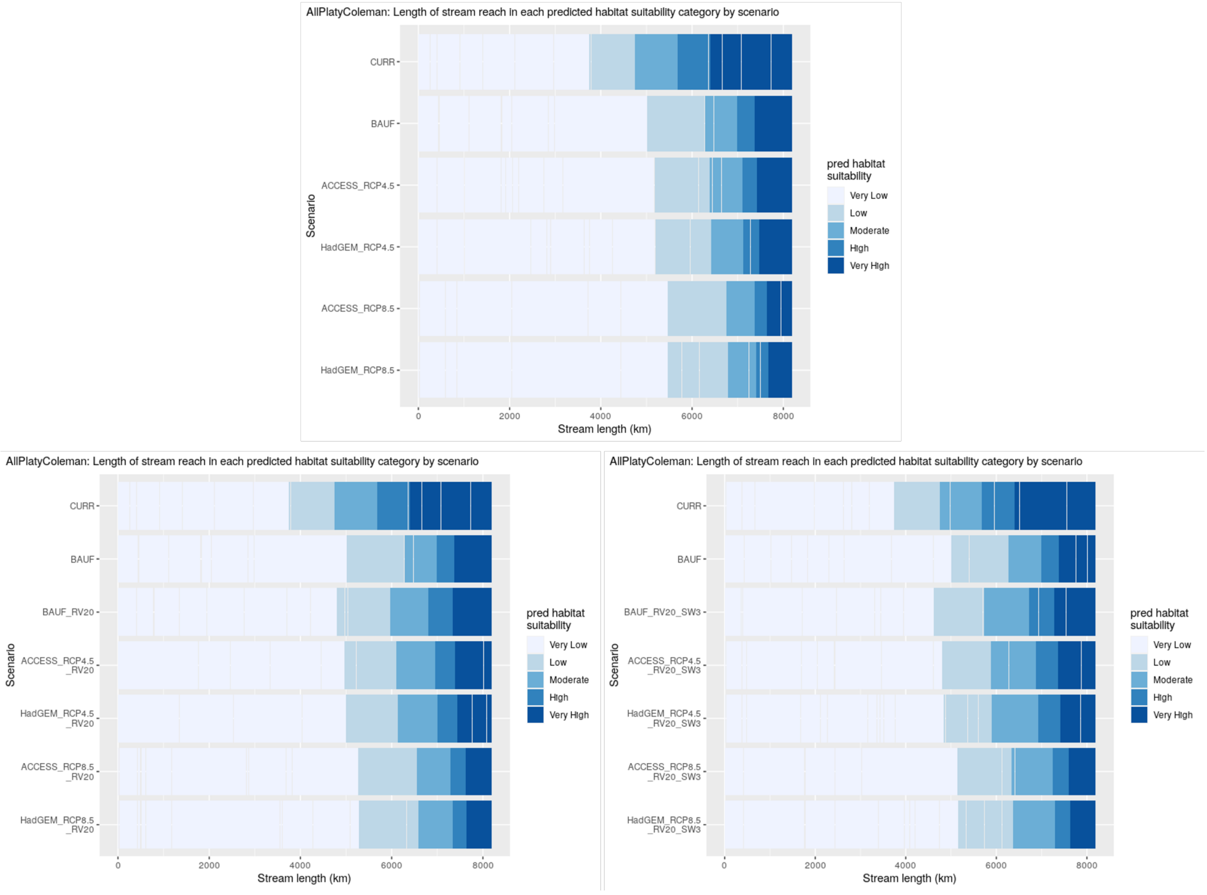


Figure 34. Summary stacked barplots for male-female platypus ('AllPlatyColeman') of stream lengths in each predicted habitat suitability category by scenario for climate change-impacted scenarios with no mitigation action (top), for CC-impacted scenarios with RV20 (bottom-left) and for CC-impacted scenarios with RV20_SW3 (see Table 4 for full description of each scenario). The intervals for the predicted habitat suitability categories are: Very Low 0 - 0.10, Low 0.10 - 0.20, Moderate 0.20 - 0.30, High 0.30 - 0.40, Very High 0.40 – 1.0.

7 Application for the Mid-Term Evaluation of the 2018 Healthy Waterways Strategy

The information presented in this report was applied in two ways to support the Science Inquiry Report (Melbourne Water, 2023a) for the Mid-Term Evaluation of the 2018 Healthy Waterways Strategy.

First, changes in future (2070) predictions for air temperature and mean annual runoff - between what was originally used in HSM models at the start of the Strategy and the updated climate information available - were summarised and reported. This included a summary of consequent changes to HSM predictions for macroinvertebrates, female platypus and for two climate change vulnerable native fish species, River Blackfish (*Gadopsis marmoratus*) and Ornate Galaxias (*Galaxias olidus*).

Second, a qualitative assessment was undertaken at the HWS sub-catchment scale to identify 'climate change stronghold' (CCS) and 'climate change vulnerable' (CCV) sub-catchments. This qualitative assessment was performed by Melbourne Water. CCS sub-catchments were considered areas to be "resilient" to climate change based on recent down-scaled Victorian Climate Projections; VCP19. It is important to ensure these areas are managed appropriately to ensure they remain resilient. CCV sub-catchments were considered areas which are predicted to be even more impacted by climate change than predicted in the current strategy. These areas are important because the HWS may not have considered adequate climate change adaption actions in setting long-term targets. To determine CCS and CCV sub-catchments, the spatial distribution (using HSMs) of values made in 2018 (CURR and BAUF) were compared with 'worst case' (HadGEM2_CC_RCP 8.5) updated climate-change predictions using the VCP19 dataset. The criteria used to assist in the assessment of CCS and CCV focus area sub-catchments are available in Table 5 and described in greater detail within the HWS Mid-term Evaluation Synthesis Methods document (Melbourne Water, 2023b). Due to time and data constraints, this assessment was only performed for three key values using HSMs for platypus (female only), fish (climate sensitive species: River Blackfish and Ornate Galaxias), and macroinvertebrates. Finally, sub-catchments were grouped into those with moderate or greater underlying environmental conditions (Group A) and those with a high proportion of low or very low conditions (Group B). This provides information that may help prioritise effort based on findings of the HWS Mid-term Evaluation.

In some cases, a sub-catchment was identified as belonging to CCS and CCV. This is possible because the climate change assessment occurred on species individually and at spatial scales smaller than sub-catchments. For instance, River Blackfish may be predicted to remain stable in the upper part of a sub-catchment but decline in lower parts of the same sub-catchment.

The results of the CCS and CCV assessment are available below in Figure 35.

Table 5. Criterion used to determine 'Focus areas' or HWS sub-catchments from a climate change perspective for platypus, fish and macroinvertebrates.

Focus area	Lines of evidence / criteria
CCSs Climate stronghold	Difference between CURR (2018 baseline) versus HadGEM2_CC_RCP 8.5 (worst-case-scenario of the new climate change projections). Qualitative assessment: Stream reaches in the majority of the sub-catchment showed minimal change in predictions, focussing on reaches with High and Very High habitat suitability.
CCVs Climate vulnerable	Difference between BAUF (climate assumptions made in 2018) versus HadGEM2_CC_RCP 8.5 (worst-case-scenario of the new climate change projections). Qualitative assessment. Stream reaches in the majority of the sub-catchment showed large declines in suitable habitat.

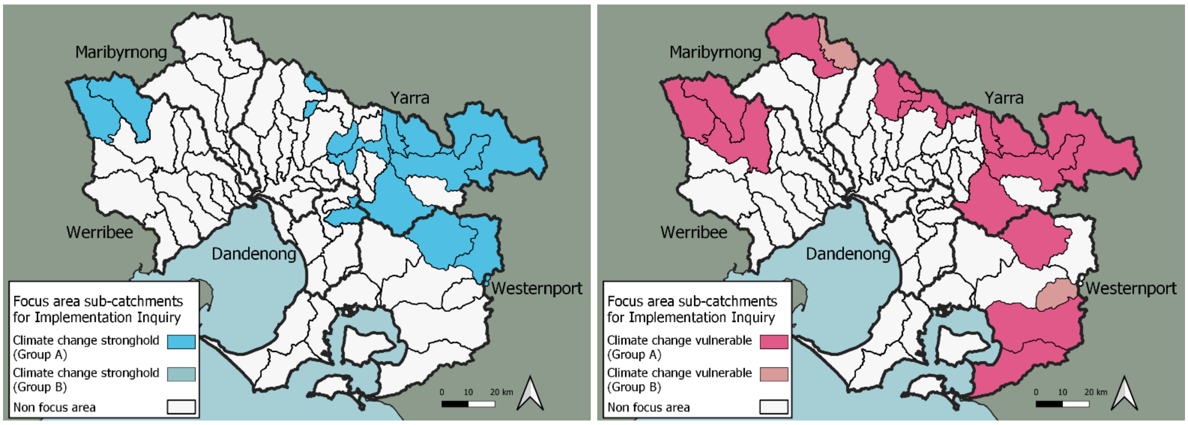


Figure 35. Sub-catchments identified as being (a) climate change strongholds (CCS; left) and (b) climate change vulnerable (CCV; right) for one or more of four aquatic taxa/species: macroinvertebrates, River Blackfish, Ornate Galaxias, and platypus. Classifications were based on differences between "baseline" habitat suitability predictions and predictions that use mean annual temperature (from VCP19) and mean annual runoff depth (from BoM). Sub-catchments are shown as those with moderate or greater underlying environmental conditions (Group A) and those with a high proportion of low or very low conditions (Group B). This provides information that may help prioritise effort based on findings of the implementation inquiry. Note: there are no Climate change stronghold focus areas in Group B.

8 Discussion

We return to our starting questions: do we get very different predictions using more sophisticated and detailed climate change data and/or methods of modelling drying patterns and intensity? And are our mitigating actions robust under a range of plausible climate futures? The answers differ by instream taxonomic groups of interest. The pattern of impact observed for different taxa under moderate emission pathway RCP4.5 and high emission pathway RCP 8.5, relative to the BAUF scenario used in HWS 2018 is summarised in Table 6, along with an indicator of the effectiveness of mitigating actions.

Table 6. Summary of impact on instream taxa groups under moderate emission pathway RCP 4.5 and high emission pathway RCP 8.5, relative to the BAUF scenario used in HWS 2018, along with indicators of the effectiveness of mitigating actions. Down arrow (↓) indicates reduced habitat suitability for that emission scenario with more arrows denoting more severe reduction. Plus (+) sign indicates positive benefit from the mitigating action with more pluses denoting larger benefits.

	Macroinvertebrates lumar	River Blackfish	Ornate Galaxias	AllPlaty	FemPlaty
'RCP 4.5 Moderate' relative to HWS 2018 BAUF		↓	↓	↓↓	↓↓
'RCP 8.5 high' relative to HWS 2018 BAUF		↓↓↓	↓↓↓	↓↓↓	↓↓↓↓
Influence of revegetation on its own	++	negligible	+ (in lower habitat suitability reaches)	+	+
Influence of revegetation in combination with stormwater amelioration	+++	negligible	+ (in lower habitat suitability reaches)	+	+

For macroinvertebrates, as assessed by the lumar index predictions, using the updated projections of runoff and temperature did not, at the aggregate PPWP region-level, differ very much from that of the BAUF scenario used in HWS 2018 (see Figure 15, Table 6). Spatially-explicit areas of difference are presented in Figure 16. For macroinvertebrates, revegetation on its own (RV20) and in combination with stormwater amelioration (RV20_SW3) were effective mitigating actions under the updated climate change-impact scenarios (Section 4.1, Table 6).

For the two native fish species of focus, Ornate Galaxias had a more detrimental predicted response to the updated runoff and temperature projections than River Blackfish. For River Blackfish, the predicted outcome under RCP 4.5 with ACCESS 1.0 and HadGEM2_CC was not too dissimilar to that under the BAUF scenario used in HWS 2018. But the predicted outcome under RCP 8.5 was considerably poorer relative to BAUF, and more severe with HadGEM2_CC than with ACCESS 1.0 (left image, Figure 19). For Ornate Galaxias, the predicted outcome under ACCESS 1.0 RCP 4.5 is poorer relative to BAUF and poorer still, under HadGEM2_CC RCP 4.5. At RCP 8.5, there were no streams in the highest predicted habitat suitability category of 0.75-1.0 and only very small lengths of stream in the category of 0.60-0.75 (right image, Figure 19). For River Blackfish, revegetation on its own (RV20) and in combination with stormwater amelioration (RV20_SW3) had little benefit as a mitigating action under the updated climate change-impact scenarios (Section 5.1, Table 6). For Ornate Galaxias, revegetation on its own (RV20) had some limited benefit as a mitigating action, and this was strengthened when combined with stormwater amelioration (RV20_SW3). But ultimately, the RV20 and RV20_SW3 actions did not amount to substantial mitigation under the updated climate change-impact scenarios (Section 5.1, Table 6).

For AllPlatyHWS, the predicted outcome under the ACCESS 1.0 and HadGEM2_CC moderate emission (RCP 4.5) pathways are clearly worse than that under BAUF (Table 6), and the predicted outcome under the high emission (RCP 8.5) pathways are even worse still (left image, Figure 26). For AllPlatyHWS, revegetation on its own (RV20) and in combination with stormwater amelioration (RV20_SW3) were effective mitigating actions under the updated climate change-impact scenarios (Section 6.1, Table 6).

FemPlaty also had poorer predicted outcomes for RCP 4.5 with ACCESS 1.0 and HadGEM2_CC, relative to BAUF, and severe declines relative to BAUF, under RCP 8.5 with ACCESS 1.0 and HadGEM2_CC (right image, Figure 26, Table 6). Under HadGEM2_CC RCP 8.5, there were no streams in the 'Very High' predicted habitat suitability category for FemPlaty (right image, Figure 26). For FemPlaty, revegetation on its own (RV20) had some limited benefit as a mitigating action, and this was strengthened when combined with stormwater amelioration (RV20_SW3). But ultimately, the RV20 and RV20_SW3 actions did not amount to substantial mitigation under the updated climate change-impact scenarios (Section 6.1, Table 6).

For AllPlatyColeman, the predicted outcome under the ACCESS 1.0 and HadGEM2_CC moderate emission (RCP 4.5) pathways are slightly but not greatly worse than that under BAUF. The predicted outcomes under the high emission (RCP 8.5) pathways are ,however, notably worse still than that under BAUF (left image, Figure 32). For AllPlatyColeman, revegetation on its own (RV20) is quite effective as a mitigating action under RCP 4.5 with ACCESS 1.0 and HadGEM2_CC., but the effectiveness of RV20 is reduced under RCP 8.5 with ACCESS 1.0 and HadGEM2_CC (Section 6.2).

Revegetation in combination with stormwater amelioration (RV20_SW3) is quite effective as a mitigating action under RCP 4.5 with ACCESS 1.0 and HadGEM2_CC., but again, the effectiveness of RV20_SW3 is reduced under RCP 8.5 with ACCESS 1.0 and HadGEM2_CC (Section 6.2).

8.1 Limitations

There are three important areas of limitations that are important to clearly acknowledge: i) HSM predictions using VCP19 mean annual temperature and BoM mean annual runoff projections are in the realm of extrapolation, ii) our HSMs are correlative and *not* process-explicit, and iii) cascading and compounding impacts have not been considered.

Extrapolation

We used the 'dsmextra' R package (Bouchet et al. 2020) to conduct quantitative, spatially explicit assessments of extrapolation on the basis of two established metrics: the Extrapolation Detection (ExDet) tool (Mesgaran et al 2014) and the percentage of data nearby (%N). We used dsmextra's functions to (a) calculate these metrics, (b) create tabular and graphical summaries, (c) explore combinations of covariate sets as a means of informing covariate selection and (d) produce visual displays in the form of interactive html maps.

Bouchet et al. (2020) describe three types of extrapolation:

1. **Univariate** extrapolation, when ExDet values < 0. This is also known as mathematical, strict, or Type 1 extrapolation, and represents conditions outside the range of individual covariates in the reference sample.
2. **Combinatorial** extrapolation, when ExDet values > 1. This is also known as multivariate or Type 2 extrapolation and describes novel combinations of values encountered within the univariate range of reference covariates. Such combinations are identified based on the Mahalanobis distance metric (D2), a well-known and scale-invariant measure of multivariate outliers (Rousseeuw and Zomeren 1990).
3. Lastly, ExDet values between 0 and 1 denote predictions made in **analogue** conditions. These correspond to what is commonly referred to as interpolation (so actually, not extrapolation as such!)

Most influential covariate (MIC) refers to the covariate that makes the largest contribution to extrapolation for any given grid cell In **univariate** extrapolation, this is the covariate that leads to the highest negative univariate distance from the initial covariate range. In **combinatorial** extrapolation, this corresponds to the covariate whose omission (while retaining all others) makes the largest reduction in the Mahalanobis distance to the centroid of the reference data.

Figure 36 shows an example extrapolation assessment using the HadGEM2_CC RCP 8.5 projection for mean annual temperature and the RCP 8.5 project for mean annual runoff. Barring the outer fringes of the PPWP region, we are, with the updated climate data, extrapolating across large areas of the region (orange to brown) and the univariate extrapolation is largely driven by mean annual temperature (red).

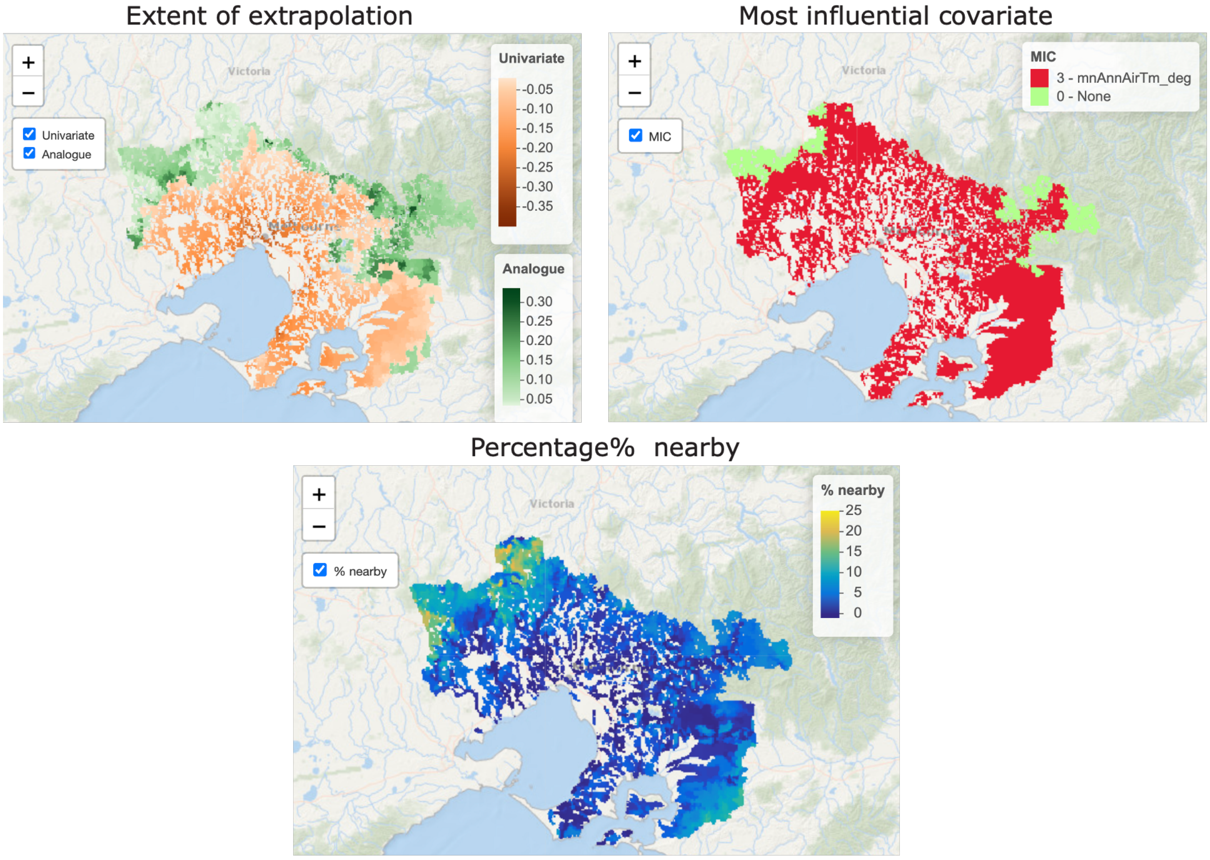


Figure 36. Example extrapolation assessment where mean annual temperature is the HadGEM2_CC high emission pathway RCP 8.5 projection and mean annual runoff is the RCP 8.5 projection for 2070. Extent of extrapolation is depicted in the top-left image, most influential covariate is identified in top-right image, and percentage nearby is mapped in the bottom-centre image.

Correlative rather than process-explicit models

Despite our very conscious intent regarding choice of variables (see Intro/Background and Table 1), HSMs are correlative, statistical models rather than process-explicit models. That is to say, they do *not* mechanistically model population and life-history processes that we know are important for population processes and persistence. Examples of these processes include reproductive rates, dispersal as part of life-history process or movement to colonise or re-colonise habitats.

Our HSMs also do not represent impacts of acute disturbance events such as fire and debris flows into waterways, landslips, extreme rainfall events, floods, storm surges, droughts, heatwaves and blackwater events. Nor do our HSMs model things like sub-lethal effects on physiology (that can impact on fitness, survival and reproductive capacity) nor changes to biotic interactions (e.g. predator-prey or invasive species interactions or disease and pathogen dynamics). These processes could very well become important with increasing climate impacts but our HSMs cannot provide answers with respect to these processes.

Cascading and compounding impacts

There has been an increase in extreme heat events associated with warming and according to CSIRO and BoM (2022), temperatures are expected to continue to rise in all seasons and hot days and warm spells are projected with very high confidence. There has been an increase in extreme fire weather and in the length of the fire season across large parts of Australia since the 1950s, and there have been more frequent and larger fires especially in southern Australia (CSIRO and BoM, 2022). Harsher fire-weather is projected with high confidence. Despite the declining cool season rainfall in south-east Australia over the last two to three decades, short-duration (hourly) extreme rainfall events ('rain bombs') have become more intense (CSIRO and BoM, 2022) increasing the risk of flash flooding. Regions which are expected to experience continued long-term drying may nevertheless still experience increases in extreme rainfall (CSIRO and BoM, 2022). This will lead to a complex mix of effects on streamflow, flood, erosion and landslips risk (CSIRO and BoM, 2022). Ongoing sea level rise could increase coastal inundation, coastal erosion and storm surge risks. 'Compound extremes' where multiple extreme events occur together or in sequence can compound their impacts and also amplify other stressors. Thus far, compounding and cascading impacts have not been considered but there are limits to adaptation and there will be important trade-offs to consider as the effectiveness of available adaptation options decreases with every increment of warming.

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