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Development of a regional climate change model for *Aedes vigilax* and *Aedes camptorhynchus* (Diptera: Culicidae) in Perth, Western Australia

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Abstract

Mosquito-borne disease is a significant public health issue and within Australia Ross River virus (RRV) is the most reported. This study combines a mechanistic model of mosquito development for two mosquito vectors; *Aedes vigilax* and *Aedes camptorhynchus,* with climate projections from three climate models for two Representative Concentration Pathways (RCPs), to examine the possible effects of climate change and sea-level rise on a temperate tidal saltmarsh habitat in Perth, Western Australia. The projections were run under no accretion and accretion scenarios using a known mosquito habitat as a case study. This improves our understanding of the possible implications of sea-level rise, accretion and climate change for mosquito control programmes for similar habitats across temperate tidal areas found in Southwest Western Australia. The output of the model indicate that the proportion of the year mosquitoes are active increases. Population abundances of the two *Aedes* species increase markedly. The main drivers of changes in mosquito population abundances are increases in the frequency of inundation of the tidal wetland and size of the area inundated, increased minimum water temperature, and decreased daily temperature fluctuations as water depth increases due to sea level changes, particularly under the model with no accretion. The effects on mosquito populations are more marked for RCP 8.5 when compared to RCP 4.5 but were consistent among the three climate change models. The results indicate that *Ae. vigilax* is likely to be the most abundant species in 2030 and 2050, but that by 2070 *Aedes camptorhynchus* may become the more abundant species. This increase would put considerable pressure on existing mosquito control programmes and increase the risk of mosquito-borne disease and nuisance biting to the local community, and planning to mitigate these potential impacts should commence now.

Introduction

Mosquitoes are poikilotherms and the temperature of the surrounding environment affects many aspects of mosquito physiology and life cycle characteristics such as time of hatching, the rate at which it can move through its sub-adult stages, its adult body size and fecundity, its mortality, and the health off its subsequent offspring (Becker, 2010). Mosquitoes are linked to a range of diseases across the globe, with the potential to affect the majority of the global population, whether through the discomfort of their bites or the diseases they carry (World Health Organization, 2020). Mosquito populations and mosquito control are the focus of considerable research effort and financial investment around the world (Tomerini, 2008; von Hirsch and Becker, 2009; Ferguson, 2018). In the majority of states and territories in Australia, state and local governments are directly involved in mosquito management and control, with significant costs incurred through the use of personnel, equipment, surveillance, chemical control applications, biological intervention, physical habitat modification and cultural control (public education and behavioural change) strategies (Tomerini, 2008). Within Western Australia many local authorities conduct larval monitoring focussed on controlling larval stages of mosquitoes, before they emerge as adults, using highly selective compounds, such as (S)-methoprene, an insect growth regulator, and *Bacillus thuringiensis subspecies israelensis* (Bti), a microbial insecticide (Department of Health (Western Australia), 2021). This involves larval monitoring, commonly conducted using a dipper at the larval habitat site (Silver, 2008). Government mosquito control programmes are effective at reducing the incidence of mosquito-borne disease (Tomerini *et al.*, 2011), and while reducing the rate of mosquito-borne disease in humans is an obvious benefit, others include; improved amenity via reduction in nuisance biting, reduced mosquito-borne disease in animals, and can further lead to improved tourism productivity and higher real-estate values (Tomerini, 2008). This means that even if new interventions curb the effect of existing mosquito-borne diseases, and no novel diseases emerge, mosquito control programmes are likely to still be required until species-specific mosquito population suppression interventions, such as *Wolbachia* infection (Ferguson, 2018), become accepted and widely used.

It is well accepted that the climate is changing. Mosquitoes are highly responsive to environmental changes, but the exact effects of climate change on mosquito populations will vary dependant on species and location. Climate change is complex, but increased air temperature, extreme weather events, including heavy rainfall and longer dry periods are expected (CSIRO, 2020). The ambient air temperature in Southwest Western Australia has increased by 1.1 °C over the period 1910–2013 and is predicted to increase by a further 1.1–4.2 °C by 2090, compared to the 1986–2005 baseline, assuming the current level of human carbon emissions (Hope *et al*., 2015). The sea-level in the Perth region is expected to increase by 0.07 to 0.18 m by 2030 when compared with the 1986–2005 baseline level, and 0.27 to 0.84 under RCP4.5 and RCP8.5 scenarios by 2090 (Hope *et al*., 2015). These predictions will have a significant impact on the mosquito species that inhabit these areas, particularly those subject to tidal inundation such as wetlands and mangroves.

A further complicating factor is wetlands accretion. Over extended periods, tidal wetlands may accumulate sediment. The rate of accretion of this type is uncertain, location specific, and highly variable with documented estimates of the effect of wetland accretion and simultaneous sea-level rise varying, from a net loss of wetland area, to a marked increase in wetland size (Rogers *et al*., 2012; Alizad *et al*., 2016; Breda *et al*., 2021). Site specific accretion may negate or accelerate some of the effects of climate change on local mosquito populations.

Incremental climate changes can decrease or increase mosquito abundance via several mechanisms. Changes that result in temperatures being more frequently within the optimal development range can reduce larval development periods (Headlee, 1940; Headlee, 1941; Headlee, 1942), decrease low-temperature related female mortality (Brady *et al*., 2013), allow expansion of the geographic range of mosquito species into areas previously too cold to inhabit (Gage *et al*., 2008), and allow a higher number of breeding cycles per season (Kearney *et al*., 2009; Qian *et al*., 2020; Qian *et al*., 2022). But as mosquitoes also have an upper thermal development limit (Huffaker, 1944), increased temperatures may push a mosquito species outside of its optimal thermal range, increasing time taken to complete development and increasing mortality rates. The change in other environmental variables is also important. For example, if increased temperature is not accompanied by increased humidity or rainfall then larval habitat and adult survivorship can be reduced (Githeko *et al*., 2000).

Extreme rainfall and associated flooding can increase larval habitat in depth, size, and number, or may flush larval mosquitoes from their habitats. Increased humidity can also lengthen adult lifespan (Schmidt *et al*., 2018). All these changes combined could increase evolutionary selection for more desiccation resistant eggs and diapause mechanisms (Kearney *et al*., 2009).

The ability to predict the abundance of mosquito populations is valuable for mosquito control managers. In Western Australia, mosquito surveillance has been shown to be a useful method of predicting Ross River virus incidence (Walker *et al*., 2018). Many statistical models incorporate mosquito abundance as a means to predict Ross River virus transmission (Qian *et al*., 2020), and models have been developed to predict environmental drivers of mosquito abundance (de Little *et al*., 2009; Kokkinn *et al*., 2009), however neither of these are designed to allow for the targeted local-scale examination of incremental changes to climate. Projections for mosquito population abundance and mosquito-borne disease incidence exist and have been made at a global and Australia-wide level for dengue mosquito vectors (Kearney *et al*., 2009; Ryan *et al*., 2019). As the impact of climate change on the mosquito population is likely to vary dependant on the mosquito species and environmental conditions in any given existing or potential mosquito habitat, a model incorporate these factors is required (Russell, 2009). A mechanistic model, using environmental inputs (including air temperature, rainfall, and tidal height), has been developed to estimate current populations for three common Australian mosquito vectors of Ross River virus, including *Aedes vigilax* (Diptera: Culicidae); *Aedes camptorhynchus* (Diptera: Culicidae) and *Culex annulirostris* (Diptera: Culicidae), within a tidal saltmarsh environment on the Swan River in Southwest Western Australia (Staples *et al*., 2023). However, no existing studies to predict the impacts of climate change on Australian mosquito populations at a local scale have been conducted.

The two *Aedes* species occupy distinct ecological niches within the saltmarsh habitat, with *Ae. vigilax* populations more abundant in the hotter summer months (Howard, 1973). Each species may be affected differently by the altered weather patterns brought about by long term climate changes (Kokkinn *et al*., 2009).

A mechanistic model of mosquito development requires fine-scale estimates of environmental variables, such as hourly air temperatures and tidal heights. Tidal height is strongly influenced by sea-level rises, estimates of which vary dependant on the Representative Concentration Pathway (RCP), as do estimates of future air temperature. At least 35 global climate models have been produced as part of the Coupled Model Intercomparison Project for the World Climate Research Project. Eight of these global climate models are available as application-ready datasets including daily time series projections for air temperature and other weather variables as part of the CSIRO's Climate Futures Framework for use in risk assessments (Clarke *et al*., 2011). Global climate models are robust and have been providing accurate predictions since the 1970's (Hausfather *et al*., 2019).

In this study, we combine a mechanistic model with weather projections from three climate models to examine the possible effects of a range of possible climate change scenarios on a known mosquito habitat. This will allow a projection of implications of climate change for mosquito control programmes in temperate tidal areas found in Southwest Western Australia. Of particular interest are the number of days of the active mosquito season (relating to potential disease transmission) and changes to the abundance of mosquitoes during peak developmental periods.

Materials and methods

The mosquito development model for *Ae. camptorhynchus* and *Ae. vigilax* is as described in Staples *et al*. (2023). These species have a preferred larval habitat of saltwater and brackish tidal waters (Lee and Commonwealth Institute of Health (University of Sydney), 1980; Leihne, 1991). *Aedes camptorhynchus* and *Ae.*

vigilax are believed to be responsible for a high proportion of Ross River virus transmission in Southwest Western Australia (Harley *et al.*, 2001; Choi *et al.*, 2002; Russell, 2002). Both emerge in high numbers from the tidal waters of the Swan River and are capable of dispersing many kilometres from the site of emergence (Chapman *et al.*, 1999; Porter & Holland, 1992 in Jardine *et al.*, 2014; Robertson, 2006 in Jardine *et al.*, 2014).

Both species survive unfavourable environmental conditions via a diapausing egg stage. Their oviposition site preferences overlap with both preferring samphire dominant vegetation habitats (Carver *et al.*, 2011). Kokkinn *et al.* (2009) state that *Ae. camptorhynchus* prefer sites in high tidal zones that are recharged by rainfall and groundwater and occasional very high tides in the cooler months, while *Ae. vigilax* prefer lower tidal areas, higher salinity levels and emerge in higher numbers in the warmest months of the year.

Larval mosquito abundance is most sensitive to the presence of water and to water temperature, which are projected in the model using sea-level and air-temperature inputs. Sea-level estimates are available for different RCP, not for specific climate models. These sea-level rise estimates have been combined with daily observed tidal fluctuations from baseline year to give estimates of future hourly tidal heights. Of the weather variables produced in the global climate models, changes to air temperature will have the highest impact on the rate of mosquito development and survival. Weather data for three different global climate models, ACCESS 1.0, CanESM2, and MIROC5, for the periods 2028–2031, 2048–2051 and 2068–2071 were used. The global climate models have been scaled and weather estimates made available as 5×5 km gridded data sets (CSIRO and Bureau of Meteorology, 2022b). These three climate models were selected, from the eight available as application-ready datasets, to represent the middle, low and high range of the projected change to air temperature (CSIRO and Bureau of Meteorology, 2022a). The baseline study period was July 2018 to June 2021, which allowed two calendar years to be modelled, and three July to June mosquito seasons. As they have their activity peak in summer, models for *Ae. vigilax* were run from July to June for three years in each decade (2028–2031, 2048–2051, 2068–2071). *Aedes camptorhynchus* remain active over the winter period so the models for this species were run from January to December for two years in each decade (July 2029–June 2030, July 2049–June 2050, July 2069–June 2070).

In summary, model sets were run for three decades, with and without accretion scenarios, for RCP 4.5 and RCP 8.5, using weather data from three climate models, giving 36 data sets for each mosquito species. The model was run to simulate three separate years for *Ae. vigilax*, and 2 years for *Ae. camptorhynchus*, giving a total of 180 individual model year simulations.

Study site

The modelled study site represents Ashfield Flats, a suburban tidal wetland abutting the Swan River located to the east of Perth, Western Australia, and is a known mosquito vector habitat. The ground at the site is flat, varying from 0 mm to 400 mm in height over the main area of interest and contains two shallow waterbodies, fig. 1, which are periodically inundated by high tides associated with the Swan River and is dominated by Samphire vegetation (Department of Biodiversity Conservation and Attractions, 2019). The area is subject to routine monitoring of the larval/pupal and adult mosquito stages using larval dippers and encephalitis virus surveillance carbon dioxide (CO_2) light traps, respectively and mosquito control chemicals are applied in response to heightened larval mosquito activity. Once increased larval numbers are identified the briquet formulation of (S)-methoprene is applied, which lasts several months, supplemented by Bti (D. Sorenson, personal communication, 21 March 2017).

Model input variables

Rainfall, daily maximum and minimum air temperature, evapotranspiration and relative humidity were accessed as 5×5 km gridded daily data for two Representative Concentration Pathways (RCPs), RCP 4.5 and RCP 8.5, representing medium and high emission scenarios, respectively. Weather data for a single 5×5 km grid point which included the Ashfield Flats (31.92 S, 115.9 E) was extracted as a timeseries.

Regional projected monthly mean pan-evaporation was obtained for the Perth Airport Meteorological Station for each Climate Model and RCP (CSIRO and Bureau of Meteorology,

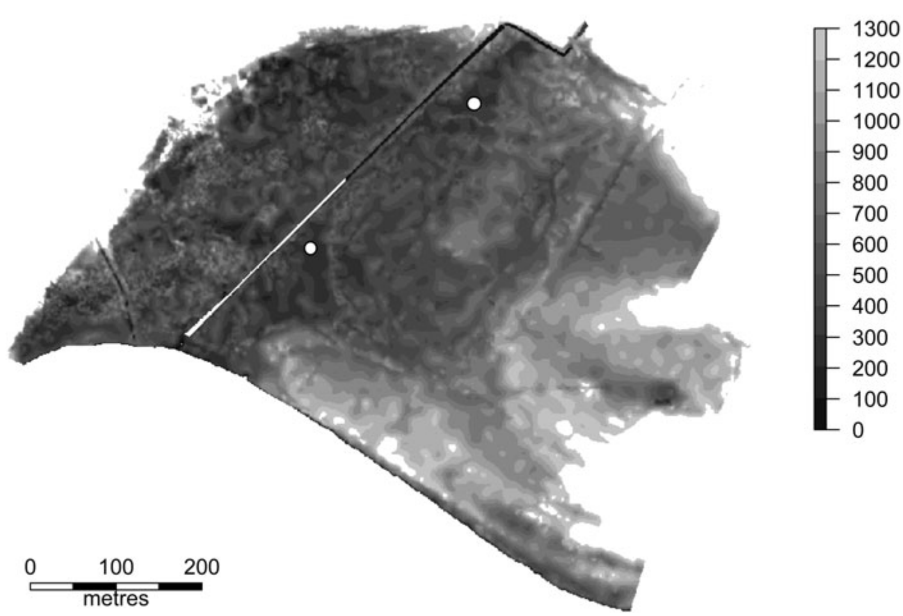

Figure 1. Ashfield flats site map showing 100 mm contour break levels and the location of the two water bodies studied.

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Table 1. Model data inputs, scale, transformations, and references

Input variable	Timestep	Geographic scale	Data availability and transformation	Reference
Tide height (m)	Hourly	Regional -SSWFW	Projected sea level rise for the Fremantle Wave Station, added to 2019–2021 observed hourly river heights at the Barrack Street Jetty Tide Station.	(CSIRO and Bureau of Meteorology, 2021; Department of Transport, 2021)
Accretion (mm)	NA	National - Australian	2030- Δ18.2 mm 2050- Δ 61.8 mm 2070- Δ 116.4 mm, added to 2019 ground level and bank heights.	(Breda *et al.*, 2021)
Pan evaporation	Day	Regional - SSWFW	Projected monthly mean, divided into hourly figures.	(CSIRO and Bureau of Meteorology, 2022b)
Evapo-transpiration	Daily	Local - 5 × 5 km grid	Projected daily figure, no transformation required.	(CSIRO and Bureau of Meteorology, 2022b)
Rainfall	Hourly	Local - 5 × 5 km grid	Projected daily amount, applied at midnight each model day.	(CSIRO and Bureau of Meteorology, 2022b)
Air temperature	Hourly	Local - 5 × 5 km grid	Projected max/min daily temperature, interpolated to hourly values (R, chillR package).	Data:(CSIRO and Bureau of Meteorology, 2022b) Interpolation: (Luedeling, 2022)
Air pressure	Hourly	Local meteorological station	No projections available, 2018–2021 mean used as hourly figure	NA
Relative humidity	Hourly	Local - 5 × 5 km grid	Projected daily mean, used as hourly figure	(CSIRO and Bureau of Meteorology, 2022b)
Windspeed	Hourly	Local meteorological station	1991–2010 monthly mean, used as hourly figure	(Bureau of Meteorology, 2021)

SSWFW, Southern and South-Western Flatland West SubCluster Region.

2022b). Changes to atmospheric air pressure and windspeed have not been projected. Atmospheric pressure has minimal impact on the mosquito development model, so a three-year mean for Perth Airport Meteorological Station the period 2018–2021 was used. Historic monthly mean windspeeds for the period 1991–2010 for the site were also obtained (Bureau of Meteorology, 2021).

Tidal heights recorded for the Barrack Street Jetty Tide Station for the period 2018–2021 (Department of Transport, 2021) were used as the baseline tidal height to which mean expected tidal increases, as projected for the Fremantle Wave Station within the Southern and South-Western Flatlands West Sub-Cluster, were added to give hourly values. Tidal height estimates are regional, with the closest alternative gauge being Esperance, several hundred kilometres to the south, which had very similar sea-level rise estimates (Hope *et al.*, 2015).

Two sets of models were run, one set without accretion, and one set with accretion. The accretion estimate is for a low sediment environment bathtub model developed for coastal wetlands in New South Wales, Australia (Breda *et al.*, 2021).

Model input variables not available at the scale required for the mosquito development model required transformation prior to use in the model. A summary of input environmental variables and transformations for the model are provided in Table 1.

Model output variables

Model outputs include hourly water depth and water temperature for two waterbodies, as well as hourly egg, larval and adult population sizes of *Ae. vigilax* and *Ae. camptorhynchus*.

Data analysis

Multiple linear regression was conducted on the output of the mosquito model to determine predicted changes in the active mosquito season, and the change in the size of the maximum mosquito population. All assumptions required for multiple linear regression were met. The active mosquito season is considered as any modelled day in which at least 1000 adult female mosquitoes are alive. This figure was chosen as a 1:1000 was the scale required to match adult female mosquito trap counts to modelled adult female mosquito numbers at this field site (Staples *et al.*, 2023). The maximum population is the maximum number of adult female mosquitoes in each year. Accretion was treated as a factor, as was RCP, and climate model. Tidal height increase (mm) was included as a continuous variable. Decade (2030, 2050, and 2070) is highly correlated to tide (correlation coefficient = 0.97), so was omitted as from the analysis.

Results

Environment

Projected changes in waterbody depth, temperature, and surface area were analysed under each of the climate change scenarios. The expected tidal height increase was a product of sea-level rise, RCP and accretion rate, fig. 2. The expected tidal increase ascends rapidly from baseline (2020) and slows between 2030 and 2050. The increase from 2050 to 2070 is highly dependent on both RCP and accretion rate.

The mean monthly depth of the waterbodies is shown in fig. 3. The bank height of the two waterbodies (horizontal lines)

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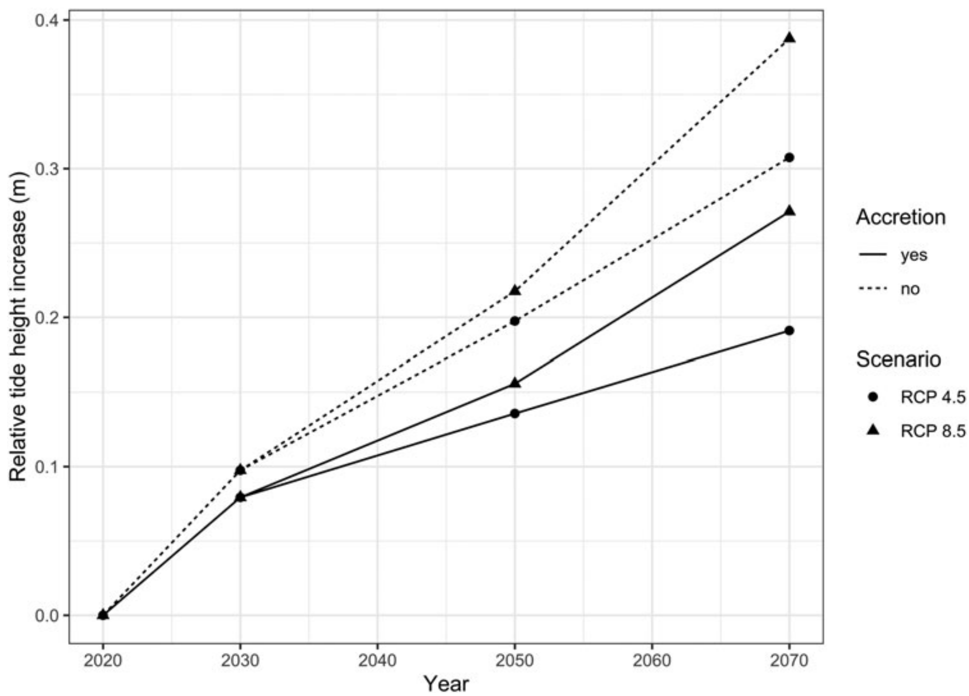

Figure 2. Projected tidal height increase by decade for RCP 4.5 and RCP 8.5, with and without accretion.

indicates the maximum depth of the waterbody when the river height is lower than the bank height. The mean monthly depth increases in all scenarios modelled, with the most rapidly increasing under RCP 8.5. By 2070 the bank height is exceeded for a larger proportion of the year, indicating that the waterbodies may become almost permanently inundated. A mean monthly water depth in excess of the bank height indicates that the river overflows into the wetland almost constantly.

Mean monthly water temperature increases under all scenarios, fig. 4. The increase varies seasonally with increases of up to 5 °C at the peak of summer, and more modest increases in winter months. The diurnal range of water temperatures decreases

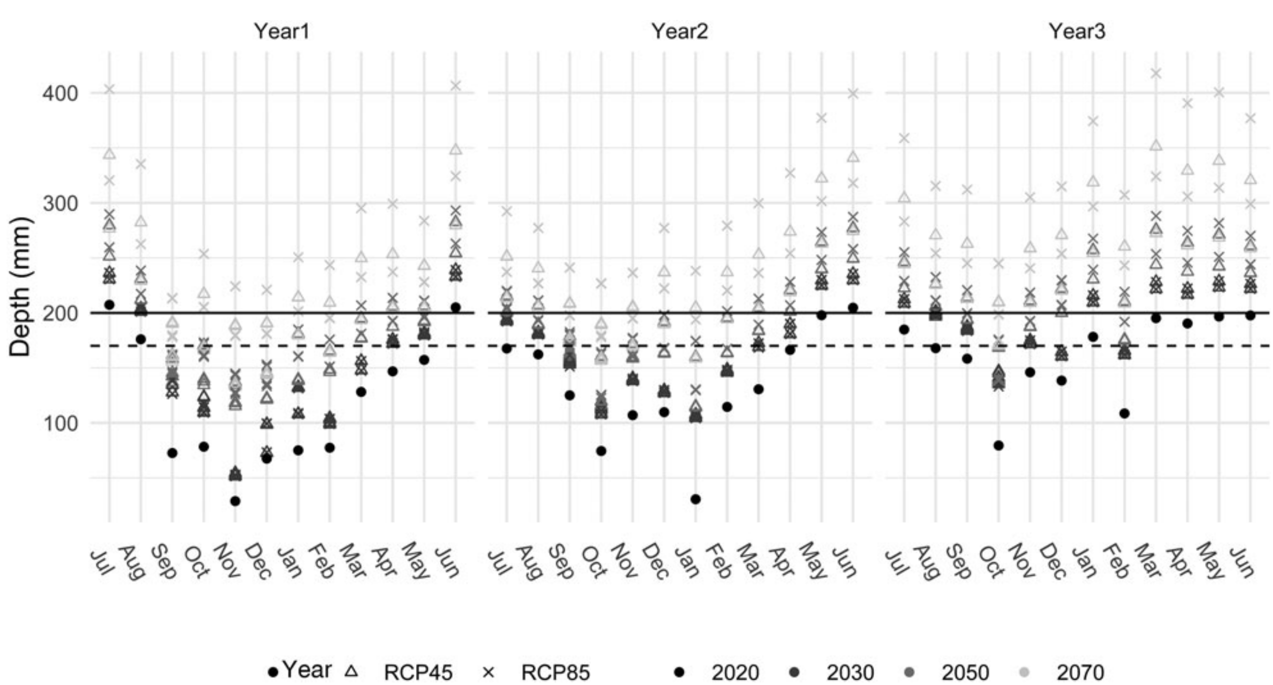

Figure 3. Mean monthly waterbody depth for each year, shown with bank heights of each waterbody, (Pond 1- dashed, Pond 2 – solid) for RCP 4.5 and RCP 8.5 and decade, with 2020 values.

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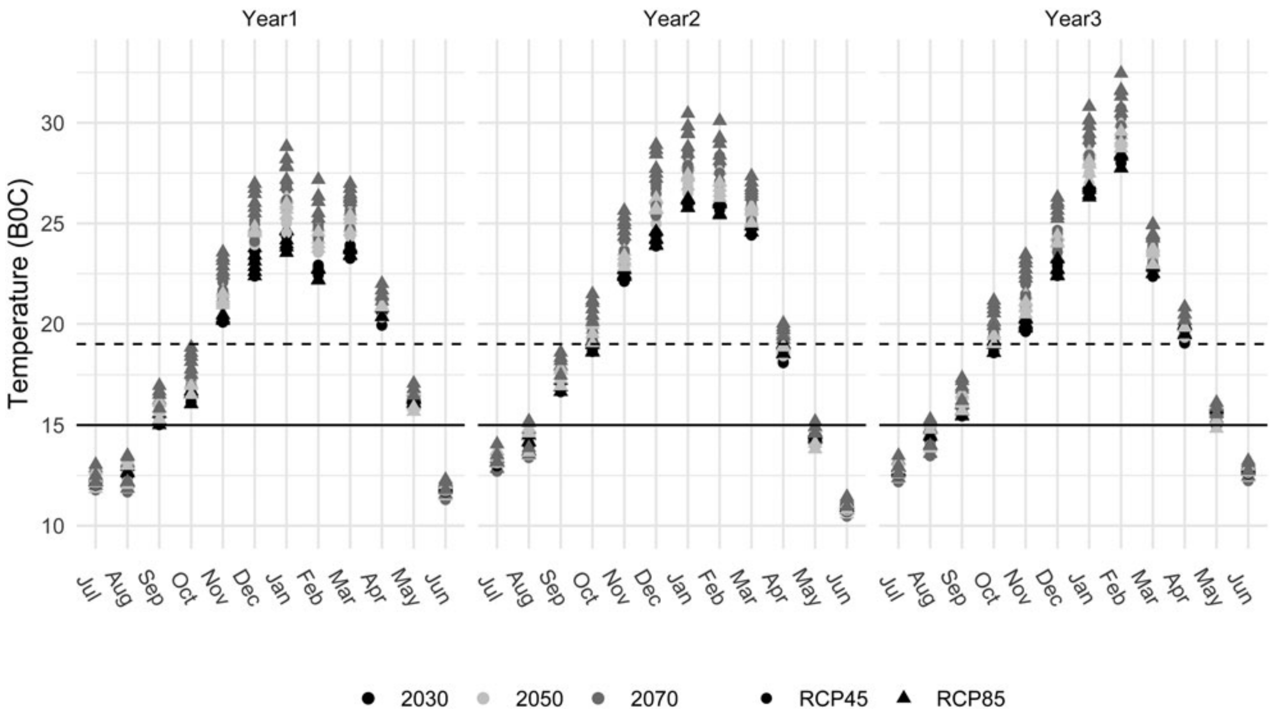

Figure 4. Mean monthly water temperature for each year, shown with minimum egg hatching temperature for *Aedes vigilax* (dashed), and *Aedes camptorhynchus* (solid), for RCP 4.5 and RCP 8.5 and decade.

with increasing water depth, and there is a smaller daily range in 2071 than in 2031, mostly due to an increase in minimum water temperature. The projected minimum daily water temperature increases from 15.3 °C in 2031 to 17.7 °C in 2071, while the projected mean maximum water temperature decreases slightly from 26.7 °C in 2031 to 25.9 °C in 2071, fig. 5. The area of land that becomes inundated increases under all climate change scenarios, fig. 6, with up to 81 additional hectares of land inundated in 2070 when compared to 2020, Table 2. A smaller area becomes inundated under the model with accretion and under the RCP 4.5 scenario.

Mosquito population dynamics

The output of the mosquito model was analysed for changes to the number of days in the active mosquito season (>1000 adult females) and size of the peak in their abundance within each decade. The models were also examined for species-specific population changes.

The number of days with at least 1000 adult females increases over time for both species, fig. 7. The number of days with a mean number of adult females less than 1000 decreases by 47 days, from 142 in 2030 to 95 in 2070. When both species are considered together, linear modelling predicts an expected increase of 0.122 active days per mm increase in tidal height ($p < 2.2 \times 10^{-16}$). Climate model and RCP was not a significant predictor in any of the models. The results of species-specific linear models are as detailed below.

Aedes camptorhynchus has an expected 237 active days per year in 2020, increasing by a mean of 0.14 days per mm of tidal height increase. The expected number of active days for the model without accretion increases by 8.8 days when compared to the model with accretion, all other things being held constant.

Aedes vigilax has an expected 121 active days per year in 2020, increasing by a mean of 0.11 days per mm increase in tidal height. Accretion decreases the number of expected days by 6.3 per year when compared to no accretion, Table 3.

The peak abundance of adult females increases for both *Aedes* species, fig. 8. As the expected peaks increased exponentially, a log-transformation was performed for both species to enable the linear modelling assumptions to be met. For *Ae. camptorhynchus*, the no accretion assumption increases the expected number by 44.8%, and the expected peak increases by 0.87% for every mm increase in tidal height. *Aedes vigilax* peak abundance was not significantly different with increasing accretion, but a 1 mm rise in tidal height increases the expected peak by 0.58%, Table 4.

Detailed species projections

Model output for each modelled year, RCP, climate model, for accretion and no accretion, for each species, are given in figs 9 and 10.

Aedes camptorhynchus increases significantly across decades, fig. 9. The projections from each of the three climate models are consistent. The model without accretion produces higher numbers of adult females than the models with accretion. In 2070 the RCP 8.5 pathway appears to have a higher peak in one year in the MIROC5 model, but lower or similar sized peaks to RCP 4.5 in the ACCESS 1.0 and CanESMC models.

Aedes vigilax adult female abundance increases across the three climate change scenarios, fig. 10. By 2070 the least productive years are equal to or greater than the most productive years in 2030. Projections are consistent across climate models, with the exception of CanESMC in 2070 under RCP 8.5 in which a distinct flattening of population occurs.

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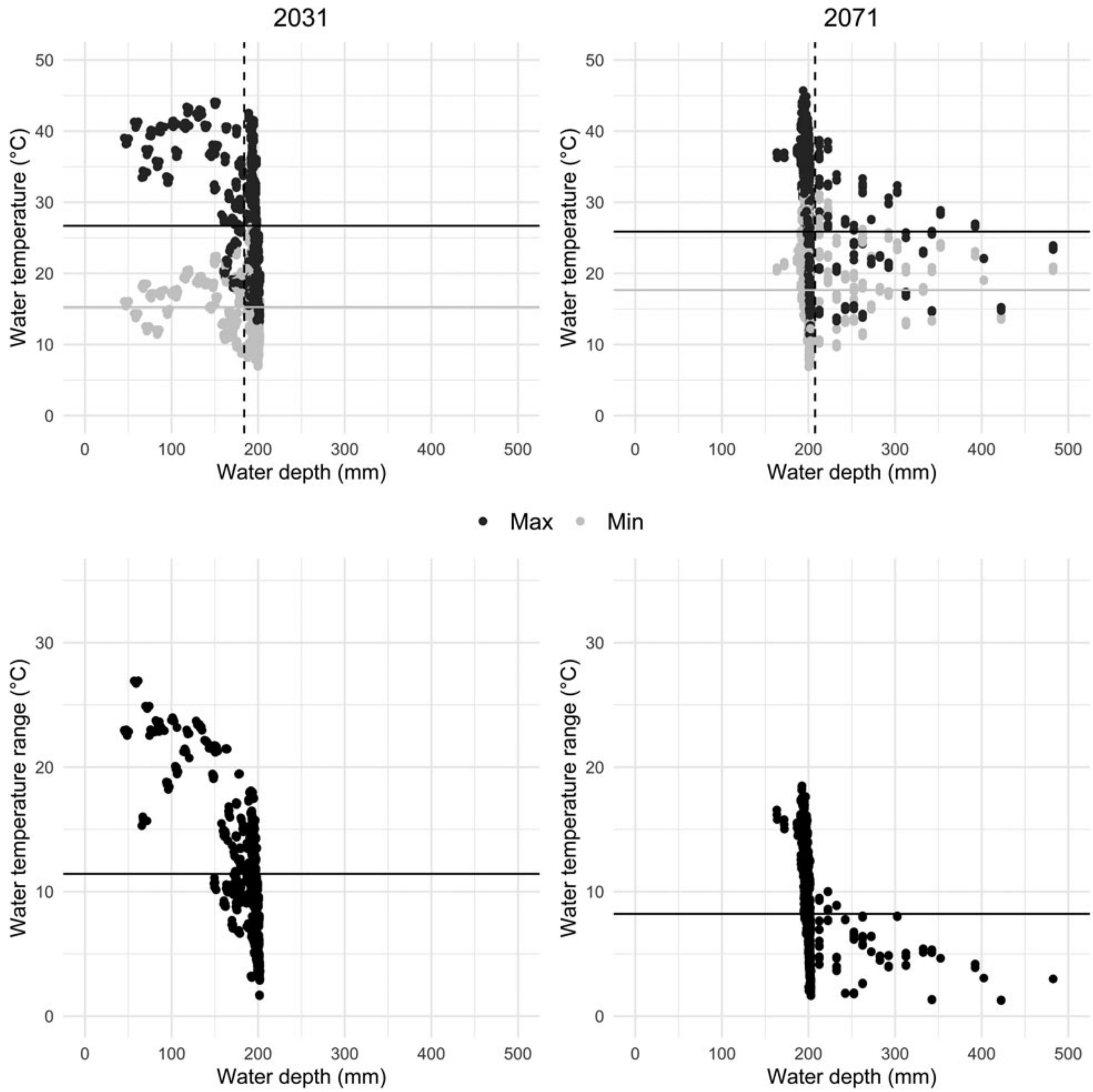

Figure 5. Modelled daily maximum and minimum water temperatures (top) and daily water temperature range (bottom), for 2031 (left) and 2071 (right), with no accretion. Solid lines indicate the mean maximum and minimum water temperature (top) and mean water temperature range (bottom). The dashed vertical line indicates the mean water depth.

Discussion

This paper presents the results of a model investigating the possible impacts of sea-level rise, accretion, and climate change for two mosquito vectors of Ross River virus and shows that female mosquito populations are likely to be larger and occur for a larger proportion of the year for both species. Although the model was run for a specific local site, it is likely that the findings will be replicated across tidal wetlands with similar topographical and climatic characteristics. The projections indicate an increase in water depth, temperature, and mosquito abundance under all modelled scenarios, the magnitude of which varies with tidal height increase, and accretion rates. These changes impact on each species in different ways and may impact mosquito control programmes and the incidence of mosquito-borne disease.

Aedes camptorhynchus

Aedes camptorhynchus is projected to have a large potential for population increase. Under the model conditions the active season extends by 0.14 days per mm of increased tidal height, giving an additional 25–54 active days per year by 2070, dependent on accretion level. The active season is projected to expand from 7 to 9 months of the year. The driver for this in the model is the mean water temperature increasing to above 15 °C for most months of the year, allowing increased reproduction in later winter and early spring. Tidal height is also a significant factor in the peak population abundance; however, inclusion of accretion in the model limits the population peak size significantly and is an important area for future monitoring. Reduced abundance under accretion can be attributed to the increased water

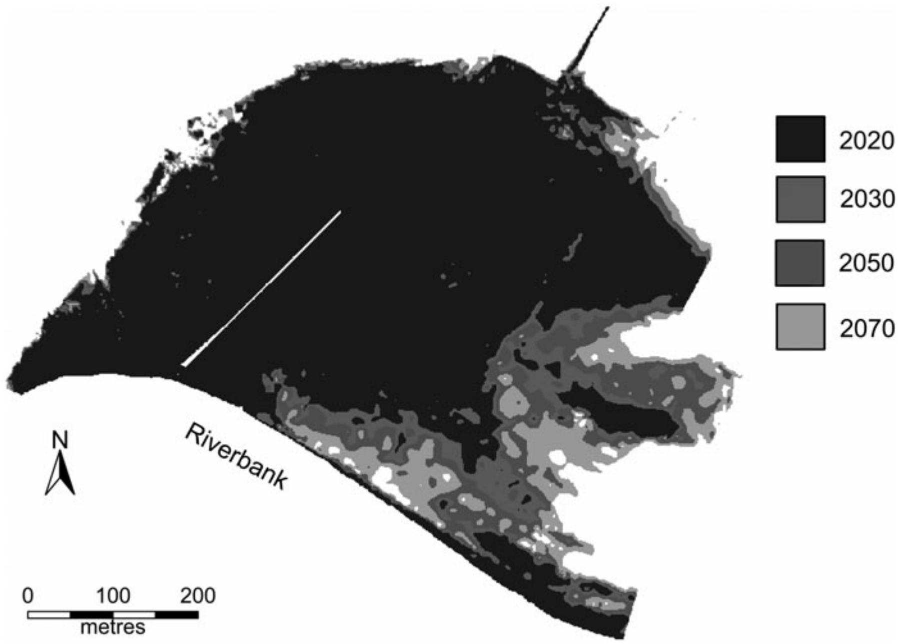

Figure 6. The maximum extent of site tidal inundation by decade.

temperature fluctuations associated with shallower water periodically exposing this species to water temperatures above its thermal limits, increasing mortality. The size of population peaks for this species increases significantly, and even the minimum projected peak in 2070 well exceeds the maximum peak levels for 2030.

Aedes vigilax

The number of days of the active season and population abundance of *Ae. vigilax* is also highly likely to increase. The mean number of days of the active season for *Ae. vigilax* is 109 days in 2030. The active season is projected to increase by 0.18 days per mm of tidal height increase, giving an additional 32.4 to 69.7 days by 2070, depending on accretion, or from around 3.5 to 6 months of the year by 2070. The magnitude of *Ae. vigilax* abundance peaks correlate with tidal height increase. Population peaks increase the most steeply of the two species examined by 2030 when compared to 2020 baseline figures, then increase more slowly in 2050 and 2070. More days of tidal inundation per year will allow increased larval numbers as tidal inundation will provide both an egg hatching stimulus and water in which larvae can develop. This increased water availability, coupled with the increase in mean minimum temperature (a result of both increased ambient air temperature and thermal buffering of deeper water), will also increase the number of days eggs of this species are above the minimum egg hatching threshold. The initial increase in frequency of tidal inundation, but with low water depth and high daily peaks in water temperature in 2030 and into 2050, is likely to favour *Ae. vigilax* over *Ae. camptorhynchus*, as *Ae. vigilax* have lower mortality at the high temperatures in shallow water in summer. As the mean water depth continues to increase from 2050 to 2070, and the diurnal water temperature range decreases, *Ae. camptorhynchus* will be within its optimal limits for development and mortality more consistently, and *Ae. vigilax* will lose this competitive advantage.

In the model projections for *Ae. vigilax* no substantial adult female population peak is projected to occur in 2069 or 2070 for RCP 8.5 under the CanESMC climate model, for both accretion and no accretion models, fig. 10. In the projections for both years there are weekly mean temperatures in July of above 19 °C, which is also the minimum egg-hatching thermal limit for this species. These warm weeks were followed by temperatures consistently below the minimum larval development threshold, and as a result the do not develop or emerge as adults. Eggs of *Ae. vigilax*

Table 2. Change in maximum water height and area inundated by accretion, RCP, and decade

		No accretion			Accretion		
Decade	RCP	Water height max(mm)	Area (m^2)	Δ Area (m^2)	Water height max(mm)	Area (m^2)	Δ Area (m^2)
2020	NA	912	231,532	NA	912	231,532	NA
2030	4.5 and 8.5	1009.5	255,416	23,884	991.3	250,723	19,191
2050	4.5	1109.5	279,584	48,052	1047.7	264,538	33,006
	8.5	1129.5	284,253	57,721	1067.7	269,363	37,831
2070	4.5	1219.5	302,167	70,635	1103.1	278,070	46,538
	8.5	1299.5	313,254	81,722	1183.1	295,817	57,285

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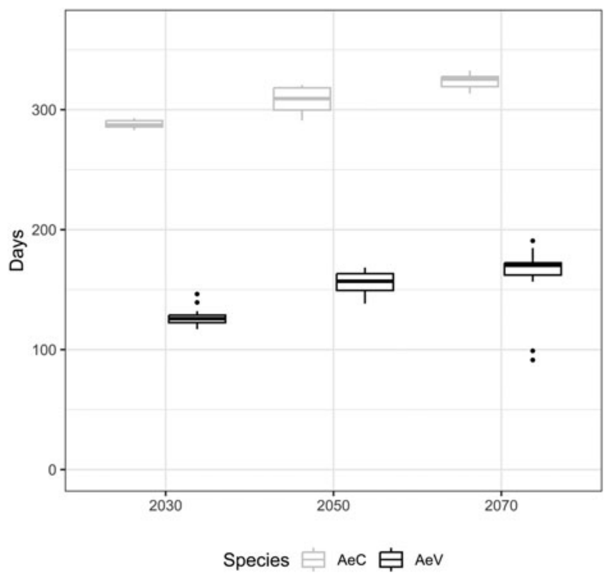

Figure 7. Boxplot of the number of days per year with over 1000 adult females for *Aedes camptorhynchus* (AeC) and *Aedes vigilax* (AeV).

have a short lifespan (Kerridge, 1971) and are known to exhibit instalment hatching (Hamlyn-Harris, 1933; Kerridge, 1971). When field collected quiescent eggs are conditioned for three days at 25 °C, 68% hatched on first flooding, compared to 10% of non-conditioned eggs, however hatching rates of 98 to 100% have been observed in eggs where a monthly mean minimum water of 11.5 °C temperature is exceeded (Sinclair, 1976; Kay *et al.*, 1981). Within the model constraints, if a large proportion of the eggs hatch early due to an extended unusual warm period, but subsequent weather conditions become unfavourable to larval survival, there are a small number of unhatched eggs remaining. The egg lifespan and hatching thresholds of this species is not well studied (Staples *et al.*, 2023), and it is possible the egg lifespan is actually significantly longer than it is for many other *Aedes* species (Sota and Mogi, 1992; Faull *et al.*, 2016), or that the minimum egg hatching threshold varies from the modelled parameters. This anomaly also demonstrates that actual mosquito populations respond to changes in weather, and so for any given climate model a range of observed population peaks will occur year to year depending on the observed weather conditions.

The model does not account for possible reductions in water salinity during summer due to more frequent tidal inundation, which may reduce the competitive advantage that the highly saline tolerant *Ae. vigilax* maintains over other endemic species. Under current conditions the site becomes hypersaline in summer as the waterbody evaporates (Department Biodiversity, Conservation and Attractions, 2021). Both *Aedes* species are tolerant to high salinity, especially *Ae. vigilax* (Kokkinn *et al.*, 2009), and the decrease in salinity due to frequent tidal inundation may provide an advantage to other endemic mosquito species.

Mosquito control programmes and mosquito-borne disease

The projected active vector mosquito season comprises of more days, the population peaks are larger, and the area of the wetland regularly inundated increases. This has potential implications for public health, related to increased mosquito-borne disease risk, nuisance biting rates, and increased costs for mosquito surveillance and control programmes.

Increases in mosquito numbers may lead to an associated increase is mosquito-borne disease, particularly Ross River virus. The magnitude of any increase is very difficult to predict as it depends on a mixture of weather, environmental, social and geographic factors (Tong *et al.*, 2008; Tall and Gatton, 2020). While the expectation may be that an increase in mosquito vector numbers would increase transmission, this is not always the case. Alteration of weather conditions due to climate change and increased urbanisation may impact the population of vertebrate hosts of Ross River virus in the area, and further studies would be needed to assess these potential impacts. Few models have been developed to investigate the role of vertebrate hosts, although vertebrate biomass, particularly that of horses, has been indicated as an area for future modelling (Choi *et al.*, 2002; Jacups *et al.*, 2008; Skinner *et al.*, 2020). Higher temperatures may decrease or increase viral replication within the mosquito, and rates of disease are also related more broadly to socioeconomic status and public health services available in the area (Githeko *et al.*, 2000; Gage *et al.*, 2008), however as previous studies have linked higher mosquito numbers to increased Ross River virus activity (Choi *et al.*, 2002; Glass, 2005; Tong *et al.*, 2005; Woodruff *et al.*, 2006; Williams *et al.*, 2009), at least some increase in disease incidence could be expected.

With or without an associated increase in mosquito-borne disease incidence, mosquito activity over a larger proportion of the year, and a larger physical area of larval habitat, will increase the potential for nuisance biting. Local communities expect a timely and effective response when they perceive the mosquito population to be high. As these sites are not domestic, where residents can monitor larval habitats themselves, this service is expected to be provided by government. In Western Australia this falls to Local Government Environmental Health Officers, with support from the Department of Health (WA). As the mosquito season becomes longer, this response will require extended larval and adult surveillance, and increased applications of pesticides and larval growth inhibitors.

The active mosquito season is projected to increase by 47 days, and tidal inundation will increase to cover an additional 4.7–8.2

Table 3. Linear model results for the number of active days per year; where AeC = *Aedes camptorhynchus* and AeV = *Aedes vigilax*

		AeC		AeV	
Variable		Days	*p*	Days	*p*
Accretion	no	8.78	2.46×10^{-4}	7.078	2.66×10^{-2}
Δ Tide	mm	0.14	6.68×10^{-15}	0.18	4.13×10^{-13}
Model			1.27×10^{-14}		1.64×10^{-12}

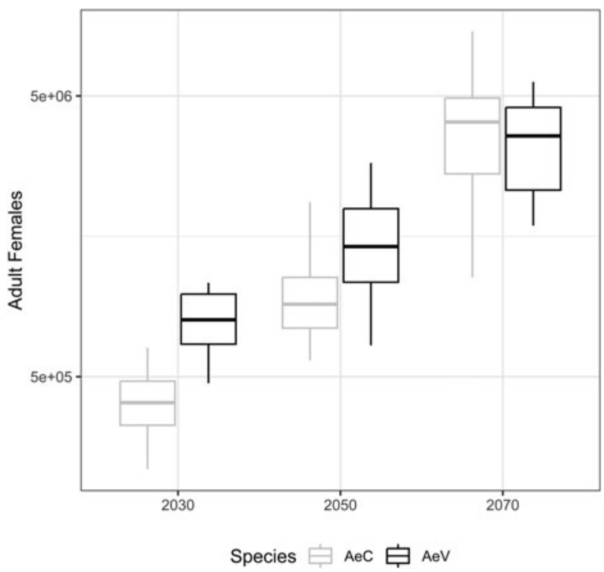

Figure 8. Log-scale boxplot of the expected peak number of adult females for *Aedes camptorhynchus* (AeC) and *Aedes vigilax* (AeV).

hectares by 2070, dependent on RCP and accretion rate. (S)-methoprene briquets have a label application rate of 1 per 10 m^2 and have been shown to last for around 120 days in Southwest Western Australia (Staples *et al*., 2016). Currently briquets are applied twice a year, and 1662 briquets were used in 2020–2021 (J. Somes – personal communication, August 9, 2021). As the active mosquito season extends, a third application may become necessary. The number of briquets required may also increase if the area of larval habitat expands. The size of the increased larval habitat is difficult to estimate as briquets are only placed in locations where water is retained after tides recede. This depends on the location of the waterbody banks, which is difficult to predict as the location and rate of accretion differ markedly depending on local conditions and topography (Rogers *et al*., 2012; Alizad *et al*., 2016; Breda *et al*., 2021), however even a relatively modest total increase of 1 hectare of waterbody size would require an additional 1000 briquets per application, which, coupled with a potential third application per year, may easily double the required number of briquets. This increased requirement could be mitigated to some extent should lower lying areas become unsuitable for larval development, however as the area inundated expands, the perimeter of the waterbody, where habitat is likely to remain suitable, will also expand and require some additional treatment. In addition to the direct cost of purchasing briquets, there are a range of additional costs including staffing time to prepare and deploy briquets floats, and to monitor the briquets while they are deployed. This has the potential to significantly impact mosquito control programmes.

If waterbody size remains constant, increases in tidal inundation height would expand the size of the productive egg-bank for both *Aedes* species, resulting in greater larval densities and still require constant chemical control. Increased use of chemical control can increase the development of resistance (Zhu *et al*., 2016). Resistance to (S)-methoprene has been reported in mosquitoes since as early as 1998 (Dame *et al*., 1998; Cornel *et al*., 2002), but *Bti* has a low risk for development of resistance in field populations (Wirth *et al*., 2004; Tetreau *et al*., 2013), and has been successfully used in combination with other mosquito control substances to partially reverse field resistance to (S)-methoprene (Cornel *et al*., 2002). The large increase in mosquito activity at this site will require enhanced mechanisms to monitor and prevent pesticide resistance, and existing mosquito control programmes must be reviewed regularly, and utilise a greater number of control strategies that are appropriately resourced.

Limitations

This study investigates the potential impact of climate change at a specific site in Southwest Western Australia and, while the result should be applicable to similar sites within the region, should be repeated at other locations for validation purposes.

This study has applied projected weather conditions within the model. Weather is inherently variable and the output given in this model cannot represent all possible given scenarios.

Apart from the inherent uncertainty involved with any future climate change predictions, the main limitations of this model are an under-estimation of mosquito mortality, especially due to larval density limits, nutrient availability, predation, and changes to water salinity levels, and the projections presented should be considered as indicative of the trend, rather than as predictions of absolute mosquito numbers. This is especially important as the model does not explicitly include the effects of larval controls. However, as mosquito populations have the potential to quickly rebound if treatment ceases, this model still remains useful in determining the magnitude of future control programmes.

The number of mosquitoes projected in this model is very large, peaking at around 5 million by 2070 for the two *Aedes* species. An intrinsic larval density limit is not included in the mosquito development model, and it has been stated that larval *Ae. vigilax* are not overly affected by density-dependence (de Little, 2011). Estimates of density limitations for sylvan mosquitoes are rare, but estimates of maximum larval biomass for urban species exceed 6000 mg/m^2 (Macia, 2009; Yadav *et al*., 2017). In general, larval mosquito weights increase logarithmically as they progress through the subadult stages (Bradshaw, 1983). Using a

Table 4. Linear model results for the peak adult female abundance per year; where AeC = *Aedes camptorhynchus* and AeV = *Aedes vigilax*.

		AeC^{β}		AeV^{β}	
Variable		Peak	*p*	Peak	*p*
Accretion	no	0.37 (44.8%)	1.82×10^{-3}	-	-
Tide increase	mm	8.69 E-03 (0.87%)	$<2 \times 10^{-16}$	5.78×10^{-3} (0.58%)	5.29×10^{-14}
Model			$<2.2 \times 10^{-16}$		5.29×10^{-14}

$^{\beta}$ indicates log transformed response variable.

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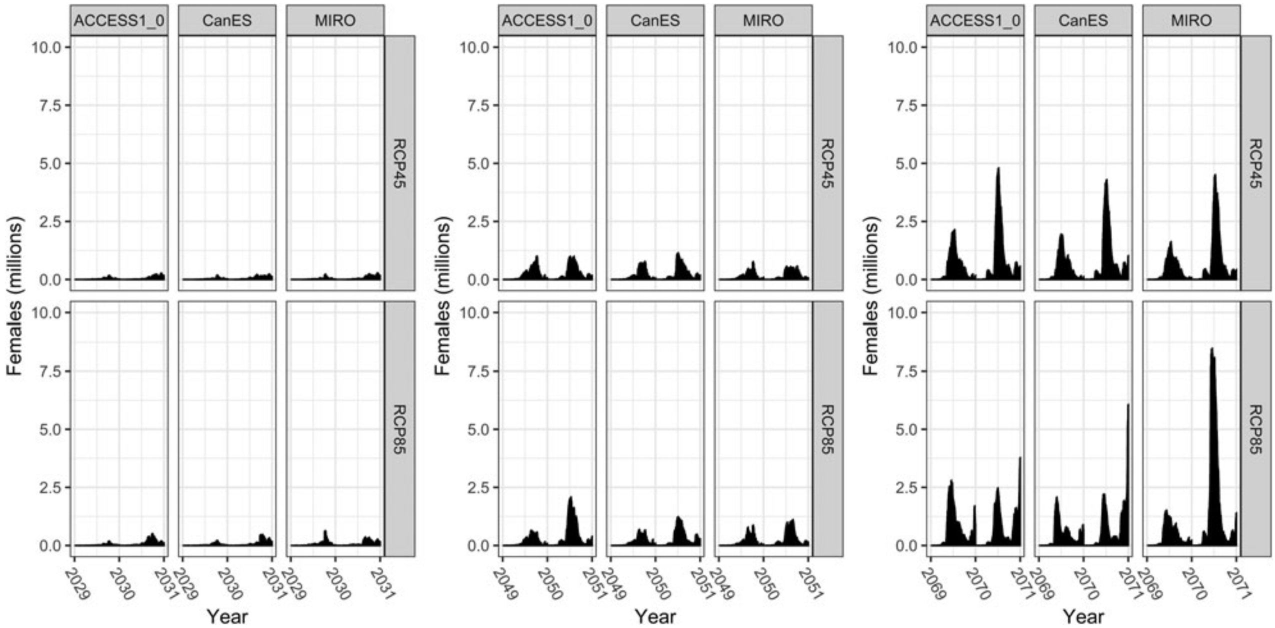

Figure 9. Cumulative adult female *Aedes camptorhynchus* population by year, climate model and RCP pathway with accretion (top) and without accretion (bottom).

mean individual larval weight of 0.5 mg gives a potential 12,000 larva per m^2. At optimal temperatures larval development can be completed within 3 to 5 days, allowing 1200 to 2000 female mosquitoes to emerge from these wetlands per square metre. In a small waterbody of dimensions 10 m × 10 m, this theoretically allows 120,000 or more mosquitoes to emerge per day. This is likely to be an over-estimation however, as the waterbodies at the study site have a much larger area, easily exceeding 10,000 m^2 after tidal recharge, adult populations in the millions are possible. These population abundance peaks also do not take into account the effect of larval chemical controls which is undertaken as a routine measure at this site (Staples *et al.*, 2023).

Conversely, other mosquito species are present at this site and under favourable conditions may outcompete *Ae. vigilax* and *Ae. camptorhynchus*. Competition of this type is not well studied for sylvan species but has been described for *Ae. vigilax* where it is replaced by *Cx. annulirostris* and *An. annulipes* as saltwater is replaced by freshwater (Kerridge, 1971). Similar examples have been demonstrated for urban species such as between *Aedes albopictus* (Diptera: Culicidae) and *Aedes aegypti* (Diptera: Culicidae) in Brazil (Braks *et al.*, 2004), and *Ae. albopictus* and *Culex pipiens* (Diptera: Culicidae) in Italy (Marini *et al.*, 2017). Competing mosquitoes may not be disease vectors or have a lower affinity for human biting so their impact may be benign to humans. However as tidal flooding is expected to increase and flooding due to rainfall decrease, replacements with less saline tolerant species are likely to be limited.

This site is likely to become permanently inundated, the exact time of which depends on RCP and accretion rates. The accretion

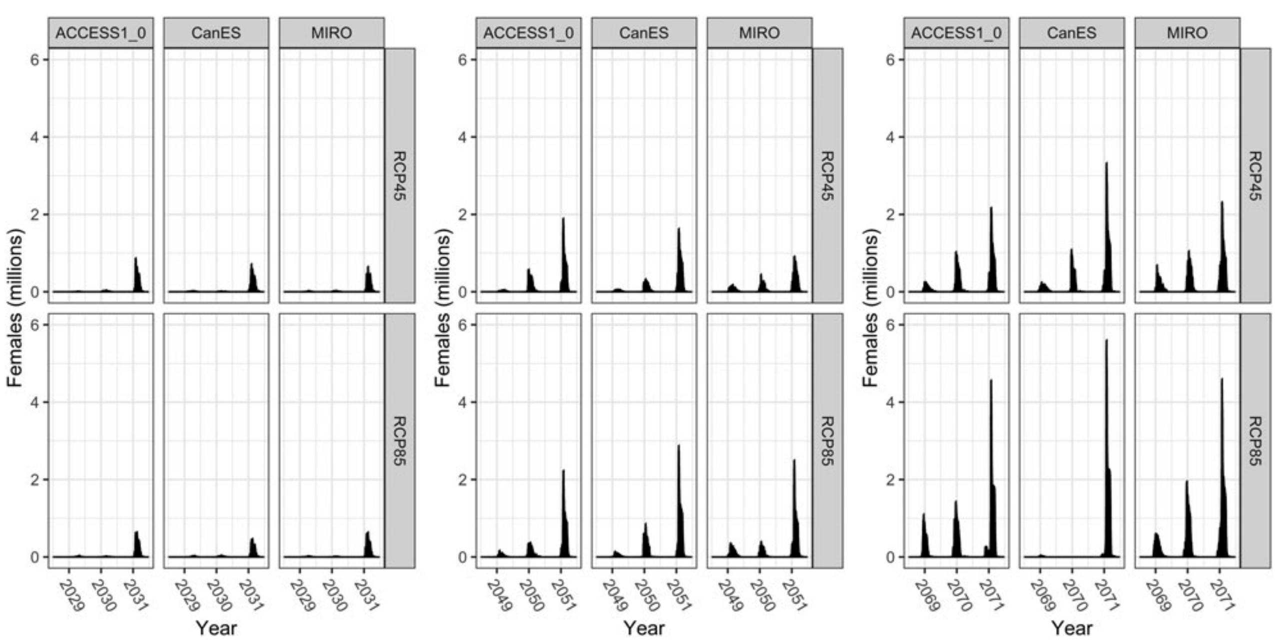

Figure 10. Cumulative adult female *Aedes vigilax* population by year, climate model and RCP pathway with accretion (top) and without accretion (bottom).

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rate is a great unknown and is an evolving area of study and is likely to be very variable depending on local conditions. If the wetland becomes permanently inundated, new predator populations may emerge, taking advantage of the large larval mosquito biomass upon which to feed, and it is likely the whole ecosystem would change, leading to the model becoming less applicable.

The increased waterline may allow reeds common in neighbouring wetlands to populate and outgrow the current samphire habitat, which is the preferred habitat for these mosquito species, or the samphire may otherwise be removed, limiting egg-laying at this site. An assumption of the mosquito model is that the samphire habitat migrates to continue to be at the pond edges as the water level increases. The newly inundated areas of the waterbodies of this study are mainly to the southeast, which is predominantly bare ground and open grassland, that has the potential to support the encroachment of samphire vegetation, which is suitable habitat for the two *Aedes* mosquito species. The migration of samphire is a reasonable assumption as ground water levels will rise along with the tidal-height rise (Rotzoll and Fletcher, 2013), and the roots of the samphire should maintain an acceptable distance from the groundwater table (Department of Primary Industries and Regional Development, 2021), while the existing vegetation becomes waterlogged and dies.

Due to their short lifespan and large number of offspring, mosquitoes are very fluid in their ability to adapt to ecological niches and changes (Bradshaw and Holzapfel, 2006; Karunaratne *et al.*, 2018). This model does not account for future adaptation or changes to the characteristics of the mosquito species, such as their minimum hatching temperatures, thermal mortality rates and many other characteristics, any of which would change the projections.

Conclusions

Under all scenarios modelled, mosquito population peaks increase, the number of days of the active mosquito season increases, and the size of the productive larval habitat increases. The projected water temperature increases so that minimum egg hatching thresholds for both *Aedes* species are exceeded for a larger portion of the year. The degree and rate of population increase is species-specific. *Aedes camptorhynchus* and *Ae. vigilax* will both increase in peak population size, with the model indicating *Ae. vigilax* dominating for the next few decades. Both species will see an increase in days of the active season. This is likely to put pressure on existing mosquito control programmes and increase the risk of mosquito-borne disease, nuisance biting to the local community, and chemical resistance among the mosquito population.

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