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Vector-borne diseases and water sensitive urban design

A rapid literature review

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Vector-borne disease and water sensitive urban design – A rapid literature review

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Terminology

Term	Description
Arbovirus	Group of viruses that arthropod vectors such as mosquitoes and ticks transmit
Host species	A larger organism that harbours a smaller organism
Mosquito-borne	Bacteria, viruses or parasites transmitted by mosquitoes that can cause diseases
Reservoir host	An organism that enables the infectious agent to reside in and multiply to transmit to other species
Riprap	A permanent ground cover of large, loose, angular rock designed to protect areas that are continuously exposed to rushing water
Vector	Transmission of a disease or parasite by an organism from one animal or plant to another
Vector competent (mosquito species)	The mosquito's physiological capability to become infected with an arbovirus and transmit it

Abbreviations

Term	Meaning
BFV	Barmah Forest virus
JEV	Japanese encephalitis virus
MREV	Murray River encephalitis virus
RRV	Ross River virus
VADCP	Victorian Arbovirus Disease Control Program
WNV/Kunjin	West Nile/Kunjin virus
WSUD	Water sensitive urban design

Introduction

Climate change affects multiple aspects of urban water management. In addition to concerns related to changes in the frequency and intensity of droughts, storms and floods, there are emerging issues related to public health. One such issue concerns vector-borne diseases and the potential connection between water sensitive urban design (as breeding habitat), mosquitoes (as vectors) and climate change (changing the range in which mosquito-borne diseases are observed).

Aim

This rapid literature review defines what is known and explores key knowledge gaps regarding the impacts of climate change on the presence of mosquito-borne disease in conjunction with water sensitive urban design (WSUD) in Victorian cities and towns. It explores whether current WSUD approaches pose a significant health risk, warranting a rethink of WSUD design and management to mitigate the risk of mosquito-borne disease to public health.

Method

This rapid literature review was conducted in 3 stages. An initial review of selected papers supplied by Melbourne Water was followed by a review of additional papers sourced from Google Scholar to add context and depth. Papers for the second stage were identified using a search with combinations of keywords and phrases, including WSUD, mosquito, climate change, Australia and vector-borne disease. Finally, additional information was reviewed and included based on recommendations from expert reviewers.

Together, these papers were reviewed to understand research topics and the evidence base on the intersection of climate change, mosquitoes as vectors and WSUD in Australia, as well as the knowledge gaps.

Limitations

The literature review was undertaken from a Victorian perspective, insofar as mosquito-borne disease risk is currently less of an issue than in northern Australia. Extrapolation of the conclusions to other, similar jurisdictions is possible if the scope and limitations of the original research are acknowledged.

It is further acknowledged that this is a partial review of the literature. The results can be interpreted as an initial test of evidence to validate the research question, and to determine the value of more detailed investigation into this topic.

Mosquito-borne diseases

Mosquitoes of concern in Victoria

Australia has over 275 species of mosquito. Not all these species bite humans, and even fewer can transmit disease to humans, as demonstrated in Figure 1.

In Victoria, 6 mosquito-borne diseases are monitored from a public health perspective: Ross River virus (RRV), Barmah Forest virus (BFV), Murray Valley encephalitis (MVEV), West Nile/Kunjin virus (WNV/Kunjin), Japanese encephalitis (JEV) and dengue virus.[1] Of these, RRV, BFV, MVEV and WNV/Kunjin are considered endemic to Australia.[2] JEV is endemic to areas of Asia and the Torres Strait, however, local transmission was detected in Victoria for the first time in early 2022.[3] While dengue virus has primarily been reported in returned travellers within Victoria, outbreaks have occurred in other parts of Australia, as *Aedes aegypti* (currently present in Queensland) facilitates transmission between humans.[4]

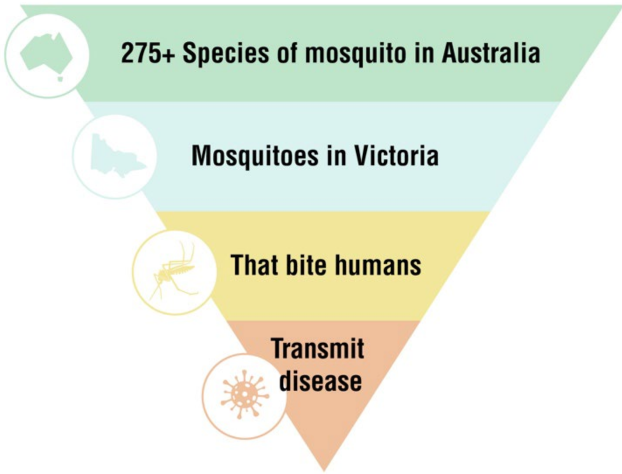

Figure 1. Visual representation of disease transmission from mosquitoes

Mosquitoes also play a role in spreading Buruli ulcers, caused by the *Mycobacterium ulcerans* bacterium. A study found possum excreta act as an environmental reservoir for *M. ulcerans*, contaminating areas where mosquitoes can pick up the bacteria. These mosquitoes then become vectors, transmitting the bacteria to humans.[8]

Table 1 summarises different mosquito-borne diseases either endemic in Australia or with the potential to be present.

Table 1. List of mosquito-borne diseases present or potential to be present in Australia

Mosquito-borne diseases	Endemic to
Ross River virus (RRV)	Australia
Barmah Forest virus (BFV)	Australia
Murray Valley encephalitis (MVEV)	Australia
West Nile/Kunjin virus (WNV/Kunjin)	Australia
Japanese encephalitis (JEV)	Asia and the Torres Strait
Dengue virus	Queensland
Buruli ulcer	Australia
Chikungunya virus	Africa, Southeast Asia, the Indian subcontinent, Pacific Region and most probably in the (sub) tropical regions of the Americas
Zika virus	Africa, the Americas, Asia and the Pacific
Buruli ulcer	Australia, West Africa, Central Africa, New Guinea, Latin America and tropic regions of Asia

There are mosquito surveillance programs across Australian states and territories. In Victoria, local councils trap mosquitoes each week and submit the samples to the Victorian Arbovirus Disease Control Program (VADCP), a state-wide collaborative program run by the Department of Health for identification, counting and virus screening. Detecting viruses in mosquito samples is an early warning that there is a health risk to local communities and that interventions to manage mosquitoes are required.[5]

Victoria's mosquito breeding season lasts from early November to late April the following year.[1] So, mosquitoes tend to be more abundant during this time. The mosquito life cycle contains 4 stages: egg, larva (i.e. wrigglers), pupa (are mobile and look rounder than wrigglers) and adult.[6] An egg-to-adult mosquito cycle may be completed in 7–14 days if weather conditions are favourable.[6] This lifecycle depends on the presence of water, and availability of food resources and suitable habitat conditions.

The Victorian Department of Health monitors and reports the presence of mosquito-borne disease and adult mosquitoes during the breeding season.[7] Several mosquito species are monitored due to their vector-competence (i.e. ability to transmit disease) or nuisance biting (i.e. biting impacts the amenity value of outdoor spaces). *Culex annulirostris* and *Aedes camptorhynchus* are the 2 primary species of concern for disease transmission in Victoria.[7] *Aedes notoscriptus, Anopheles annulipes s.l., Culex australicus, Culex globocoxitus, Culex molestus,* and *Coquillettidia linealis* are also monitored due to their potential for disease transmission and nuisance biting.[7]

Invasive species

Exotic mosquito species that are most commonly detected in imported cargo and international conveyances are *Aedes aegypti* and *Aedes albopictus (*the Asian tiger mosquito). This frequent detection reflects that species have adapted to urbanised areas in close proximity to humans and lay desiccation-resistant eggs in container habitats. Both of these species can transmit viruses with *Aedes aegypti* the primary vector for dengue, Zika, chikungunya and yellow fever. This species is already present in Queensland, but exotic *Aedes aegypti* may be resistant to pesticides or have a different vectorial capacity than the strains already present in Australia.[9] *Aedes albopictus* (known as the world's most invasive mosquito) is of greater concern because it is tolerant of cool climates, and bites aggressively during both day and night. If this species becomes established on the Australian mainland, it could enable local transmission of imported diseases including dengue, chikungunya and Zika viruses in the southern states, and possibly increase the risks of Ross River virus transmission in both rural and urban areas.[10]

Ae. albopictus is already established in the Torres Strait Islands and has been accidentally imported in cargo at major Australian ports on numerous occasions, but has been eradicated by quarantine measures.[10] The mosquito has entered Australia as eggs or larvae in cargo capable of holding water such as tyres, machinery, bulk steel and yachts, and eggs have been regularly found on imported lucky bamboo.[11] Between 1997 and 2005, 28 detections were recorded at international seaports including Darwin, Cairns, Townsville, Brisbane, Sydney and Melbourne. *Ae. albopictus* can survive colder climates because it can undergo diapause, an alternative developmental pathway that reversibly blocks developmental growth during specific transitions and enhances the organism's hibernating potential.[12] Predictive models coupled with climate tolerance experiments suggest a Torres Strait strain of *Ae. albopictus* could colonise southern Australia as far south as Victoria by overwintering in the egg stage before proliferating in the warmer months.[13]

A CSIRO and Oxitec Ltd (UK) program aims to reduce the spread of Asian tiger mosquito populations. Because female mosquitoes are the ones that bite and transmit disease, the approach is to reduce the female's ability to successfully reproduce. The program is creating a safe, effective and self-limiting strain of male Asian tiger mosquito, that when crossed with native females, produces non-biting, non-disease transmitting males. Further, a self-limiting gene prevents female offspring from surviving long enough to reproduce.[14]

Mosquito habitats

Mosquito species tend to occupy different niches or habitats in the natural and urban environments, varying across estuarine or freshwater habitats and with a tolerance for living in artificial containers.[2],[6] Their tendency to disperse by flight also varies.[2],[15] The following habitat preferences and flight distances for Victoria's mosquito species have been observed:

- *Aedes camptorhynchus* prefer estuarine, brackish marsh and river habitats and will travel many kilometres.[2]
- *Culex annulirostris* inhabits various freshwater environments, including natural or irrigated ones, having been found in drains and wastewater ponds; this species travels 2–10 km.[2]
- *Aedes notoscriptus* habitat includes rock pools, water-holding plants and artificial containers; this species travels only 250 m.[2]

While mosquito species exhibit habitat preferences, they can also be found outside of these environments. For instance, *Aedes vigilax*, a saltmarsh species found in Sydney, has been observed in freshwater wetlands.[16] Flood waters have also been identified as potential mosquito habitat, and linked with increased MVEV, RRV, BFV and JEV infection.[17]

So, while the presence or absence of habitat influences the composition of mosquitoes in a given location,[2],[16] mosquitoes can occupy a wide range of habits in, or adjacent to, urban areas, making it difficult to isolate the risk of any specific type of habitat in causing a mosquito outbreak. This finding is relevant to the question of isolating the role of WSUD in local mosquito abundance.

Factors affecting disease transmission

Mosquito presence/abundance is only a part of the bigger picture. Transmission of mosquito-borne diseases, resulting in human infection, requires aligning all components of the disease transmission pathway. This pathway is represented visually in Figure 2 and described below.

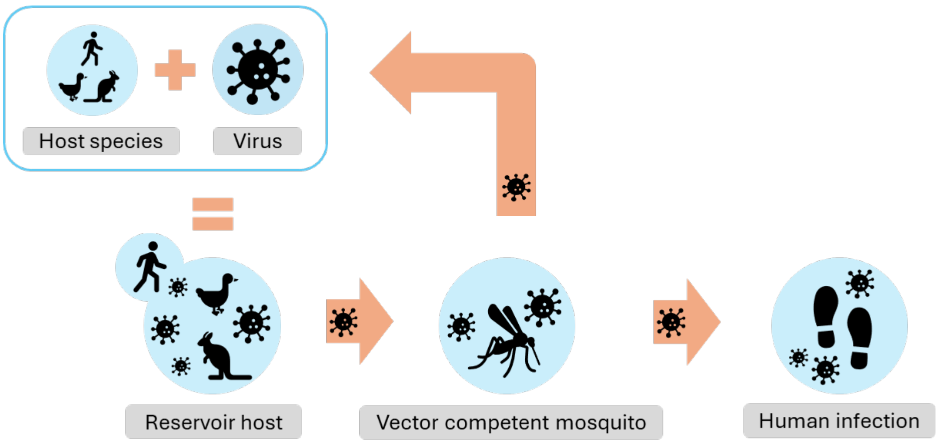

Figure 2. Mosquito-borne disease transmission pathway resulting in human infection

Disease transmission relies on the presence of a vector-competent mosquito species (i.e. a mosquito that bites and can transmit the virus), represented in the centre of the diagram. Also required is a reservoir host within the mosquito's habitat or flight distance (shown on the left side of the diagram).[2] The reservoir host species depends on the specific virus; hosts include waterbirds, macropods (e.g. kangaroos and wallabies) and possums.[15] In some instances, humans are also a reservoir host, including when RRV rates are high or for dengue virus.[4],[18] To transmit a disease, the mosquito must first bite the reservoir host and collect the virus (left and centre of the diagram). The transmission then requires a human is present in the same environment as the mosquito or within the mosquito's flight distance, and that the infected mosquito bites and successfully infects the human with the virus (centre and right side of the diagram). The following sections discuss key concepts relating to individual elements of the disease transmission pathway.

- **Prevalence of vector-competent species** – Presence in a given location (such as a wetland or rain garden) is influenced by the presence of predators, availability of habitat/standing water, appropriate water temperature, food resources and other physicochemical conditions required for development.[19],[20],[21] Other factors include the conditions for breeding and the ability of mosquitoes to disperse in the wider landscape to find new habitats.[2],[6] A visual representation of these relationships is provided in Figure 3.

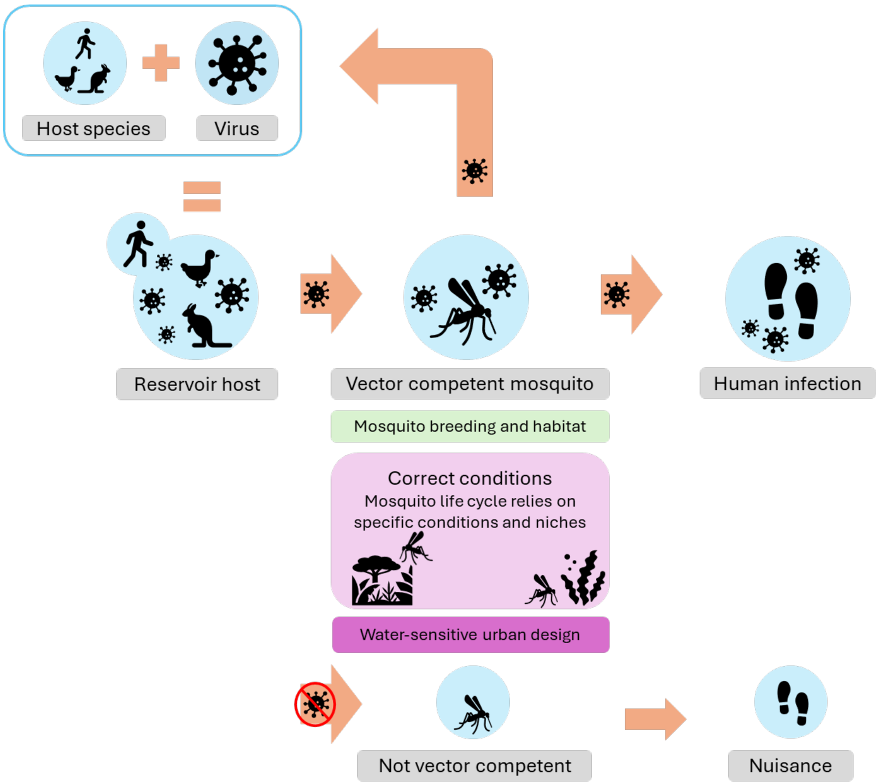

Figure 3. Vector vs non-vector competent mosquito, and the location of WSUD in the transmission of mosquito-borne diseases

- **Presence of the arbovirus** – A virus needs to be present for disease transmission to occur. The effects of this factor can be exacerbated by introducing a virus into a new urban area, such as by host migration or infected mosquito movement.[2]
- **Presence of host species** – The presence of infected host species, called reservoir species, helps to sustain a virus in an area. The host of the virus may influence infection dynamics due to hosts' relationships with the landscape (e.g. migratory birds).[15]
- **Presence of humans –** Our primary concern in this research is human health. To become infected with a mosquito-borne disease, a human must be bitten by an infectious mosquito. The risk of infection depends on factors such as the proximity of humans to mosquito breeding sites, their interaction with mosquitoes during daily activities, and their ability to prevent bites such as through changes in behaviour.[22] As demonstrated in later sections, management systems can be introduced to monitor WSUD assets and manage mosquito populations based on the proximity and exposure of humans to mosquitoes.[15],[23],[24]

WSUD as a hazard

Water sensitive urban design (WSUD) can influence the prevalence of vector-competent species, presence of host species and the presence of humans in an area. For these reasons, WSUD warrants further investigation as a vector-borne disease hazard in cities.

About WSUD

Urban development changes the way water interacts with the landscape, as hard surfaces and engineered drainage interrupt natural water flows. Pavements, roads and other sealed surfaces reduce infiltration and surface roughness.[25] As well as generating additional stormwater volumes, run-off from urban areas contains contaminants and pollutants (e.g. pesticides and oil, sediments and nutrients) picked up from urban land uses.[25]

WSUD describes infrastructure and urban design features used to manage stormwater and return urban hydrology towards more natural parameters.[26] WSUD includes a range of nature-based and engineered systems, implemented at different scales, to provide 3 main functions:

- reducing the volume of water discharged to the environment by allowing areas for infiltration, transpiration and evaporation to occur within the urban landscape[26]
- slowing the flow of stormwater and mitigating flooding, typically by providing temporary storage space for water[26]
- reducing contaminant levels in stormwater and improving water quality in receiving environments, using natural wetland processes.[26]

WSUD often includes swales, rain gardens, sediment ponds, constructed and natural wetlands, green roofs, and rain and stormwater harvesting (e.g. rainwater tanks).[25] Many of these assets have common design elements such as vegetation, a filtration layer, a storage tank, a drainage pipe or a link to an existing drain. Some may also include a gross pollutant trap, sedimentation area, disinfection unit and irrigation pipes, depending on the design.[25]

Many WSUD systems are designed for multiple objectives. For example, urban wetlands may have amenity objectives (to encourage active lifestyles), stormwater harvesting objectives (to support water security) and habitat objectives (to enhance biodiversity), as well as urban stormwater treatment objectives.[27] The result is to create naturally styled water features in urban landscape, that can be highly valued by urban communities,[28] leading to increased interest in integrating WSUD in housing developments (Figure 4).

Figure 4. Wetlands, at Marriott Estate (Vic), designed with multiple objectives and integrated into the urban landscape in close proximity to humans

Source. CRCWSC.

WSUD and mosquitoes

Because WSUD is designed to hold stormwater in the urban landscape, it provides potential habitat for mosquitoes. Indeed, mosquitoes have been found breeding in WSUD assets in Australia and around the world, including tanks, below-ground treatment systems and wetlands.[29],[19],[30],[21, 31] Rainwater tanks and constructed wetlands are the most commonly identified WSUD assets that create potential breeding sites for mosquitoes, although this finding is an artefact of the scope of the research reviewed rather than a systematic investigation of all WSUD assets.[29-31] These studies suggest WSUD may increase the risk of mosquito-borne disease transmission in urban areas.[32] It also follows that as WSUD is progressively integrated into urban areas, understanding effective management of these assets and mosquitoes will be increasingly important to reduce human health risk.[33]

The literature highlights 3 key issues relating to WSUD that influence mosquito habitat:

1. the presence of standing water in the urban landscape
2. the habitat quality of this standing water for mosquitoes
3. the (lack of) operation and maintenance of WSUD (that can enhance habitat availability and quality).

Explaining these issues is simplest for rainwater tanks. Rainwater tanks present a similar risk to that of other basic, engineered WSUD assets. They are simple water containers/conduits that lack the water flows or functional biodiversity necessary to control mosquitoes.[34] Further, rainwater tanks are often poorly maintained. Assessing the condition of rainwater tanks in Melbourne, Moglia et al. (2015) found mesh designed to prevent mosquitoes was compromised on 11.3% of tanks, and 12.5% of tanks contained mosquito larvae.[30] Standing water in below-ground WSUD assets also provides mosquito habitat. Much like rainwater tanks, these assets have organically rich standing water and stable year-round temperatures, and exclude predators.[19] In an experimental study, mosquitoes were placed into below-ground WSUD assets to determine how many could grow into adults and escape. Results showed 56% of deployed mosquitoes were captured in adult exit traps.[35]

Green infrastructure, such as wetlands, are a different situation. Designs and features that create areas of standing water (e.g. as a design feature or due to clogged drains, poor inlet energy dissipator design and dry weather inflows) are predictably problematic.[20],[21] For instance, mosquitoes are recorded in wetland outfalls areas, riprap areas and in areas with emergent or dense vegetation.[21],[29],[36] Other factors, such as biodiversity, also influence mosquito numbers, although this influence is more complex. Shallow wetlands with dense vegetation create habitat that encourages mosquito breeding,[29] and mixed wetland vegetation communities are more conducive to mosquito breeding than wetlands with single species vegetation communities.[36] Wetlands with high levels of aquatic biodiversity won't always mean a high number of mosquitoes,[16] and green roofs have fewer mosquitoes than empty rooftops and grassed areas at ground level.[37]

It is likely the quality of mosquito habitat is important, with temperature, water quality, availability of food resources and the presence/absence of mosquito predators being key variables. Water containing high levels of nutrients, sediments and organic matter was related to higher mosquito abundance because it provides an energy source for larvae. [2],[19] This situation is problematic because WSUD is intentionally designed to capture nutrient laden stormwater runoff.

Operation and maintenance of WSUD can be as much of an issue as WSUD design in influencing mosquito numbers. For example, inadequate maintenance (leading to clogged drains or overgrown vegetation) increases the potential for standing water and mosquito risk.[20]

WSUD risk in context

It is important to contextualise the mosquito risks of WSUD considering:

- WSUD relative to other water bodies in urban areas. i.e. Will reducing the mosquito risk posed by WSUD make a material change in total risk?
- the need to balance the downside risk of vector-borne disease with the other upside benefits WSUD provides.

With reference to the first, mosquito habitat takes many forms and mosquitoes are adaptable. It is also important to consider WSUD's role in promoting vector-competent species, as distinct from all species. Crocker et al. (2017) investigated mosquito assemblages of various wetlands and estuarine water bodies in Metropolitan Sydney.[15] They found higher abundances of mosquitoes in estuarine wetlands than in urban (WSUD) wetlands, and no difference in mosquito communities in urban wetlands compared with suburban areas with nearby bushland. Another study found wetlands had a higher abundance of mosquitoes than residential areas, but residential areas had more vector-competent mosquito species and higher infection rates per thousand people.[38]

It is also clear mosquito populations persist in urban areas without WSUD, because mosquitoes can use other habitats in urban environments.[32] For example, container-breeding species thrive in artificial water sources (e.g. water holding containers)[38] and other, naturally occurring water bodies can provide mosquito habitats. In some cases, urban areas without WSUD can have even higher numbers of mosquitoes.[32] These results suggest the question of reducing vector-borne disease risk is more complex than targeting WSUD; there is no evidence that reducing/removing WSUD reduces overall mosquitoes or vector-borne disease risk.

On the second point, WSUD provides a range of community and sustainability benefits. WSUD increases biodiversity, decreases the urban heat island effect and conserves drinking quality water by reusing captured storm- and rainwater within the urban landscape.[26],[25] These outcomes are valued by the community.[28] Several researchers identified a risk of compromising these benefits of WSUD through efforts to reduce mosquito risk associated with wetlands.[16],[33] From this result, it could be inferred that the trade-off may not be justified (although there is little evidence to substantiate this inference).

Climate change impacts

As a generalised statement, climate change has been identified as impacting vector-borne diseases, including mosquito-borne diseases.[2],[39] The climate variables most relevant to mosquito-borne diseases are temperature, rainfall and flooding.[39],[17] Of concern is the potential for climate change to amplify the connection between WSUD and mosquitoes and human health risk.

How is climate change a factor

Climate change is changing precipitation, temperature, fire and sea level in Victoria when compared with baseline conditions (1986 to 2005).[40] These changes are important factors insofar as they increase the risk of mosquito-borne diseases associated with WSUD. Conceptually, changing these variables may affect the range, abundance or prevalence of vector-competent species, arbovirus or host species.

Temperature

In Victoria, minimum and maximum temperatures are expected to increase in the future; some cool periods will still occur due to climate variability.[40] Of concern are the more frequent temperatures at the higher end of each mosquito species' tolerable range that promote rapid hatching and larval development.[2] Fewer cool days may also extend the mosquito breeding season, or allow mosquitoes to persist during other seasons.[19] Changes in climate could also make the environment more conducive to other vector-competent exotic mosquito species.

Rainfall

Historically, Victoria’s rainfall is highly variable, and the impacts of climate change are difficult to predict, making future rainfall highly uncertain.[40] Regardless, rainfall is inextricably linked to the lifecycle of mosquitoes; so, any changes to rainfall patterns and amounts will impact mosquito populations.[39],[17] Overall, Victoria is projected to receive less total rainfall and become drier in all seasons except summer; some very wet years will still occur due to variability.[40] Extreme rainfall events are predicted to increase, including increased rainfall intensity, heavier rainfall events of a short duration, thunderstorms with short and intense rainfall and flash flooding.[40]

Disease transmission

The impact of climate change on vector-borne disease risk remains uncertain and further research is needed. Sinclair et al. (2017) described climate as just one factor, among many.[2] In Australia, climate change is expected to reduce endemic disease transmission in some locations and increase it in others.[2] For instance, at the intersection of the edge of climate zones (e.g. tropical and sub-tropical) and the edge of the endemic range of an endemic virus, changes in the geographical distribution of mosquitoes and the human population being less immune/more receptive increases the risk of human infection.[39] Alternatively, the expansion of some mosquito species range is unlikely to be large.[2]

Combined risk

These changes can intersect and influence the risk of mosquitoes and mosquito-borne pathogens within urban environments in several ways.[15] The obvious change relates the amount (depth/area), frequency, duration and distribution of standing water in the urban landscape. Increased rainfall results in more water in the landscape (and in WSUD systems), and thus more potential mosquito habitat.

Adoption of WSUD may also increase in the future, as a form of climate adaptation. For instance, WSUD may be increasingly used to reduce flash flooding,[26],[25] making it more valuable as urban areas experience increased rainfall intensity.[40] WSUD assets may also be increasingly deployed to provide water security in the face of declining average rainfall and higher temperatures. In this instance, the risk of mosquito breeding may increase if people adopt rainwater tanks and stormwater harvesting scheme, to maintain their water security.[31],[24],[40] Climate change also influences disease transmission through changes to human behaviour.[39] For example, increased outdoor activity (such as exercising) at dawn and dusk to reduce heat exposure inadvertently increases exposure to mosquitoes if such exercise occurs near urban wetlands and lakes.[22]

Figure 5 summarises these impacts of climate change on the disease transmission pathway.

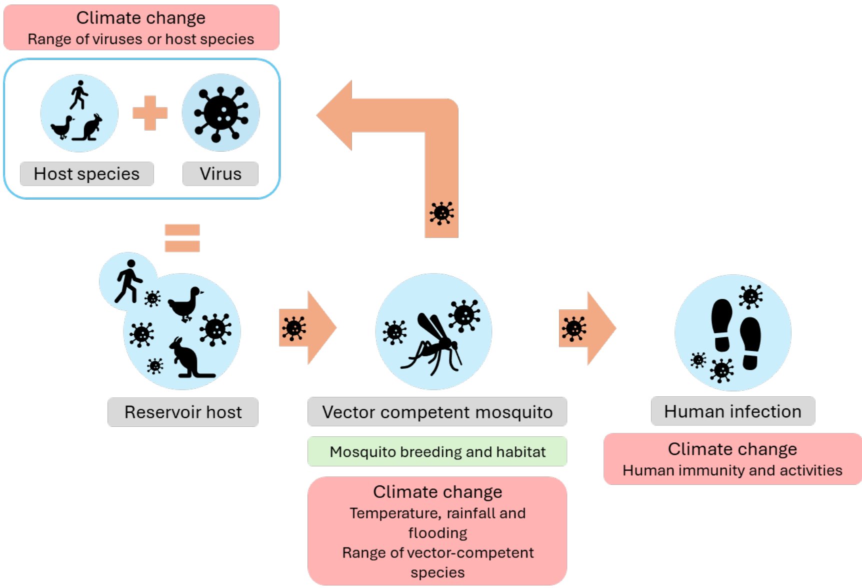

Figure 5. Climate change impacts on mosquito-borne virus disease transmission

Non-climate factors impacting the distribution of mosquito-borne disease

Climate change is only one determining factor in the transmission of mosquito-borne disease. Other factors include:

- movement of people, animals and goods inadvertently transporting vector-competent mosquito species, infected hosts and diseases to new places[2],[41]
- genetic changes that impact the virus (e.g. increased transmissibility) or the vector (e.g. preferences)[2]
- preparedness and quality of public health service response[2],[41]
- urbanisation patterns and encroachment into natural mosquito habitat areas[2]
- availability and use of effective control methods and disease treatment options[41]
- broader changes in human behaviour and land use (e.g. irrigation and water storage).[2],[41]

Management approaches

Knowledge of the links between WSUD and mosquitoes remains important to manage the risk of mosquito-borne disease.[16] To this end, Victoria previously proposed a useful management framework based on 4 key principles:[23]

1. mosquito surveillance
2. physical control (source reduction)
3. chemical control
4. mosquito bite prevention.

Specific management approaches for WSUD

Several mosquito management approaches and techniques are suggested based on these principles. Each aims to reduce the risk mosquitoes pose to human health by interrupting different components of the disease transmission pathway (Figure 2). The actions are outlined below in Table 2:

Table 2. Mosquito management approaches for WSUD

Category	Action	Impact	To note
Habitat modification	Seal access routes in tanks and harvesting systems[21],[30]	Could limit access for breeding and consequently mosquito numbers[21],[30]	Could hinder the water quality benefits provided and access for other reasons (e.g. monitoring)[21],[30]
	Fill low-lying areas in the landscape and remove containers[23]	Reduces breeding habitat availability[23]	Conflicts with the WSUD principles[23]
	Modify constructed wetlands design standards to adopt deep, open water with steep edges[29]	Optimal design for mosquito control includes steep, nearly vertical basin sides and conveyance structures that eliminate standing water[42]	Conflicts with WSUD best practice and may compromise other design standards related to water quality treatment or health and safety
Environmental management	Manage potential food resources (suspended solids and particulate organic matter in water samples) which are significantly correlated with development time (from egg to pupa)[19]	Food availability may limit larval development rate[19]	
	Manage temperature	Temperatures of below-ground WSUD suggest sites are amenable to supporting *C. Quin.* for longer periods than above-ground sites (below-ground WSUD	

Category	Action	Impact	To note
		had more consistent temperatures and with narrower seasonal variation)[19]	
	Incorporate water movement and surface disruptions (e.g. with aeration or sprinkler systems) [2],[29]	Disrupts mosquito breeding	
	Maintain sparse vegetation and areas of open water (e.g. remove overgrown vegetation)[2],[29]	Reduces mosquito habitat	
	Reduce the nutrient levels in the water[2]	Limits mosquito breeding	
Chemical and biological controls	Chemically treat larvae (i.e. larvicide)[23],[34]	Directly reduces mosquito larvae	
	Promote biodiversity, targeting species that prey on mosquitoes[2],[16],[35]	Natural biological control	
Infrastructure and maintenance	Ensure drains are not blocked, and legacy components are decommissioned or maintained to reduce risk of standing water or vegetation becoming overgrown[20],[23],[43]	Reduces breeding sites	
	Design landscape features or buffers between WSUD assets (i.e. wetlands spaced further apart than mosquito dispersal distance)[24]	Creates a barrier against mosquito travel or reduces exposure to humans[24]	
	Manage wetland water levels with specific intervals Adopt wetland (etc.) flooding and draining regimes to manage mosquito breeding[29]	The intervals determine if the method is helpful. For example, larval density was reduced when water was drained every 5 days.[29] By contrast, annual draining of wetlands could increase larval density.[44]	

These mosquito management practices are often based on assumptions about mosquitoes and their habitats, and supporting empirical evidence is lacking.[16],[33] For example, isolating the source of mosquito populations in an urban area can be challenging, making it difficult to attribute changes in mosquito populations or human infection to changes in WSUD design.[16] Further, several recommendations have a single objective (reduce mosquito habit) and may not be appropriate if they reduce WSUD's core benefits.[16]

As an additional word of caution, while management approaches for mosquitoes could be generalised, this may result in ineffective management. The specific species of mosquito (e.g. vector-competence, habitat preference) and context (e.g. place, presence of host species and climate) should inform the management approach.[16],[33] For example, if the mosquitoes in an urban area prefer container habitats, then changing the management of nearby wetlands is unlikely to provide the desired results.[16] Similarly if an area experiences frequent flooding, then reducing standing water in a WSUD asset is unlikely to affect the amount of available habitat.

Other management approaches

Harbison et al. (2010) identified confusion over roles and responsibilities among managers of stormwater assets and poor collaboration and lack of interest in managing mosquitoes/vector-borne disease, recommending greater collaboration among government.[19]

Some examples of collaborative, integrated solutions to mosquitoes and vector-borne disease risk include:

- surveillance and assessment of mosquitoes with cooperation between different levels of government such as local councils and state health departments[15],[23]
- use of urban planning decision and support tools (e.g. risk maps) for mosquitoes, to inform land use zones and urban planning[24]
- community awareness and education, including about container breeding mosquitoes and ensuring water-holding containers in residential areas do not become mosquito habitat[16],[23] or promoting personal mosquito bite prevention (e.g. wearing loose clothing, repellent, timing of activities and screens on homes).[22-24]

Summary of management approaches

Figure 6 summarises management approaches and how they fit into the mosquito-borne transmission pathway. We suggest these approaches be accompanied by clear management roles and responsibilities for agencies involved in managing WSUD and mosquito risk, understanding community values and providing community education.[16],[19]

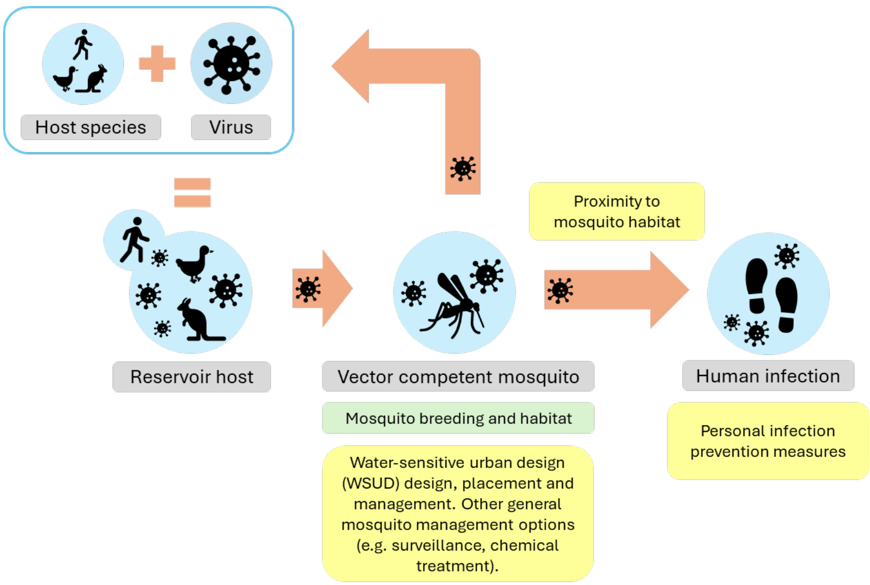

Figure 6. Management options to disrupt the mosquito-borne disease transmission pathway

Conclusion

This rapid literature review explored the connection between WSUD (as breeding habitat) and mosquitoes (as vectors), and the influence of climate change as an accelerator of disease risk in urban areas.

All WSUD assets can harbour vector competent species, including rainwater tanks, constructed wetlands, below-ground treatment systems, swales (etc.). However, research is limited on the specific risk that WSUD poses as a mosquito habitat in urban areas. While some studies discuss the potential risk posed by wetlands, below-ground storage and rainwater tanks, there is less research on other WSUD assets, such as swales or rain gardens. Some WSUD assets such as green roofs are reported to reduce the risk of mosquitoes. However, available research on urban greening (i.e. using WSUD) hints that the benefits of increased biodiversity and social outcomes may outweigh the potential health and nuisance risks of mosquitoes, when uncertainty about risk level of WSUD is considered.

The reviewed literature also revealed a complex set of factors that affect mosquito presence and abundance and the risk of disease transmission. While some of these factors have been well researched, others are based on assumptions and have limited evidence supporting them. Similarly, the evidence base for management approaches that aim to reduce risk is varied. As a result, isolating the relative risk presented by WSUD and justifying changes in management approaches is challenging.

Climate change adds to the complexity. It has already been linked with an increased risk of vector-borne disease, through changes in temperature and rainfall, and as an unintended consequence of human adaptations. Again, there is a lack of good experimental evidence on the consequences of climate change on WSUD-related risk.

The literature also remains uncertain about the best management options and adaptations. Although there is a general theme of managing biodiversity, changing design to reduce mosquito habitat quality and quantity, and harnessing urban planning (e.g. mapping high-risk mosquito areas to influence higher-density development areas) to control mosquito populations and risk, many knowledge gaps still need to be addressed to provide confidence to guide investment.

Overall, evidence is limited that WSUD is a priority hazard in transmitting vector-borne diseases. However, this conclusion does not mean there is *no* risk; only that there is no evidence to justify a change in WSUD practice, especially when the risk is balanced against the range of benefits of WSUD.

Knowledge gaps

This section describes 5 areas for further investigation, assuming there is interest in better understanding the additionality of vector-borne disease risk posed by WSUD:

1. **Understanding the nexus between WSUD in urban areas and exposure to mosquitoes.** While the characteristics of landscapes surrounding urban wetlands influence the abundance and species of mosquitoes, further research is needed to understand how the spatial placement of local scale WSUD influences risk factors such as the dispersal patterns of wetland-associated mosquitoes, exposure to mosquitoes among vulnerable human populations and disease transmission.[16] Similarly, the understanding of dynamic interactions between biodiversity, mosquitoes, wetlands and landscape traits in urban areas is limited. There is still much to learn about the interaction between mosquitoes associated with urban wetlands, other wildlife associated with these environments and adjacent human populations.

2. **Investigating the risk posed by different WSUD assets**. WSUD is highly varied in its design and application. However, most available literature on potential mosquito breeding sites concerns wetlands and rainwater tanks.[2] There is little literature on risks associated with other WSUD and urban greening assets, such as rain gardens.

3. **Providing evidence to guide constructed urban wetland design.** There is little research on how constructed wetland design influences vector-borne mosquito disease transmission. International

research suggests wetland conditions that promote biodiversity are associated with lower densities of vector-borne mosquitoes.[2] However, there is an absence of evidence-based guidelines describing the individual design parameters of constructed wetlands (e.g. edge treatments) needed to (say) promote biodiversity in ways that reduce mosquito risk.

4. **Testing the efficacy of different wetland / WSUD management practices, at various scales.** The impacts of common wetland operation and management practices on aquatic biodiversity and mosquitoes are often assumed but untested. Similarly, there is a lack of evidence on how best to manage mosquito risk in rain gardens or other WSUD assets, and across the different scales at which WSUD is planned. Understanding fine-scale risk patterns and responses is required to both manage individual wetlands/WSUD to reduce site-specific mosquito risks and also to manage and plan at the landscape scale.

5. **Developing monitoring approaches and risk thresholds** to proactively manage mosquito-borne disease risk associated with WSUD. Risk management approaches inevitably include monitoring and evaluation of risk levels. Research into cost-effective monitoring approaches in urban catchments, coupled with an evidence-based risk management framework defining thresholds for action, would facilitate early mitigation of potential mosquito issues. This research could also inform wetland design and management to maximise benefits to urban wildlife while supporting human health and wellbeing.

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