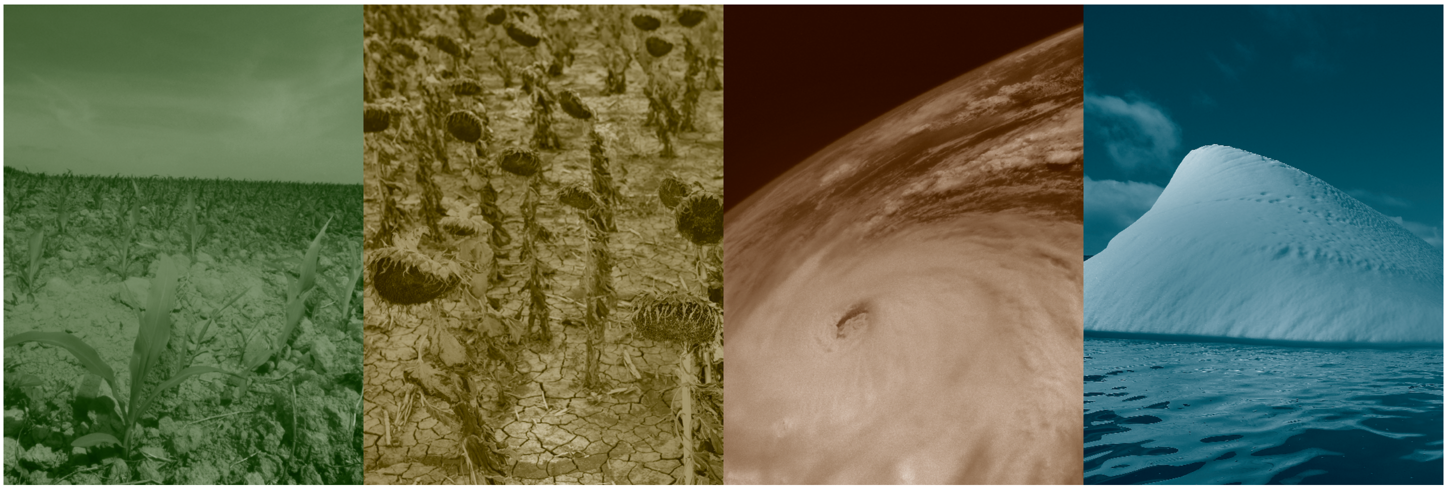
Evidence on the use of Integrated Mosquito Management to Reduce the Risk of West Nile Outbreak after a Flooding Event

A Potential Component of a Post-Disaster Integrated Mosquito Management Program



Climate and Health Technical Report Series

Climate and Health Program, Centers for Disease Control and Prevention

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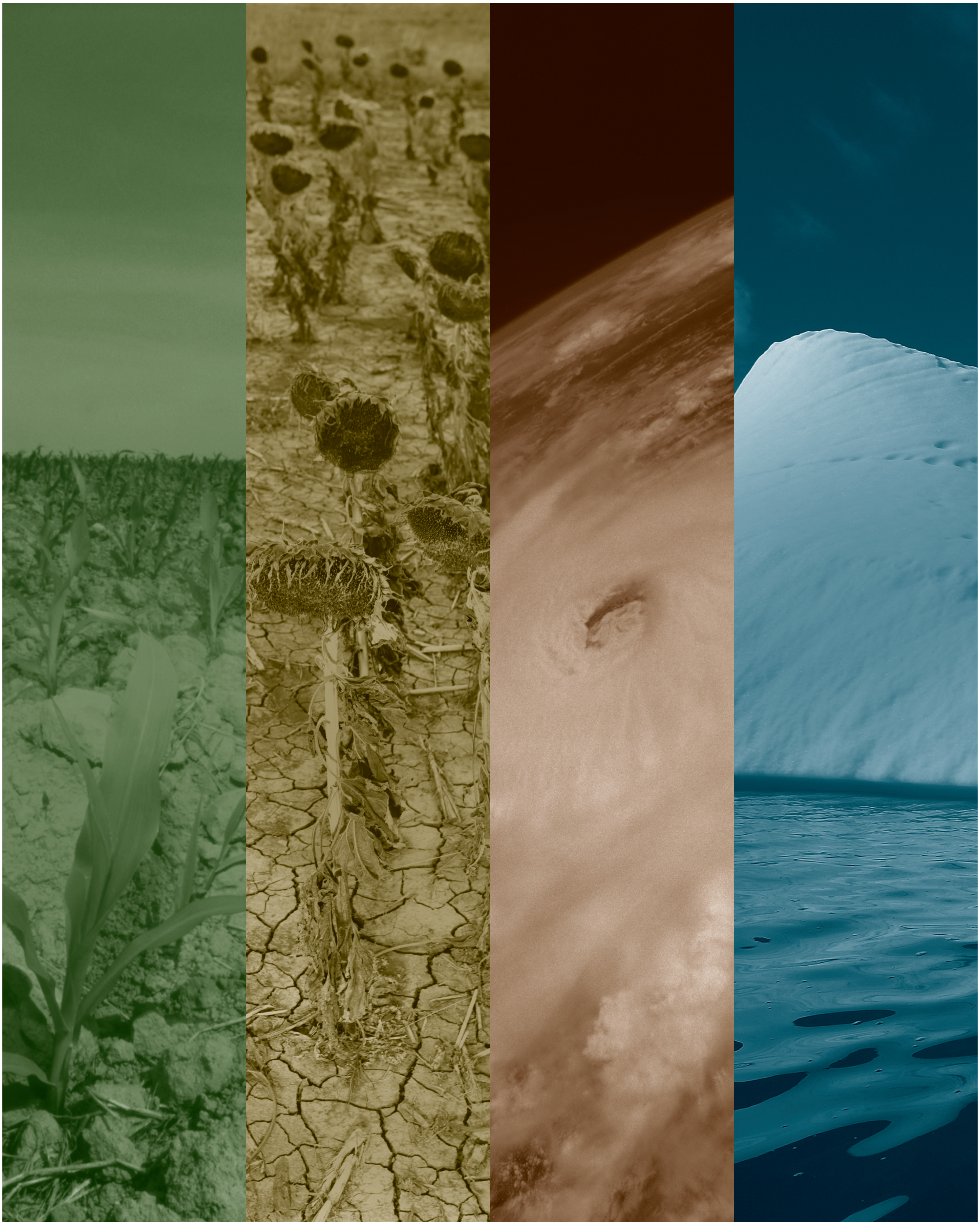

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Executive Summary

Climate change is one factor that has contributed to the changing landscape of vector-borne diseases. Shifts in weather and climate can impact the distribution and seasonality of disease vectors. This is particularly true for diseases caused by pathogens that are vectored by mosquitoes, which respond to changing temperature, weather, and precipitation patterns in ways that are complex and difficult to predict. While there are hundreds of species of mosquitoes, *Culex* and *Aedes* are two that include species with public health importance because they are known to carry many types of pathogens, including Zika, dengue, chikungunya, yellow fever, West Nile, Japanese Encephalitis and St. Louis Encephalitis viruses.[1,2] Local and state health departments have worked to prepare for and address mosquito-borne diseases; however, this is not often done in the context of a changing climate. The Center for Disease Control and Prevention's (CDC) Building Resilience Against Climate Effects (BRACE) framework is a 5 part process that enables health departments to develop strategies in combating the effects of climate change in their area.[3, 4] In this paper, BRACE steps 1–3 are applied to West Nile Virus (WNV) and its vectors, *Culex* spp mosquitoes. The impact of climate change on mosquito abundance and WNV risk are assessed, and the effectiveness of current public health interventions are investigated. There have been multiple reviews of mosquito control interventions, which have driven more sustainable and effective control of disease carrying vectors. This paper addresses the utility of such interventions in the context of an extreme flooding event, and how their effectiveness may change when implemented in these conditions.

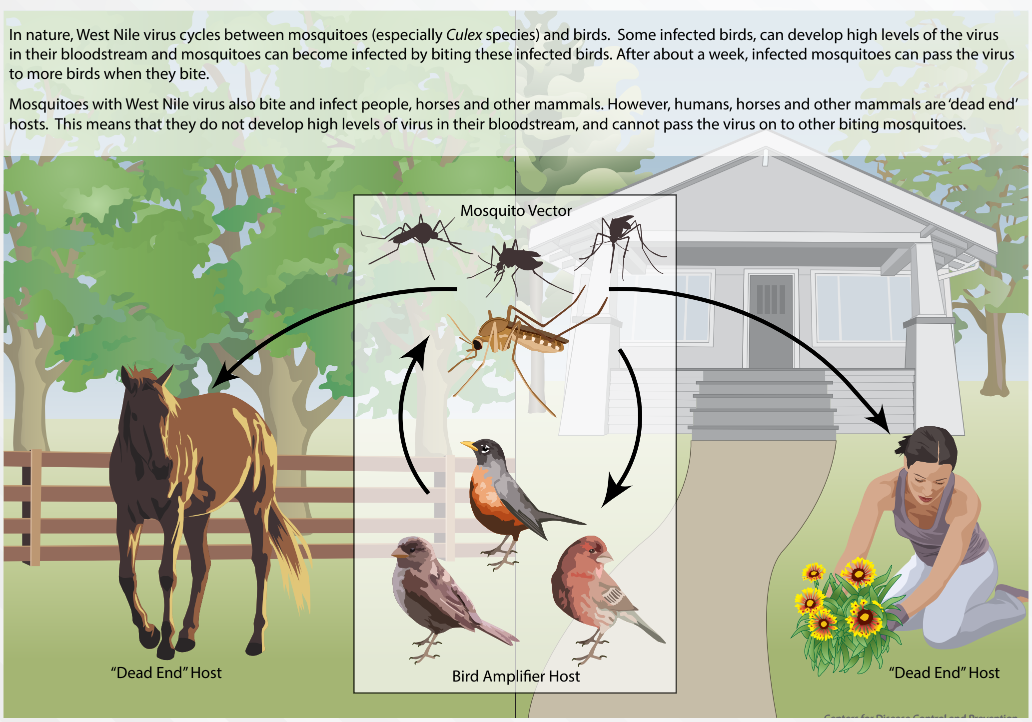
One approach to an expanding mosquito population after a flood is Integrated Pest Management (IPM). IPM addresses multiple components of a pest's lifecycle, and how it interacts with its environment.[5] Mosquito-specific IPM is referred to as Integrated Mosquito Management (IMM), a surveillance-based framework that incorporates components of education, source reduction, biological modification, and chemical control of mosquitoes. All of these interventions are accompanied by surveillance involving different parts of the WNV transmission cycle, including mosquitoes, birds, horses, and humans.[6] In order to be successful, IMM requires involvement by multiple levels of government and open communication between different departments. The key barriers towards implementing IMM are a lack of organizational support and insufficient funding. However, in a disaster scenario such as a flood, an IMM approach can help streamline and define roles and make addressing a growing mosquito population more efficient and cost-effective. While many methods are still being examined, there are several that have proven to be useful and could be effective for use by health departments and their partners in responding to a flood.

Background

Culex spp mosquitoes

Culex spp mosquitoes are the main vectors of West Nile Virus (WNV) in the United States.[7] There are a variety of species of *Culex*, with various feeding times and hosts from which they take a blood meal.[8] For example, *Cx. pipiens, Cx. restuans, Cx. salinarius, Cx. tarsalis,* and *Cx. quinquefasciatus* are all crepuscular (sunset or sunrise) and nighttime feeders.[8] If the main carrier of WNV in a region is known, public health departments and residents can take steps towards reducing or avoiding the culprit population. Because different species of mosquitoes have a variety of preferences for their blood meals, each play different roles in the amplification of WNV within the environment, as well as the infection of humans. *Culex pipiens* and *Cx. restuans* feed on birds, which allows them to play an important role in amplifying WNV in host sources.[8] *Culex. quinquefasciatus, Cx. nigripalpus* and *Cx. tarsalis* are known as "bridge species," in which they bite infected birds and subsequently feed on humans.[8] These species are often seen in different regions of the US. For example, *Cx. quinquefasciatus* is common in southern states.[2] A study by Kilpatrick et al. proposes that *Cx. pipiens* might also be a bridge species.[9] Through these species, WNV is then introduced into the human and equine population. *Aedes* spp are more likely to carry other pathogens such as dengue, chikungunya, yellow fever, or Zika viruses.[1]

Figure 1. WNV Transmission Cycle[10]



Culex spp Mosquitoes and Floods

Some species, such as *Cx. pipiens* and *Cx. tarsalis,* have variable feeding habits throughout their season, which can amplify the transmission cycle.[9] *Culex. pipiens* will begin its season feeding on birds, spreading WNV within the avian populations. Its most often reported avian blood meal is American Robin, which migrates late in the summer.[9] It is hypothesized that increased avian diversity, as seen in Latin America, may dilute WNV in the bird population, reducing the risk of spill-over into humans.[11] Later in summer and fall, *Cx. pipiens* then begins to feed on humans, causing an increase in WNV cases.[9] By understanding the interactions of mosquitoes and bird populations, health departments can better predict and prepare for possible outbreaks.

Mosquitoes are common after a flood. Many factors, including the time period after the initial flooding, will determine the dominant species.[12] Floods will initially wash away *Culex* spp larvae, as eggs are laid in rafts that sit on the water surface.[12,13] "Floodwater *Aedes* species," including *Aedes vexans*, lay their desiccation-proof eggs in moist soil.[14] The eggs hatch after a flood results in excess standing water, and adults emerge within a few days.[12]

After the floodwater recedes, pools of standing water often remain. Adult female *Culex* spp mosquitoes are often attracted to these pools, and populations will often rebound two weeks after a flood.[13] Various species of *Culex* mosquitoes also prefer different larval habitats, which means that they will have varying responses to the environment after a flood. In general, *Culex* spp mosquitoes prefer man-made structures that are filled with stagnant and possibly polluted water, such as ditches or retention ponds.[15] This type of water must be standing (stagnant) for a period of time, and this provides a window of time in which interventions can be performed to prevent and reduce the number of *Culex* spp before WNV can take a foothold in the mosquito population.

Culex spp population densities depend on the species that is prominent in a given region. Knowing the common species of the region can assist in understanding what type of risk exists in the area after a flood. In some areas, droughts and a lack of rainfall can increase mosquito and bird interactions, and lead to a subsequent increase in WNV cases.[7] Some species such as *Cx. tarsalis,* thrive in polluted water, which can include tailwater (water downstream from a structure such as a dam or bridge), sewage runoff, irrigation canals, or storm drains.[7,16] However, this species is only prominent in the western United States, so response plans must be modified depending on which species is most prominent in the area.[16]

The risk for a WNV outbreak after a flood occurs is difficult to discern. Multiple studies have shown that *Culex* spp mosquitoes commonly lay eggs in standing water in storm drain overflow, which would be prominent after a flood.[17] Many cities in the United States use Combined Sewage Overflow (CSOs), which mix rainwater and sewage and send the combination to a treatment facility.[18,19] If there is heavy rainfall, the system can become overwhelmed, necessitating diversion into bodies of water or drainage ditches.[18] These systems can produce large amounts of mosquitoes after a heavy rainfall.[17] Initially, the rush of water decreases *Culex* spp populations as larvae are swept away.[18] However, 5–10 days after flooding, a large increase in *Culex* spp populations are observed as the mosquitoes can lay eggs in the polluted standing water where this is no competition for food or predation.[18] CSOs were used in Atlanta, Georgia until 1999; however, they were found to be unable to properly control waste water during flooding events.[18] Ultimately, the Atlanta CSOs were determined to be in violation of state and federal level clean water legislation, resulting in a modified system.[18] The Environmental Protection Agency (EPA) estimates that currently 860 communities in the United States use CSO systems, particularly older cities in the Midwest.[19] It is therefore important to understand the risks that infrastructure and changing precipitation patterns pose with respect to WNV transmission, and identify actions that can be adopted to prepare for these possibilities.

In several flooding events, surveillance was conducted and use of adulticides was limited to areas in which mosquitoes have tested positive for WNV.[20,21] Adulticides are pesticides that are dispensed in ultra-low volume sprays, and kill adult mosquitoes as they fly.[22] Adulticides are often applied to the area, reducing the mosquito populations, which may contribute to a lack of a direct causal effect between floods and WNV. However in the case of Hurricane Katrina in 2005, the number of neuroinvasive WNV cases doubled in affected areas from 23 cases in 2005 to 55 cases in 2006.[23] It is suspected that destruction of homes led to people spending more time outdoors.[23] Another possibility is that the destruction caused by the hurricane led to the creation of *Culex* spp mosquito habitats.[23] While historically WNV outbreaks have not been associated with flooding events, evidence from the outbreak following Hurricane Katrina indicate that continued surveillance and application of control methods may be considered, especially in flood-prone areas. After Hurricanes Harvey and Maria in 2017, there was significant concern that there would be a WNV outbreak.[24] However, evidence has not yet emerged as to the impact of these hurricanes on WNV cases.

Health Impacts—West Nile Virus

WNV is an arbovirus (arthropod-borne virus) that was observed for the first time in the United States in New York in 1999.[25] There have been thousands of cases throughout the United States since then, including outbreaks in 2002, 2003, and 2012.[26,27] WNV can be difficult to monitor because around 80% of cases are asymptomatic.[25] After a bite from an infected mosquito, there is an incubation period of between 3 to 14 days, which can be longer if the patient is immunocompromised.[28] Most people who develop symptoms will develop a non-neuroinvasive version of WNV, called West Nile Fever.[29] Symptoms include fever, headache and bodyaches.[29] Less than 1%, or about 1 in 150 cases, will develop neuroinvasive WNV in which encephalitis, meningitis, or acute flaccid paralysis (AFP) can occur.[30] Neuroinvasive WNV can cause muscle weakness or other neurologic side effects, requiring long-term medical interventions.[31] Between 1999 and 2016, there have been 21,574 cases of neuroinvasive WNV in the United States reported to the CDC, including 1,888 fatal cases.[29] Risk factors for neuroinvasive WNV include diabetes, old age, and male sex.[32] It is important to note that while asymptomatic cases can be difficult to capture via surveillance, they are not a risk to spread WNV via a mosquito vector, as humans are a dead-end host.[25] There have been cases in which WNV was transmitted through receiving blood or organs from infected donors.[33] All blood donations in the US are currently tested for WNV.[33] However, not all organ donations are tested, as they can only transmit infection if transplanted in the first weeks after a primary infection.[33] There is currently no specific treatment for WNV, and there is no vaccine or antiviral treatment available for humans.[34] Equine vaccination programs have been successful in preventing WNV cases in horses.[35]

There have been few studies assessing the economic impacts of WNV cases. The cost of medical treatment depends mostly on the type of West Nile the patient develops. One longitudinal study by Staples et al. investigated the initial and subsequent costs of medical treatment for WNV. They determined that the median initial cost of AFP was $20,774 (in 2012 dollars), while the median cost for a patient with non-neuroinvasive disease was $4,467.29 AFP and neuro-invasive WNV can be associated with health effects months to years after the original diagnosis.[29] Since the introduction of WNV into the US in 1999 until 2012, the total cost of hospitalized cases and deaths was estimated at approximately $778 million.[29] This number includes an estimated $449 million in lost productivity caused by WNV-related deaths.[29]

Impact of Climate Change:

Weather Variables and *Culex* spp

Culex spp populations are strongly influenced by weather patterns, and changes to one variable can have impacts over the course of multiple seasons.[36] The climate variables known to have impacts on *Culex* spp populations are temperature, precipitation, and atmospheric moisture.[36] Depending on the species of *Culex*, the geographical area, and the time of year, these variables can have a myriad of impacts on mosquito populations.

In general, increasing temperature seems to increase the case incidence of WNV nationally.[37,38] High temperatures are positively correlated with transmission of WNV through faster viral replication as well as larger mosquito populations and faster larval development.[39–41] Some models developed recently are accurate at predicting a WNV outbreak 4 weeks in advance given a temperature increase.[13,40] Increased temperatures over winter months are also associated with higher WNV rates.[37,42] In 2012, there was a WNV outbreak in the Southeastern US, which researchers determined was most likely due to a warm winter, a wet spring, and a dry summer.[42] Overall, high temperatures serve to increase the prevalence of WNV in summer months while hindering its recession in the winter.[43]

The association between precipitation and WNV transmission is more complicated. Volume and frequency of precipitation, along with the time of year and species of mosquito contribute to the rate of WNV transmission. For example, immediately after a heavy rain, *Culex* spp eggs and larvae are washed away, causing a decrease in the population.[44] At this stage, there is an increase in floodwater mosquitoes, such as *Aedes vexans*.[44] *Culex* spp are able to complete the aquatic phase of their developmental cycle in the pools that remain from a flood, causing an increase in the population in the weeks afterwards.[21] There is currently some evidence to support that both light and heavy precipitation can increase rates of WNV, particularly in the weeks following the event.[38] However, an increase in population may not translate to an outbreak of WNV. One Canadian study found that while the population of *Cx. tarsalis* increased with an increase in total precipitation, the WNV infection rate decreased.[45] They hypothesized that increases in precipitation reduces the ability of avian carriers and mosquitoes to interact.[45] It is possible that the time of year during which flooding occurs may play a role in translation to WNV risk.

The relationship between precipitation and mosquito populations is complex, and often depends on which *Culex* species is being considered. A study by Hahn et al. found that in the Eastern half of the United States, WNV rates will increase in the event of a drought.[37] This assessment was supported in a Chicago-based study of *Cx. pipiens* and *Cx.restuans,* which noted that low precipitation and high temperatures lead to the highest increase in larval populations.[12] However in the Western United States, increased rainfall was shown to increase WNV cases.[37] It should be noted that this study is in opposition to previously observed patterns outlined by Landesman et al. in 2007. This study indicated that higher precipitation in the East was more likely to result in a WNV outbreak.[46] These different results exemplify the difficulty in determining clear patterns for the spread of vector-borne diseases. It also demonstrates the importance of local surveillance, as more information is required to develop consistent and specific predictive models.

Climate change will continue to impact weather patterns, and may cause both an increase and decrease in precipitation levels in different areas throughout the US.[47] As some studies indicated, different parts of the US may see an increase in WNV in the event of a drought. Therefore, this evidence is also important to consider when analyzing the effect of climate change on WNV.

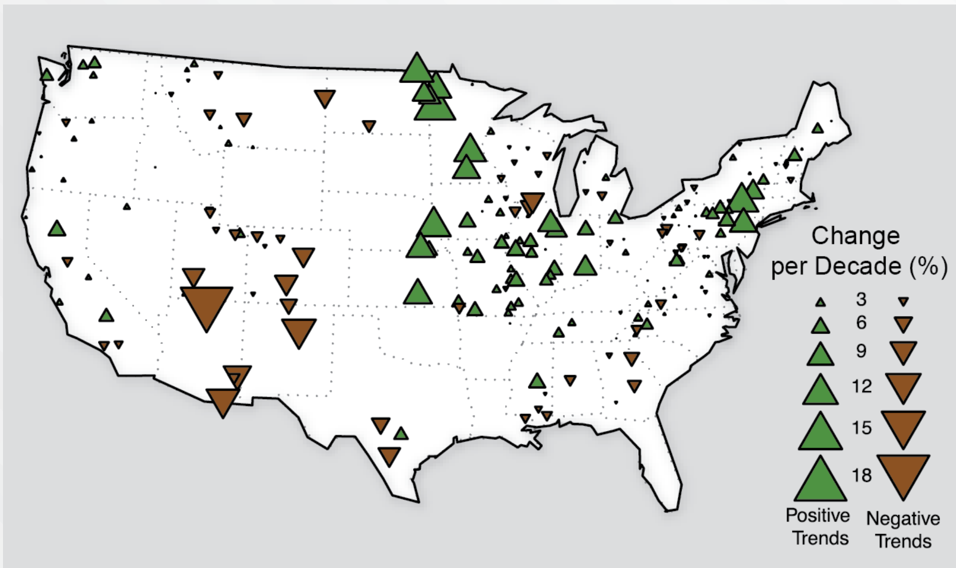
As estimated by Hahn et al., *Culex* spp in the eastern half of the US will become more prevalent in the event of a drought.[37] Some researchers have predicted that this is because the *Culex* mosquitoes present in the Eastern US (*Cx. pipiens* and *Cx. restuans*) are often found in containers.[48] A lack of precipitation allows for pools to become "eutrophic," or inundated with organic material.[48] Dry weather might also result in a lack of natural predators, increasing survival of larvae.[49] Other data have determined that a combination of a drought followed by flooding may be the most contributory to a rise in *Culex* spp populations. A study conducted in Florida found that a dry spring followed by a wet summer would most likely increase the risk of WNV.[50] Researchers estimated that a dry spring allows for increased interaction between avian hosts and mosquitoes, amplifying the concentration of WNV in these species.50 Substantial precipitation during the summer could then increase the mosquito population, causing a WNV to spill over into human populations.[50] This specific scenario resulted in an outbreak of St. Louis Encephalitis in 1990, and the authors estimated that due to their similar transmission pathways, an outbreak of WNV could occur given similar weather patterns.[50] This pattern was also observed in Pennsylvania, in which a drought followed by precipitation led to a significant increase in mosquito density in local wetlands.[51]

Droughts can also impact the transmission of WNV to humans, not just the local mosquito populations. Reduced precipitation influences the ability of female mosquitoes to release their eggs. *Culex. pipiens* females can retain fertilized eggs for up to five weeks while they find a spot to oviposit.[52] It is hypothesized that increasing the amount of time a female holds her eggs increases the risk that she will pass WNV vertically to her offspring.[53]

Climate Change and Flooding

The International Panel on Climate Change and U. S. Global Change Research Program both predict that there will be an increased frequency and intensity of storms and floods in certain areas in the United States in the coming years.[54,55] Trends in flooding events show an increase in floods in the Midwest and Northeast, while downward trends have been observed in the Southwest (Figure 2).

Figure 2: Trends in Flood Magnitude 1920s though 2008[56]



The number of rainfall events has increased, as well as the amount of rain falling during those events.[55] It is also estimated that rising temperatures have and will continue to influence the frequency and intensity of hurricanes.[57] Increases in precipitation can also impact the possibility of overflowing storm or sewage systems, which could lead to both an increase in bacterial infection from contaminated water, as well as an increase in mosquito populations.[57, 58] It is also expected that rising sea levels will impact flood risks, and lead to more substantial flood damage in coastal areas.[59]

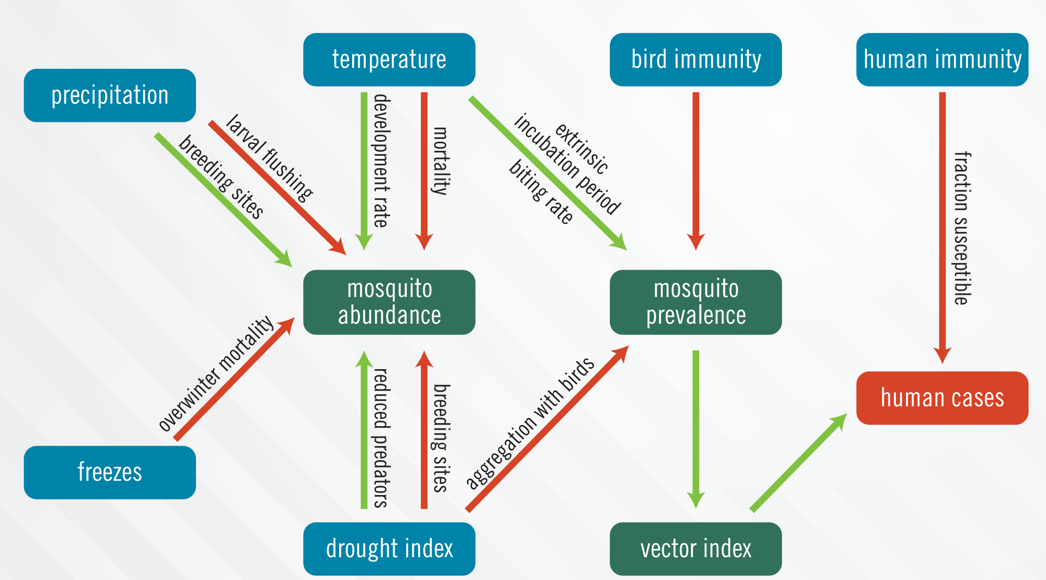
Culex spp and Climate Change

Climate change is influencing the spread of arboviruses in both predictable and novel ways. Estimating the influence of climate change on the many variables that contribute to an arbovirus outbreak is difficult. However, some states are using novel techniques to determine areas of highest risk, as well as where the risk might spread with increased temperatures and changing weather patterns. An assessment of risk factors determined that living next to stagnant water, increased time outdoors, and a lack of physical barriers all contribute to risk of exposure to WNV.[60] In a flood scenario, residents whose homes are destroyed will be in a vulnerable situation, and could be at a higher risk for contracting WNV.[61]

Climate change may impact WNV transmission by influencing vector survival, host migration, and human exposure. Studies have shown that *Culex* spp larvae will develop through to the adult stage faster given an increase in temperature.[62] There is some indication that rising temperatures will result in longer active seasons, with mosquitoes surviving longer into the fall.[41,63] However, this result depends on the geographical location within the US. In some areas, increasing temperatures may positively impact *Culex* spp populations. One study by Reisen et al. indicated that increasing temperatures in California resulted in increased survival of female *Culex* spp mosquitoes over the winter.[64] Other studies have indicated that an increase in temperature will result in an increased mosquito population after several weeks.[13,38,62,65] In one study, ambient temperature was the most important factor contributing to a WNV outbreak.[62]

However, in some cases, extremely high temperatures have been shown to reduce *Culex* spp populations.[41] There are some predictions that climate change will change the geographic distribution at which *Culex* spp mosquitoes are most abundant and where WNV is commonly reported.[66] In areas that are already warm, including Texas and Arizona, rising temperatures may reduce *Culex* spp populations, possibly lowering the disease risk because of a shorter active season.[41,63] More northern areas might be more susceptible in the future. As Figure 3 demonstrates, WNV outbreaks are not only influenced by weather patterns, but by previous exposure of humans and birds to the virus.[67] One study also found that a naïve bird and human population is one of the most important variables leading to a WNV outbreak, which makes these locations vulnerable to seeing many more cases in the future.[66] Naïve bird populations have not been previously exposed to WNV, and therefore do not have any population immunity.[67] It is therefore a concern that the movement of *Culex* spp to new areas will contribute to outbreaks in locations at which WNV was previously unseen.[67,68]

Figure 3: Variables influencing the spread of WNV from mosquitoes to humans. Green arrows are positively correlated; Red arrows are negatively correlated[66]



The full impacts of climate change are difficult to predict. Estimating the spread of vector-borne diseases is difficult to study, as there are many contributing variables. Establishing quantitative risk estimates such as active thresholds for WNV spillover into human populations is difficult, and often change depending on the location. It is possible that increasing temperatures will shift the active season for *Culex* spp mosquitoes. It is also possible that areas that have previously seen few cases of WNV might be more exposed to outbreaks. It is due to this uncertainty that local and state health departments may consider planning interventions and procedures that can be put in place to reduce the risk of WNV. Using Integrated Mosquito Management as a framework for action, these organizations can combine multiple evidence-based methods to best protect their constituents and their environment.

Evidence and Description of IPM

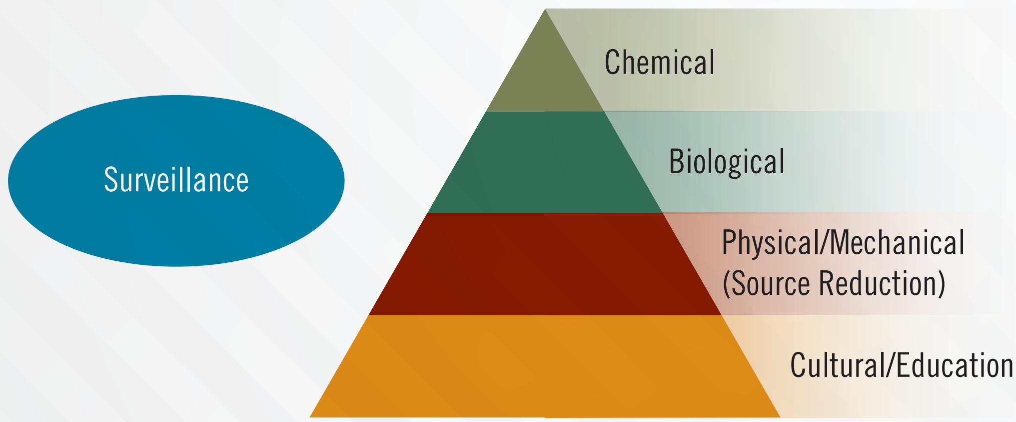
IMM, IVM, or IPM?

Integrated pest, vector, and mosquito management are frameworks that public health departments can use to reduce the health impacts of various animals. While there are no formal definitions of the distinction between the three approaches, different organizations prefer to use different language depending on the type of animal they are trying to address. Integrated Pest Management (IPM) refers to using integrated methods to reduce the impact of pests on a variety of outcomes, including human health, agriculture, or economic security.[69,70] This can include any animal or plant that can have a negative impact on society, in any number of ways.[69] IPM is therefore a much more general definition than IVM (Integrated Vector Management), which focuses on pests of public health importance. This includes any vector that can transmit pathogens to humans, such as ticks, mosquitoes, or sandflies.[71] This approach is general, but still focused on pathogen transmission from a vector to humans. Integrated Mosquito Management (IMM) is an approach that focuses solely on mosquito management; however, as seen in the interventions discussed earlier, these interventions consider a variety of variables to increase the effectiveness against mosquitoes. All of the approaches in IMM, IVM, and IPM have similar goals and frameworks, as they consider human and animal habitats and behaviors to better manage health risks.[72] They also emphasize the use of surveillance, which determines the need for multiple interventions, or possibly no interventions at all.[72]

CDC released an Intervention Assessment on possible methods that can be used to address outbreaks of mosquito-borne diseases.[73] This assessment includes an evidence-based review of multiple components of IMM.

Historically in the US, mosquito management has largely consisted of pesticide applications, especially adulticide sprays.[74] As mosquitoes have become more resistant to pesticides, a more comprehensive approach is required.[74] The core component of IMM is a strong surveillance program, to determine the mosquito species and population density, as well as WNV infection in mosquitoes, birds, or humans and other mammals.[74] Each component of the IMM pyramid is developed and guided by surveillance (Figure 4). Gaining information over multiple years will help to establish a baseline for mosquito activity, which will allow for educated decisions to be made in response to a flood. Surveillance will determine the size and scope of the interventions required, as well as which interventions would be the most helpful.[75] Surveillance could also determine which areas would be the most significant source of mosquitoes after a flood, allowing for targeting of specific geographically areas.[76]

Figure 4: IMM Model Based on model from Pennsylvania State University[77]



Another significant component of IMM includes cultural and educational interventions. In general, education includes the importance of avoiding mosquitoes, the dangers of WNV, and methods people can take to reduce exposure. After a flood, it will be particularly important to disseminate this information, especially in the weeks following the event as the floodwaters recede and *Culex* spp populations begin to rise.

Physical interventions with respect to IMM are often related to source reduction, in which locations that can support high mosquito populations are investigated and surveyed. Some areas, such as storm drains, can be modified before a flooding event occurs. These areas can also be targeted by biological or chemical interventions after a flood. Other areas, such as wetlands, might be protected because of their environmental significance. These areas can still be surveilled for changes in mosquito population density or presence of WNV, and biological or chemical interventions may be implemented if necessary.[74] Using surveillance to determine possible sources of mosquitoes can allow for changes to those areas in order to reduce standing water.[74]

Biological methods require understanding the target species' natural habitat, nutrient sources, and predators. Using this knowledge, public health departments can develop interventions that modify these components and reduce mosquito populations in multiple ways. For mosquito management, common biological control methods are introduction of predators in order to use components of mosquito's natural habitat or predators, and include use of mosquito-eating fish such as *Gambusia* or *Pimephales promelas* into flooded areas to consume larvae.[5,78,79] These fish have been added to permanent ponds or wetlands throughout the US and the world.[5] However, the use of *Gambusia* in particular has become unpopular, as there is worry concerning the introduction of an invasive species, as well as recent data that indicate their overall lack of effectiveness.[80] In addition, health departments may not have the capacity to raise and distribute fish.

Biological control also includes use of genetically or physically modifying mosquitoes to reduce their reproductive ability.[81] *Wolbachia*, a type of symbiotic bacteria that reduces the number of offspring, has shown promising developments when infecting *Anopheles* mosquitoes. However, while this technique has shown promise in the *Anopheles* population and malaria reduction, recent data indicate that *Wolbachia* infection may increase the infectivity of *Culex* spp, particularly *Cx. tarsalis*.[82] Another technique is to irradiate male mosquitoes and release them, resulting in zero viable offspring. The final type of genetic modification is Release of Insects with Dominant Lethal genes (RIDL), in which mosquito DNA is altered to express a gene that is stable under laboratory conditions but lethal in the wild. This technique has been used on other pest insects, and is still in development for mosquitoes. In general, while these interventions are appealing because of their targeted nature, there is a lack of supporting evidence that they are effective in reducing WNV transmission from *Culex* spp.[81]

Chemical interventions are the most well known and most commonly used in mosquito management. In an IMM model, use of larvicides and adulticides should be determined through surveillance and understanding of mosquito species.[74] Ideally, the use of adulticides and larvicides work to reduce large numbers of mosquitoes quickly, as well as reduce mosquito infection rate of WNV.[83,84] While chemical interventions are highly efficacious to reduce mosquito populations of multiple species, there are trade-offs to their use.[83]

After a flood occurs and interventions are conducted, the final step is to evaluate the effectiveness of the policies and procedures that were implemented. Using this evaluation, improvements can be suggested and more information can be given to other health departments to help multiple cities and states be prepared for future flooding disasters.

Preparing for a Disaster:

Surveillance

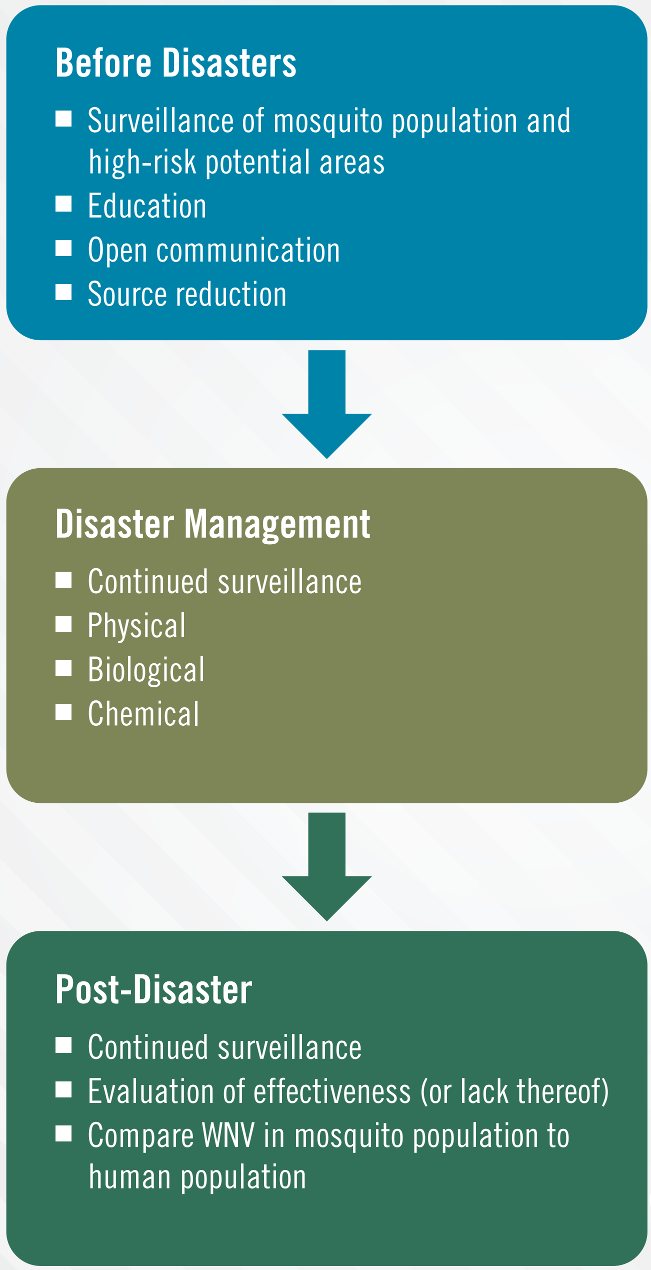
Surveillance is a guiding component of IMM, and can be performed at each stage of intervention. It is an important component of preparation for a disaster, as the information helps guide policies implemented in response to a flood (Figure 5). There are several different methods of surveillance that may help predict WNV outbreaks among communities. One of the most useful methods is mosquito surveillance, which can determine abundance of the mosquito population, species, and infection with WNV or other pathogens.[6] Mosquito surveillance also includes testing for resistance to control interventions, particularly larvicide or adulticide. Other methods of surveillance include equine or dead bird reporting, which require public knowledge and involvement to maintain an accurate estimate. Sentinel chickens are another way to measure WNV presence in the area. A final surveillance method is human reporting, in which patients with confirmed cases of WNV are reported.[85]

During the Midwest Flood of 1993, there was an increase in the *Culex* spp population, and subsequent fear of a St. Louis Encephalitis (SLE) or Western Equine Encephalitis (WEE) outbreak.[20] Mosquito, bird, and human-based surveillance was conducted in several states in the region.[20] It was determined that there was no increased risk of SLE as the flooding had occurred later in the summer, when nighttime temperatures and vector population densities were low.[20] The states affected by the flood decided against the use of adulticides and there was no subsequent outbreak of SLE or WEE cases in either 1993 or 1994.[20] The use of surveillance in this flood response cost the states a combined $390,000; while the estimated cost of adulticide would have been greater than $10 million.[20]

The first step of surveillance is to determine the species of mosquitoes that are common in the area and define the possible impact their presence can have to the community, whether it be economic or health-related.[6] The species that will be targeted are then determined and studies are conducted to determine the spatial (geographic) and temporal distribution for the species in question. This can be done by measuring eggs, immature, and adult mosquitoes using a variety of collection techniques. It is important to note that while surveillance is associated with significant costs initially, the healthcare cost of treating illnesses caused by infection with arboviruses is often substantial as well. It is therefore prudent to dedicate time, resources, and labor towards addressing current and potential future mosquito habitats.

After a flood there might be several genera of mosquitoes present, depending on the time of year, geographic location, and temperature.[13,44] A rise in either floodwater or container-inhabiting *Aedes* genus would require different intervention techniques with more attention towards emptying containers and surveilling for dengue or chikungunya.[55] Using surveillance technology will help assess the danger of a WNV outbreak, as well as develop specific treatments for *Culex* mosquitoes.[65]

Figure 5: Intervention Timeline



While it is important to understand the distribution and populations of various mosquito species, surveillance can also provide insight into the rate of WNV infection among the mosquitoes.[40] Using CDC gravid traps and carbon dioxide (CO2) baited traps are some of the most effective ways to measure mosquito vectors in an urban environment.[86] Using different infusions such as grass or hay can help specifically target ovipositing *Culex* spp mosquitoes.[87] These are female mosquitoes that have already taken at least one blood meal and are looking for a place to lay eggs.[87] Gravid traps therefore target mosquitoes that are most likely infected with WNV, allowing them to establish a more accurate estimate of both mosquito concentration and WNV prevalence.[86] Gravid traps work to establish an estimate of baseline mosquito populations and species, and will serve as an early alert system if these variables change. There is evidence that using gravid traps for surveillance can also reduce the number of reproducing mosquitoes.[86] In one season in Fort Worth, TX,[94] gravid traps captured 45,000 female mosquitoes.[86] Researchers estimated that this reduced the *Culex* spp population by 1,500,000 female mosquitoes.[86] Therefore, surveillance can serve dual purposes for IMM. However, surveillance traps are not generally used for control and should not be the only method of control, as large spikes in populations might overwhelm their effectiveness.[88]

Captured mosquitoes can give an estimate of mosquito population as well as WNV activity.[89] This can be combined with geographic data to determine the proximity of WNV-infected mosquitoes to urban areas or residences.[90] This information can also give the "vector index level," which is the measured infectivity of local mosquitoes.[91] The index takes into account the abundance of the vector species, the composition in relation to other species, and infection rate of the target mosquitoes.[91] All states report WNV activity to ArboNET, which allows for central organization of these data.[92] Some cities such as Boulder, Colorado, have a threshold vector index level, above which an organized control response will occur.[89] For the county, a vector index of greater than 0.75 would result in emergency spraying, although other counties in Colorado have a lower threshold of 0.5.[93,94] While Boulder has not had a WNV outbreak that required largescale spraying, there is an emergency response plan in place through which aerial spraying will be conducted in congruence with public education.[90]

Mosquito surveillance can also estimate resistance to pesticides, and can help health departments know when control methods should be modified to adapt to changing susceptibility. For example, some populations of *Cx. quinquefasciatus* have shown resistance to malathion since 1975, so testing for surveillance is important to complete before pesticides are used.[95] Similarly, while permethrin-treated clothing is often used to protect people from *Aedes* spp, recent studies have shown that in some areas, *Culex* spp may be resistant to the chemical.[96,97] Knowing where these locations are can help local health departments or mosquito control programs determine the most effective chemical intervention for their area.

However, testing for mosquito resistance is not common among mosquito control programs. In a study conducted by the National Association of County and City Health Officials (NACCHO), only 14% of vector control programs reported that they conduct pesticide resistance testing in their area.[85] Pesticide resistance is important to determine, especially in the context of outbreak prevention and management, as effective pesticides should be established before they are required in an emergency. Some researchers recommend development of pesticide policies that specifically target a species of mosquitoes, and rely on surveillance data over pre-scheduled applications.[97]

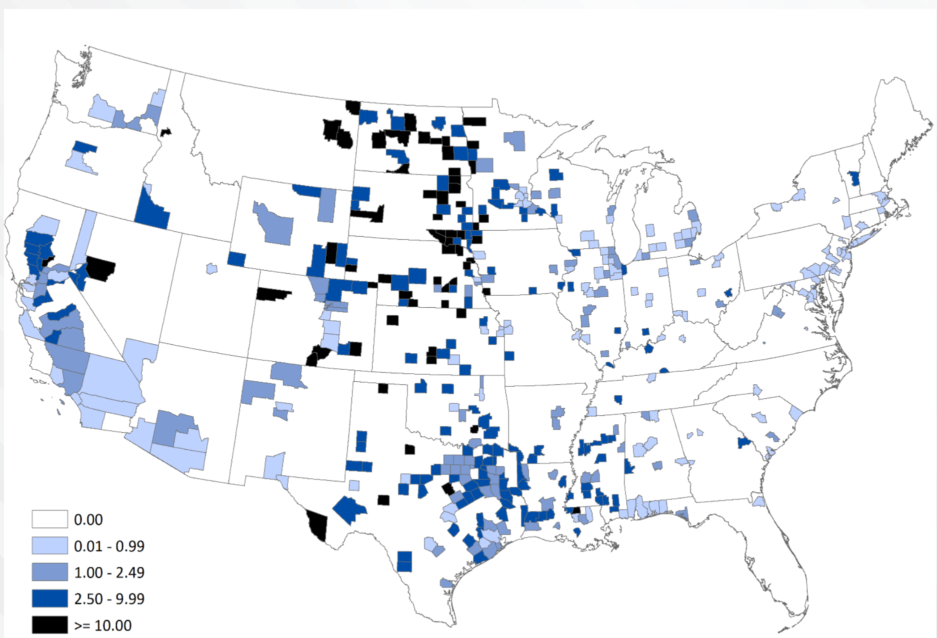
In order to assist in determining potential resistance, the CDC provides a bottle bioassay, in which live mosquitoes can be tested.[98,99] The bioassays are effective because they allow departments to test multiple chemicals and concentrations for resistance.[99] They also determine "time mortality data," which measures the length of time that an insecticide takes to enter and act on a vector.[98] These assay kit are free, and can be ordered by contacting **CDCBottleAssayKit@CDC.gov**.

Surveillance also includes testing bird populations for WNV, as they are the amplifier host for the virus.[100] Dead birds can be an important sign that WNV is in the area. In one study, collection of dead birds was one of the most cost-effective ways to measure the presence of WNV.[100] It is also important to know which types of birds are in the area, as only certain species can carry and spread WNV.[11] Sentinel chickens are also a useful method to determine the location of WNV vulnerability.[100] Sentinel chickens are flocks of seronegative chickens that can be stationed throughout a county or state.[100] They are tested at regular intervals for WNV, giving officials another method by which to determine the presence or movement of WNV in an area.[100]

Some states, such as Louisiana and California, no longer screen dead birds for WNV. When WNV was first introduced into these areas, the birds were naïve, and screening would therefore give a good indication of whether or not the virus was present nearby. However, the use of dead birds to determine risk is less sensitive after the initial outbreaks. One study proposes that this might be because the public is no longer as concerned about the presence of WNV, so the reporting of dead birds has decreased.[40] One report from Louisiana, a state that discontinued dead bird monitoring, stated that when WNV is established in an area, the majority of birds would most likely test positive for WNV without resulting in an outbreak.[101] These areas have thus chosen to concentrate their resources in other aspects of surveillance and management.[101]

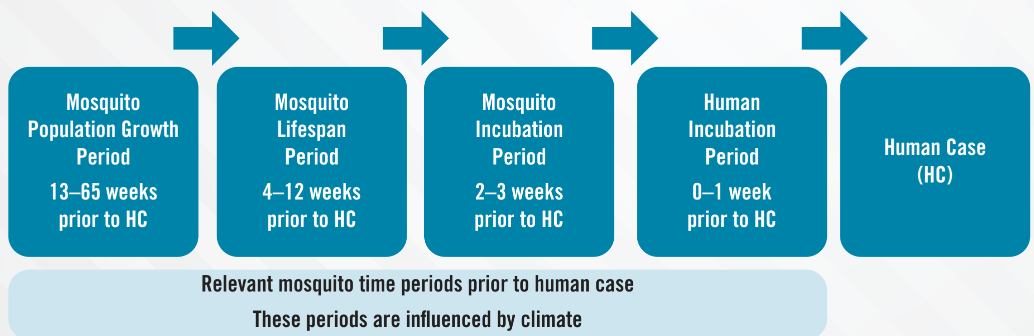
At the onset of WNV in the US, equine populations were also observed for infection, as they are also a dead-end host for the virus.[35] However, due to vaccination efforts, equine infection rates have decreased substantially, and horses are no longer a sensitive measure for WNV presence.[35]

Figure 6: ArboNET—Average Annual WNV Incidence 1999–2016[102]



Human surveillance of WNV infections is universally conducted throughout the US.[26] These cases are reported to ArboNET, a surveillance system from the CDC (See Figure 6). However, there is currently a debate as to the accuracy of human surveillance. The primary difficulty with human cases is that only 20% will be symptomatic. Of these cases, it is likely that some infected patients may not seek medical attention because of their vague symptoms. This results in further underreporting of the virus, even though there is lost productivity if the patient misses work. Patients who do seek medical attention will often not present with symptoms until several days after the primary infection, leading to a delay in reporting. There is also a lack of timely reporting among health care systems. One study from Colorado found that 49% of WNV cases were not reported (to the Colorado Electronic Disease Reporting System) within the state-mandated seven day interval.[103] Another study found that these factors combined most likely cause delays in reporting between two to six weeks after the original infection.[35] This interruption can hinder public health responses, increasing risk for constituents. There is also a natural incubation period that occurs in humans, lasting up to fourteen days.[104] As Figure 7 demonstrates, assessing only human cases will result in an slowed response, as WNV has already been established in the mosquito population.[104] It is therefore important to combine human reporting with mosquito and bird surveillance, as this can help create a proactive, rather than reactive, response to WNV.

Figure 7: Ecological Factors to WNV Transmission[104]



Using surveillance technology can help health departments determine or predict the scope and type of threat that they may be facing.[75] To develop these predictions, consistent and accurate data collection will help prepare for WNV outbreaks. However, many states are struggling with dedicating resources towards surveillance. In October 2017, NACCHO released a report concerning the preparedness of US public health programs for mosquito-borne diseases.[85] Forty-six percent of the programs interviewed did not perform routine mosquito surveillance.[85] However, of those that did, 85% used the surveillance to modify and refine their treatment decisions.[86] It was determined that southern states have the most competent vector control programs, while there was a lack of competency in some western states that have the highest rates of neuroinvasive WNV in the US.[27, 85]

A consistent mosquito surveillance program will also provide data that can be used for program improvements after a disaster occurs. By understanding the changes to mosquito populations and habitats, health professionals can determine the most effective interventions. This information can also be useful to other health departments in developing their own outbreak response programs. Using data to evaluate and refine a response program also comprises the fifth step of the BRACE program.[3]

Source Reduction

One of the basic components of IMM is to reduce larval habitats used by mosquitoes.[70,105] For some *Aedes* mosquitoes and *Cx. quinquefasciatus,* which commonly lay eggs in in open containers or spare tires, encouraging residents to regularly empty out containers can help reduce transmission of disease.[106] However, many other *Culex* species utilize water sources in areas that are difficult to fully drain or dry out. These areas include flooded agricultural fields, storm drains, sewage run off, or flooded residential areas.[58,107] Therefore, while educational campaigns to reduce water collection in residential containers is helpful for overall mosquito population reduction, it may not be significantly helpful to reduce the risk of WNV in the area.

While reducing larval habitats has a significant impact on reducing mosquito populations, this step can be difficult because some sources, such as swamps or marshes, are environmentally significant and cannot be drained or filled in.[6] Mosquito control programs often collaborate with environmental and ecological protection programs to develop source reduction techniques that will not negatively impact the ecosystem of these areas.[6]

Storm water and wastewater management is another aspect of source reduction for *Culex* spp. A report released by the Florida Coordinating Council on Mosquito Control outlined some of the best practices for source reduction. While the report states that overflow from these areas are common mosquito habitats, research into the specific effects of overflow on their population is limited.[6] Current control efforts of these areas include larvicide, herbicide and vegetation management, adulticide, and larvivorous fish. Agencies involved in managing these facilities can increase their knowledge and awareness of best management practices for mosquito population reduction, as implementation would reduce the possible sources for an outbreak.6 The report identifies several uses of treated wastewater that have the potential to result in mosquito habitats.[6] This includes irrigation systems, holding ponds, and use of wastewater for agricultural or industrial purposes.[6] These areas can all become *Culex* spp habitats without proper prevention methods, so considering and modifying aspects of their design is important in managing mosquito populations.[6] This would be useful to reduce the economic and possible ecologic cost of pesticides. The report also noted that in some areas, such as wastewater systems which are moved constantly, even larger amounts of larvicides would be required.[6] Therefore, source modification through design changes will have a significant impact in reducing *Culex* species, and can reduce the use of pesticides.

Before a disaster occurs, a survey can be done of problem areas that are likely to retain water in the event of a flood. One possibility is to involve residents, who have a specific knowledge of their area. Getting residents involved in the planning and management of possible mosquito habitats might also help with the education of the dangers of mosquito exposure and WNV. Another possibility is to utilize GIS technology and satellite imaging to obtain an estimate of problem areas, which can then be addressed.[76] These areas can then be modified to reduce their ability to be harbors for ovipositing species.

Phased Response

While specific interventions of IMM will be discussed, it is also a goal of this paper to define how these techniques will be integrated into a post-flood response. One of the key components of IMM is preparation, and many interventions are most effective when planned before a flooding event occurs. All components of IMM can be guided by surveillance, which also requires pre-established baselines to be most effective. Floods are highly variable events, and their impact depends on precipitation, infrastructure, and population density. While a flood requires considerable planning and response efforts, the possibility of a WNV outbreak could be considered. As outlined previously, the changing climate will impact WNV distribution in a variety of ways, and surveillance should be consistently performed to determine the risk of a WNV outbreak in the weeks after a flood. By having recognized roles and procedures outlined before a disaster occurs, public health officials will be able to incorporate arboviral prevention in previously established guidelines.

A Community Assessment for Public Health Emergency Response (CASPER) may help public health officials determine both the existing health status and priorities of the community.[108] This provides a methodology for response after various disasters, and can be well-developed towards a post-flood assessment. Public health officials can use the CASPER framework to investigate the impacts of the flood on residents. This includes damage assessment, local information about flood water height, and information about possible sources for *Culex* spp breeding habitats. CASPER also provides other questions relevant to a comprehensive post-flood response effort, allowing for multiple dangers and negative outcomes to be addressed or avoided.[108]

If massive precipitation raises concerns about a flood, it is possible to use Geographic Information System (GIS) technology to determine how rising flood waters could impact the surrounding area, and which locations would be at the highest risk. This technique is being used in some cities, such as Davenport, Iowa.[110] It has led to more accurate predicting of how various flood levels will impact the city and environment.[110] It could also be possible to determine if floodwaters would impact sewage treatment or processing, as this could provide suitable larval habitats for *Culex* spp.

While flood control and response often requires specialized planning depending on the city or area, there are several pre-established WNV outbreak intervention plans that can be adapted to many local health departments. Using surveillance data, the CDC has released a phased approach to a WNV outbreak, associating surveillance information with risk categories and recommended responses (See Table 1).[90]

By using surveillance to determine the stage of the outbreak, the various interventions can be incorporated to other parts of post-flood disaster management. This includes consistent education about application techniques, communication, source reduction, and biological and chemical control. The specific interventions within each of these categories, as well as their effectiveness, will be discussed in the remainder of this paper.

Table 1: CDC's Phased Response to WNV Outbreak (copied from "West Nile Virus in the United States: Guidelines for Surveillance, Prevention, and Control")[90]

RISK CATEGORY	PROBABILITY OF HUMAN OUTBREAK	DEFINITION	POTENTIAL ACTIVITIES AND RESPONSES
0	None	No adult mosquito biting activity (vector species).	
1	Low	Biting adult mosquitoes active (vector species). OR Epizootic activity expected based on onset of transmission in prior years. OR Limited or sporadic epizootic activity in birds or mosquitoes.	Develop or review WNV response plan. Review mosquito control program. Maintain source reduction projects. Secure surveillance and control resources necessary to enable emergency response. Review and update community outreach and public education programs.
2	High	Sustained transmission activity in mosquitoes or birds. OR Horse cases reported. OR Human case or viremic blood donor reported.	Response as in category 0, plus: Conduct Integrated Vector Management program to monitor and reduce vector mosquito abundance. Conduct environmental surveillance to monitor virus activity (mosquitoes, sentinel chickens, avian mortality, etc.). Initiate community outreach and public education programs focused on personal protection and residential source reduction.
3	Outbreak in progress	Conditions favor continued transmission to humans (i.e., persistent high infection rate in mosquitoes, continued avian mortality, seasonal mosquito population decreases not anticipated for weeks) OR Multiple confirmed human cases or viremic blood donors.	Response as in category 2 plus: Intensify emergency adult mosquito control program repeating applications as necessary to achieve adequate control. Monitor effectiveness of vector control efforts Emphasize urgency of personal protection, including use of repellents, through community leaders and media.

Evidence for Post-Flood Interventions

Table 2: Examples of Interventions and Resources

INTERVENTION CATEGORY	EXAMPLES
Risk Communication	Educating the public about their risk of contracting WNV or other arboviruses, and methods they can use to reduce exposure to mosquitoes. This also includes education about pesticide use and safety. (Banks et al., 2014) (Bonds, 2012) (City of Boulder Office of Environmental Affairs, 2006) (Centers for Disease Control and Prevention [CDC], 2017) (Covello et al., 2001) (Dykstra, 2008) (Richards et al., 2018) (Rose, 2001) (Suckling et al., 2014)
Physical: Source Reduction	Addressing and monitoring possible and established mosquito breeding habitats such as modification of storm water management systems, unmaintained swimming pools, natural bodies of standing water, freshwater and saltwater marshes, and temporarily flooded locations such as drainage ditches (Connelly et al., 2009) (Anderson et al., 2017) (Dent,1995) (Colborn et al., 2013)
Biological	■ Acoustic Larvicide: using soundwaves to kill larvae (Fedregill et al., 2015) (Connecticut Department of Energy and Environmental Protection, 2014) ■ Mosquito-eating fish (Eg. Gambusia): Fish that eat mosquito larvae (City of Boulder Office of Environmental Affairs, 2006) (Cameron & Lorenz, 2013) (Silberbush & Resetarits, 2017) (Blaustein, 1992) (Watchorn et al., 2018) (Irwin & Paskewitz, 2009) (Walton, 2017) (Marti et al., 2006)

INTERVENTION CATEGORY	EXAMPLES
Chemical	■ Larvicides: Use of aerial, truck or direct application to water sources. Chemicals or bacteria that target mosquito larvae. Examples of commonly used larvicides are included. (Rose, 2001) (Connelly et al., 2009) (Lacey, 2007) Temephos (Regulations.gov, 2011) Bti and Ls (Lacey, 2007) (Lawler, 2017) (Ritchie et al., 2010) (Stockwell et al., 2006) (Pauley et al., 2015) Methoprene (Lawler, 2017) (Butler et al., 2006) (Baker & Yan, 2010) Spinosad (Mertz & Yao, 1993) (Garza-Robledo et al., 2011) (Shah et al., 2016) ■ Adulticides—Ultra-Low Volume spray from trucks or planes. Targets flying adult mosquitoes. (Environmental Protection Agency [EPA], 20b 17) (Anderson et al., 2017) (Bonds, 2012) (Carney et al., 2005) (Mutebi et al., 2011) (Lothrop et al., 2008) (Duprey et al., 2008) (Pawelek et al., 2014) (Ruktanochai et al., 2014)

Risk Communication

One of the primary interventions for IMM is education and communication concerning mosquito management.[105] Individual residents can mitigate risk of contracting WNV by limiting exposure to mosquitoes.[110] This is often framed as the "4 D's" of prevention: DEET, Dawn and Dusk, Dress, and Drain.[110] This helps educate people to use insect repellent when outdoors, and to limit outdoor times at dusk and dawn, when *Culex* are the most active.[110] If there are residents who spend an increased amount of time outdoors at these hours, it is recommended that they wear long sleeved shirts and pants, which can be treated with permethrin.[111] As mentioned above, recent research indicates that even in areas where *Aedes aegypti* are resistant.[96] The efficacy of permethrin is often dependent on the location and population of *Culex* spp mosquitoes, and research concerning resistance could be conducted to ensure protection against *Culex* spp.[99,111] A recent study has indicated that *Aedes aegypti* are still susceptible to permethrin treated clothing even in resistant areas.[96,97,111] However, treated clothing must also be accompanied by treating any exposed skin with insect repellent.[111]

In the event of a flood or hurricane that has caused widespread destruction, it would be important for first responders and volunteers to take these precautions of wearing appropriate clothing, insect repellents, and limiting their time outdoors when *Culex* spp are active. This would be particularly important in the weeks after the event, as this is when *Culex* spp would repopulate the area, and there could be a greater risk for WNV transmission. In developing a communication plan in an emergency, it is important to incorporate three key components: simple messaging that clearly outlines risk, maintenance of communication before and during an emergency, and acknowledgement of public concern.[112] In an emergency after a flood, residents will have multiple concerns about their safety, and there will be many dangers to health unrelated to WNV that should be addressed. However, in the weeks that follow a flood, it is important to remember the rising risk of WNV that occurs as these primary hazards recede.

After Tropical Storm Allison hit Louisiana in 2001, there was a significant increase in mosquito populations, which raised concern about an arboviral outbreak. As residents began returning after the flood, health officials from the Federal Emergency Management Agency (FEMA) and the Louisiana Office of Emergency Preparedness released advice to limit risk of mosquito encounters:[113]

- Repair all screen doors and windows that may provide access for mosquitoes.
- Minimize outdoor activities between dusk and dawn.
- Wear long sleeve shirt and long pants when spending time outdoors in likely mosquito habitat.
- When outdoors, use insect repellent containing DEET, according to instructions on the label.
- Empty all containers that hold water and turn over garbage cans, wheel barrows and spare tires.

On an individual level, residents can also be informed to check for possible sewage leaks on their property.[114] If this is not addressed, it could provide habitats for *Culex* spp populations.[114] These recommendations are simple and relatively easy to achieve, and it is likely that such precautions could be integrated into a post-flood communication effort.

As one of the main methods to reduce *Culex* spp populations after a flood is application of pesticides, the communication campaign should distribute information about the safety and risks of this intervention. While studies indicate that adulticide applications are one of the best methods to reduce *Culex* spp numbers, they are usually applied using aircraft, which can cause undue worry in the community.[83,112] While truck application may be a useful alternative if residents are opposed to aerial administration, some adulticides are not approved for truck application, and efficiency and speed are the primary goals of control after a disaster.[74] It is often the responsibility of the local health department to disseminate information to residents about truck or plane paths, as well as the timing of the spray, informing residents beforehand could be useful in improving community awareness and perception of the intervention.

Healthcare providers should also be educated about presentation of various diseases that are common after a flood.[115] Patients can be exposed to contaminated water, dangerous materials, and infectious diseases carried by displaced animals. Because WNV fever can often mirror other diseases, it is important to educate healthcare providers to the signs of WNV, and encourage testing for arboviral infections.[115]

It should be noted that in the event of a devastating disaster such as Hurricane Katrina, first responders and workers may also be displaced, and might not be able to contribute to surveillance or communication efforts. In these cases, it is important to prioritize which interventions are most needed to reduce human morbidity and mortality.

Biological Control

Biological controls can be implemented after a flood occurs. An interesting method listed in Connecticut's larvicide plan is the use of an acoustic larvicide device, which uses sound waves to kill larvae.[116] There is some data that this method is effective at killing mosquito larvae; however, there was no subsequent evidence that it had been utilized on a large scale.[117] A method that has been mentioned often in literature is the use of *Gambusia affinis*, or mosquito-eater fish, into areas with standing flood water.[5,118] However, there is evidence that *Gambusia* eat zooplankton as well as mosquito larvae.[5] The loss of zooplankton allows for the growth of phytoplankton population, which is a food source for mosquito larvae.[5] *Gambusia* have also been seen to consume larvae of natural mosquito predators.[119] It is therefore hypothesized that *Gambusia* may not be as effective at reducing larval populations as once hoped. Ovipositing *Culex* spp have also been seen to avoid pools filled with *Gambusia* to a more significant degree than pools filled with other types of mosquito-eating fish.[118]

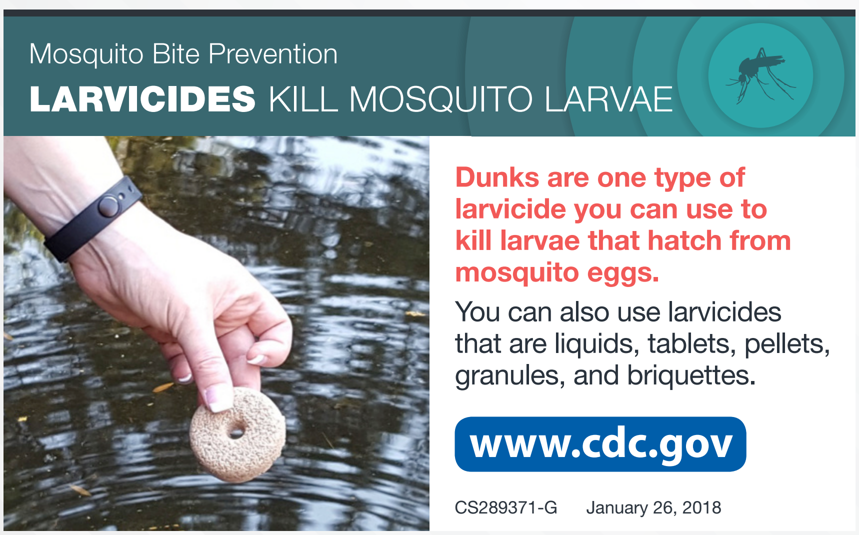
Another type of mosquito-eating fish is *Pimephales promelas* (fathead minnow), which is native to areas throughout the Midwest.[79] The minnow can survive in low-oxygen environments, allowing it to survive in areas with high organic content as well as over winter seasons.[78,79] The ability to raise and store the fish in a variety of environments throughout the year would reduce the requirements for restocking locations with standing water or that are constantly flooding. In a case-control study, use of minnows reduced the quantity of pesticides needed to maintain a reduction in larval populations.[78] A key limitation to the use of larvivorous fish is the maintenance of a consistent water level that will not be impacted by heavy rains or droughts.[78]

There is also concern that some *Gambusia* species are not native to much of the United States and there is a risk of introducing an invasive species into waterways and ecosystems.[5] There are several species of fish, such as *Lepomis cyaellus* or *Aphredoderus sayanus,* which have been shown to be effective at reducing mosquito larval populations.[118] These fish can be used in areas where they are native but *Gambusia* are not.[118] Release of mosquito-eating fish into flooded areas is also a slower method by which the mosquito population might be reduced.[120] At least one study has indicated that release of larvivorous fish does not control mosquito populations.[119] Overall, the use of larvivorous fish can be considered as an adjunctive intervention to be used with other components of IMM, but the ecological and environmental impacts of their use should also be considered.[80]

Chemical Control

Chemical control has historically been the most effective method of reducing mosquito populations as well as WNV transmission.[74,83,84,121,122] Chemical interventions are often divided by their influence on different parts of the mosquito lifecycle: adulticides and larvicides. Larvicides are applied to bodies of water that cannot be reduced, in order to reduce the larval population before they develop into pupae and then adults.[74] Adulticides are often used to cover a large area of land and to quickly reduce the number of adult mosquitoes.[83] Larvicides can be applied directly to bodies of water, while both types of pesticides can also be applied aerially to achieve larger coverage.[6] Larvicides can be found in a variety of products such as granules, floating bait, briquettes, or flowable concentrate (Figure 8).[123] Different application methods are used to treat a variety of habitats in which *Culex* spp larvae can thrive.[123]

Figure 8: Example of Larvicide Dunk[124]



Larvicides are effective because they target mosquitoes before they have taken a blood meal or reproduced. Types of larvicides include insect growth regulators, microbial larvicides, organophosphates, and surface oils and films.[6] They can be applied directly to habitat sources or aerially to target larval habitats.[6] Aerial application allows for a more widespread application, especially if areas are inaccessible by ground equipment.[6] While historically organophosphates were commonly used as larvicides. In 2011, in accordance with a request from the manufacturer of Temephos, the organophosphate larvicide was issued a cancellation order.[125] The manufacturer of Temephos could no longer sell products after 2015, although remaining stocks can still be used by mosquito management programs.[125] Some larvicides are comprised of a single strain or a mixture of bacteria: *Bacillus thuringiensis israelensis* (Bti) and *Lysinibacillus sphaericus* (Ls).[123,126] These bacteria produce spores filled with crystals, which are then digested by mosquito larvae.[123] The toxic spores work quickly, and can result in larval death within an hour.[123]

Spinosad is another type of larvicide which, like Bti and Ls, is an insecticide derived from a species of bacteria.[127] Spinosad has been proven effective against *Cx. quinquefasciatus,* as well as *Aedes* spp.[128] One study showed that spinosad was effective 90 days after an application.[128,129]

Another larvicide is methoprene, which mimics the hormones of a juvenile mosquito, inhibiting immature stages from molting into adults.[126] Under laboratory conditions, methoprene is continuously effective for up to 5 months after one application.[130] However, like Bti and Ls, methoprene is also limited by storms and extreme weather, and will likely require reapplication after such an event occurs.[130] One significant benefit to methoprene is that is that it is more effective in debris-filled catch basins.[131] It is hypothesized that methoprene binds to organic material, causing it to last longer in and maintain its effectiveness longer than in clean catch basins.[130] This research indicates that methoprene may be very useful in managing areas after a flood, as they might have higher concentrations of organic content.

Pre-treatment of high-risk areas is one method that has been suggested to prepare for floods, to address the larval habitat before they produce any mosquitoes. One study found that dry Bti could be applied to containers up to 8 weeks before a rain, and effectively reduce larval populations.[132] However, data on this method are limited with respect to its effectiveness against *Culex* spp and their habitats. It is probable that extreme weather events such as flooding or hurricanes would wash away the product.133 While this would also cause *Culex* spp larvae and eggs to be washed out as well, the flooded areas can become quickly repopulated after the storm without any impact from larvicide.[133] Therefore, the utility of pretreatment is likely limited in preparing for a large-scale natural disaster.

Larvicides are an effective method to control larvae populations. However, significant surveillance is required to determine the areas that need to be treated.[73] Application of chemicals can also create worry about impacts on the health of humans, non-target species, and the environment. However, there is little indication that use of larvicides negatively impact non-target species, if they are applied in correct amounts.[123,126,134]

Another possible concern is that mosquitoes will developing resistance to insecticides. A key component of surveillance is consistently testing mosquitoes for resistance to different active ingredients. By consistently testing the population for signs of resistance, a health department can ensure that they are using the most effective method. A study in New York in 2005 found that Bti resistance can develop in discrete areas, leaving some areas more vulnerable than others.[135] In order to combat this, one study advises to utilize a combination of larvicides.[126] This same study noted that Bti was not as effective in water with high organic content, which some species of *Culex* prefer.[126] In these cases, Ls may be the preferred method of larvicide. Using surveillance as a guide, it might be useful to apply a combination of two types of larvicides, in accordance with the labels, to compensate for environmental interactions with the bacteria.

Adulticides are pesticides targeted at killing adult mosquitoes, while they are most active and in flight.[84] While one of the results of IMM could be to reduce the need for adulticide use, there is evidence that its use could disrupt the WNV cycle and can reduce the number of human cases during an outbreak.[84,122,136] After a WNV outbreak in California in 2005, researchers found that the use of adulticides was successful at reducing the total number of human cases.[84] Adulticides should therefore be considered in the event of a flood or possible WNV outbreak as a quick and effective method to reduce WNV cases.

There are multiple types of adulticides, which can be applied in one of two methods: residual spraying and space spraying.[73] Residual sprays are applied on the ground to vegetation, and will be picked up by an adult mosquito when it lands to rest.[73] It will last in the environment for a few weeks, allowing for long-term control of populations in these specific areas.[73] However, these types of pesticides require application away from people in order to reduce possible negative side effects of exposure.[73]

Space spraying uses ultra-low volume (ULV) droplets to aerially distribute pesticides in large areas.[73] This method is helpful to quickly, effectively, and safely reduce the mosquito population.[73] Because ULV requires small concentrations of microscopic droplets, there is not a significant risk to humans in the area, and multiple studies indicate that the risk of WNV is more substantial than possible health risks from aerial pesticides.[83,137] There is also evidence that the aerial ULV application of a pyrethrin-based insecticide did not have a significant impact on non-target species larger than a mosquito, including honeybees when applied after sunset.[138] In order to further reduce human exposure, adulticides should be applied at night, or during dusk and dawn, when mosquitoes are most active and people are more likely to be indoors.[74]

Ideally, using IMM will reduce the amount of chemicals needed to achieve similar results. This will reduce some of the side effects of pesticide use, such as accidental exposures, effects on non-target species, and insecticide resistance.[6] Another issue with use of insecticide is that it has a short effective period.[139] One study found that while mosquito populations dropped significantly after an application of adulticide they rebounded within days of the treatment.[139] As adulticide application only provides temporary control of the mosquito population, it is important to combine adulticide use with other, longer term methods and possible reapplication of the adulticides.

Example of IMM: Boulder, Colorado Mosquito Control Program

The city of Boulder, Colorado began their West Nile Virus Mosquito Management Program (WNV MMP) in the spring of 2004. The state has observed over 5,300 cases of WNV disease between 1999 and 2016, as well as over 2,300 cases of neuroinvasive disease, so the virus is active in the area.[27] The program was designed to conduct surveillance and respond to possible WNV outbreaks in the region. It had outlined six goals and objectives to reduce the risk of WNV in the area as well as improve Boulder's ability to respond to an outbreak. These objectives included: determining larval habitat locations for *Culex* spp and using Bti larvicide in those areas, testing adult mosquito populations for WNV, and developing a plan for when and how to mobilize resources in the wake of an outbreak including what criteria to use for an outbreak, and educating the public about WNV.

The city then funded surveillance of possible and existing mosquito larval habitats in 2003 and 2004, and subdivided them into *Culex* spp habitats and those that mainly supported nuisance mosquitoes.[37,140] These locations were then mapped out so that locations that supported *Culex* spp development could undergo surveillance more frequently.[140] The goal of the original 2006 report was to only apply larvicide to locations that were currently supporting *Culex* spp mosquitoes specifically. This ensured that only locations that were currently supporting *Culex* spp development were treated with larvicide, limiting labor and cost required.[140] In response to nuisance mosquitoes (species that don't carry pathogens), the report recommends to educate the public about preventing mosquito development and using repellant and clothing to limit exposure.[140] However in 2007, it was decided that areas heavily populated with nuisance mosquitoes could also be treated in order to limit their impact on widely-used public spaces.[89,141]

Boulder, CO also conducts surveillance for adult mosquitoes, using CO2 baited light traps as well as gravid traps.[141] Using data gained from the first few years of surveillance, the city uses sampling zones instead of single trapping sites, which allows for more information to be collected consistently over a large area.[141] The city also determined that *Culex* spp are most common in the late summer, and therefore reduced surveillance in early spring and fall.[141]

The report also established a task force of various teams that could design and implement a WNV response plan. Various governmental departments were divided into two teams: the technical team which would lead mosquito control, and Public Affairs which would guide communication about the outbreak to both response teams and the public.[140] This response plan helps plan roles for various agencies, and assist in streamlining communication and decision making in the response effort.

Public education includes the *One Bite* campaign, which explains the "4 D's" of prevention (DEET, Dawn and Dusk, Dress, and Drain), as well as stories from re sidents who were infected with WNV. They also provided a phone resource, which the public could call to get more information about WNV, surveillance efforts, and pesticide concerns.[141]

Implementing IMM: Challenges and Barriers

Because of its many components, there can often be difficulties in the implementation of IMM. These problems largely stem from lack of funding or clearly delineated roles. The lack of funding for WNV surveillance and prevention may be affected by periods of time with no major outbreak. The most recent wide-spread outbreak was in 2012. However, because of the impacts of climate change discussed earlier in this paper, it is important for state and local health departments to be aware of the increased risk of WNV. In a similar vein, state and local departments, as well as independent organizations, can develop plans which can be used in the event of an outbreak or emergency.

One of the most significant issues with the use of IMM in response to a flood is the cost of the interventions. The expense associated with labor and establishing and maintaining surveillance equipment is a common reason for lack of consistent IMM across the country. While surveillance is a primary component of IMM, it can be expensive to establish and maintain. Some components of surveillance, such as materials for testing pesticide resistance, are freely distributed through organizations like the CDC. However, the cost of labor required to perform and interpret these tests can be expensive for a local health department. While consistent surveillance is important in preparing for an outbreak, public and political opinion for arbovirus research, prevention, and control may wane in the years occurring between WNV outbreaks.

Nationally, many county and city health departments demonstrate a shortage of funding, labor, or both. A study of health officials by the Council of State and Territorial Epidemiologists (CSTE) determined that 15 out of 47 states interviewed provided financial support for larvicide, while another 14 would do so with enough funding.[92] These results indicate that in areas of the country, there are locations that are underprepared for a possible outbreak of WNV. While funding for vector-borne diseases is often difficult, it is hoped that understanding and presenting the benefits of IMM could assist in obtaining funding. Understanding the impacts that climate change has on mosquito populations and WNV risk are also important components towards developing a funded arboviral response program.

The second difficulty in implementing IMM is that there is commonly a lack of established roles between the various health departments that serve an area at various levels. Without clear delineated roles, there is a high probability that there is overlap in some areas of planning, while others are incomplete. It is therefore important to understand the roles that different levels of government have in performing these interventions.

Organizational Roles and Potential Responsibilities

Mosquito control is typically handled by state and local governments, so there may be substantial differences in methods and approaches throughout the US.[85] This decentralized organization gives local jurisdictions the opportunity to develop programs that can fit their geographic and ecologic needs. However, this lack of consistency can also result in confusion between various levels of government as to their role in vector response. Collaboration between state and local health departments, as well as between ecological and agricultural departments, can improve effectiveness of mosquito control. In some states such as Florida, there are Mosquito Control Programs (MCPs), which are entities that organize and plan a coordinated response to mosquito populations.[6] While it is difficult to draw consistent conclusions about each state's approach to vector control, an overview has been created to understand the general methods by which mosquito control is performed across the country, and what the role of a health department might be in this process.

Local health departments (LHDs) are often charged with surveillance of mosquitoes, both an estimate of their numbers and the presence of WNV. Some health departments also ask for citizens to alert them to dead birds in the area, so that they can be investigated for infection. However, other states have moved away from this procedure, and instead focus resources on mosquito and human cases.[6,101] In the event of a flood, this surveillance data will be crucial in determining which areas are the most at risk, and where adulticide and larvicide should be distributed.

LHDs are often the most knowledgeable resource about the specific needs and risks of their communities, and are thus important sources of information to their constituents in the event of a flood. For example, after Hurricane Harvey in 2017, the Harris County Department of Public Health in Texas communicated with the public through news releases and phone hotlines for residents to ask questions about pesticides or WNV.[142] The department also released a map of spray areas in the county, which could help increase awareness of the post-flooding pesticide application throughout the area.[142]

State health departments often work to organize and present information collected from local jurisdictions. They are sometimes responsible for presenting data accumulated from various county health departments to determine which counties have the highest rates of WNV. This can determine which locations should be given assistance with funding, labor, or materials to manage mosquitoes. They can also present updates about WNV risk to a larger audience than local departments. Many state websites present this data in weekly reports throughout the WNV active period, to educate the public as to the relative risk of WNV throughout the state. State health departments also often provide training for local health departments, and can therefore ensure consistent education and methodology across the state.[115] Testing centers for dead birds or mammals, as well as mosquitoes, are also often done at the state level.[92,115]

In many states, the state health department conducts surveillance for reported human cases of WNV. It also utilizes data obtained from local districts and non-governmental associations. However, some states have not developed an outbreak-response plan that uses these data for interventions. Although WNV cases have subsided in many areas since the last outbreak in 2012, mosquito control plans could still be useful to create for two key reasons. The first is that with the uncertain impact of climate change on vector-borne disease, it is possible that WNV may become more prevalent in the area. The second is that the response to WNV can in some regards be similar to that of dengue or chikungunya. While those arboviruses are carried by *Aedes* mosquitoes, some interventions, such as applications of larvicides and adulticides would be similar.[8]

In Washington State, local and state health departments have collaborated to develop comprehensive plans of roles and responsibilities given a WNV outbreak. In this plan, local health jurisdictions would conduct surveillance for mosquito activity and WNV presence in the local area.[115] These entities would be able to determine the scope of the viral activity in their district, and would also have knowledge about available resources.[115] Counties and municipalities would be responsible for distributing pesticides on local problematic areas, using the data obtained from the LHD surveillance.[115] Hospitals must report WNV cases to LHDs, which then report them to the state department. This chain of communication may not immediately capture cases, as in one Colorado study, 51% of WNV cases were reported to the disease reporting system within the required 7 days.[103] This is another indication why mosquito surveillance can be a more sensitive measure of WNV risk than human cases.

In some areas, Mosquito Control Districts (MCDs) are entities specifically responsible for mosquito surveillance and control. They can work to assist the local health department (LHD) with data-gathering by setting up and assessing mosquito and larval traps. They can also coordinate efforts between LHDs and state health departments to distribute larvicide and adulticide in high-risk areas.[115] In Washington state, MCDs are allowed to enter any property to determine whether it is a high-risk area for mosquito breeding.[115] MCDs can also participate with mosquito and dead bird collection.[115] MCDs are useful because they have dedicated staff, funding, and resources that can be used to maintain consistent surveillance and control of mosquito populations.

WNV often presents as a season-long outbreak, followed by periods with few cases. Because of this, some states will reduce funding for their MCPs when WNV rates are low. An example of this is North Carolina, which was impacted by Hurricane Irene in 2011—the same year the state government dissolved their Public Health Pest Management (PHPM) section.[143,144] In the 1970s, North Carolina established the PHPM section to be a leader in training and supporting local Mosquito Control Programs (MCPs).[143] It was disbanded in 2011 due to budget cuts, which removed the central coordinating body from the state.[143] In a survey of North Carolina MCPs in 2014, 70% of respondents reported that dissolving the PHPM section may have hindered their ability to control mosquitoes, and could result in an outbreak of mosquito-borne diseases.[143]

After Hurricane Irene landed in 2011, the increase in standing water led to a subsequent increase in mosquito populations.[143] This required a large-scale response by MCPs throughout the state of North Carolina; however, due to budget cuts, many MCPs were not sufficiently funded to prepare for such a scenario.[143] In Washington and Tyrell counties, two of the poorest in the state, aerial spraying was unavailable for almost two months after the hurricane due to budget constraints.[143] This resulted from a lack of funding as well as unclear organizational roles after the removal of the PHPM. As in many emergency scenarios, the response was more reactive than proactive.[144] There was no increase in WNV cases after the hurricane; however, developing a response plan could help reduce exposure to workers and residents in the future.[143]

During the recent Zika virus outbreaks in 2016, North Carolina allocated both state funds and grants from the CDC towards enhancing both detection and control infrastructure.[145] This included hiring entomologists and laboratory specialists to assist counties in detecting and preventing arboviral outbreaks.[145] It also expanded collaboration with university entomology experts, and increased the scope of surveillance for *Aedes* spp mosquitoes.[145] While these efforts were focused mostly controlling a possible Zika outbreak, rebuilding parts of the PHPM program will also address other arboviral outbreaks as well, including WNV.

Conclusion

As climate change continues to impact human and mosquito populations, it becomes increasingly important to develop plans and interventions that can be implemented in response to a catastrophic event. While data is still being collected, there is evidence that floods can precipitate a WNV outbreak, and can cause a significant impact on both the health and economy of the local area. By developing an integrated mosquito management approach, state and local health departments can work together to address exploding mosquito populations through multiple methods. Components that are implemented before a flood such as surveillance and source reduction can provide guidance and ensure that methods used are safe, effective, and sustainable. Most literature agrees that the most effective intervention at the present are pesticides. Regardless of method used, educating the public and maintaining open communication lines between departments and levels of government will always remain critical in the event of a WNV outbreak.

By using the BRACE framework to address vector borne diseases such as West Nile Virus, health departments can ensure they are performing mosquito reduction interventions that are evidence based, and account for the changing climate and flooding events.

Resources/Appendix

Association of State and Territorial Health Officials. Before the Swarm: Guidelines for the Emergency Management of Vector-Borne Disease Outbreaks

February 2015: http://www.astho.org/Programs/Environmental-Health/Natural-Environment/Before-the-Swarm/

Provides a checklist and guidelines to prepare for and address various vector-borne disease outbreaks. It has specific guidelines for WNV, and reviews multiple components of outbreak management, including communication with the public, health professionals, and emergency responders.

CDC. CASPER Toolkit

May 2018. https://www.cdc.gov/nceh/hsb/disaster/casper/overview.htm

Toolkit for post-disaster planning and management, which provides public health workers with accurate and quantifiable data on the state of health of residents. It provides information that public health workers can use to allocate funds and labor to the most pressing issues.

CDC. West Nile Virus Prevention

August 2017. https://www.cdc.gov/westnile/prevention/index.html

Information about personal protective methods that individuals can use to reduce risk of mosquito bites.

CDC. Mosquito Control for Vector Control Professionals

December 2017. https://www.cdc.gov/westnile/vectorcontrol/vector-control-professionals.html

Information about mosquito surveillance, including resources about human cases, bioassay information, and species of birds and mosquitoes that contribute to the WNV cycle.

CDC. West Nile Virus in the United States: Guidelines for Surveillance, Prevention, and Control

June 2013. https://www.cdc.gov/westnile/resources/pdfs/wnvGuidelines.pdf

Information on bird, equine, mosquito, and human surveillance for WNV. Evidence based information on methods of integrated mosquito control including program, individual, and community based actions. Provides methods of calculating a vector index by using surveillance data.

Florida Coordinating Council on Mosquito Control. Florida Mosquito Control

2009. http://mosquito.ifas.ufl.edu/Documents/Florida_Mosquito_Control_White_Paper.pdf

Outlines the goals of mosquito control, and evaluates strategies that can be used by Florida and other states.

An update was published in 2018: https://fmel.ifas.ufl.edu/media/fmelifasufledu/7-15-2018-white-paper.pdf

Harris County Public Health and Environmental Services. Case Study: Texas West Nile Virus

2014. https://cdn1.sph.harvard.edu/wp-content/uploads/sites/1607/2014/03/Section-5.-Case-Study-Texas-West-Nile-Virus.pdf

After a WNV outbreak in Harris County in 2012, the Texas State Department of State Health Services requested an assessment of the public health response to the outbreak. The report determined organizational and logistical barriers that contributed to the size of the outbreak, and mentioned interventions that were implemented throughout and after the outbreak.

**National Association of County and City Health Officials. Mosquito Control Capabilities in
the U.S.**

2017. https://www.naccho.org/uploads/downloadable-resources/Mosquito-control-in-the-U.S.-Report.pdf

Presents data obtained from local health departments concerning the state of mosquito control in various areas throughout the U.S.

Washington State Department of Health. Guidance for Surveillance, Prevention, and Control of Mosquito-borne Disease

2008. https://www.doh.wa.gov/portals/1/Documents/Pubs/333-149.pdf

Washington distributed a guidance document in 2008 that outlined roles and responsibilities for various governmental and non-governmental entities within Washington. The document also determines "alert levels," with criteria to meet each level, as well as guidelines for control.

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