HARRIS COUNTY PUBLIC HEALTH MOSQUITO AND VECTOR CONTROL DIVISION EMERGENCY RESPONSE TO HURRICANE HARVEY: VECTOR-BORNE DISEASE SURVEILLANCE AND CONTROL

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ABSTRACT. Hurricane Harvey made a landfall on the Texas Gulf Coast on August 25, 2017, stalling over Harris County as a tropical storm for 4 days (August 26–29), dumping approximately 127 cm of rain. This tremendous amount of rainfall overwhelmed the county's natural and man-made drainage systems, resulting in unprecedented widespread flooding. Immediately following, Harris County Public Health Mosquito and Vector Control Division conducted a countywide emergency vector control response by integrating surveillance, control, and education strategies. This included landing rate counts, mosquito and avian surveillance, arbovirus testing, ground-based ultra-low volume (ULV) and aerial pesticide spraying, and community outreach. The immediate response lasted for 4 wk through September, resulting in 774 landing rates, 49,342 ha treated by ground-based ULV, 242,811 ha treated by aerial ULV, 83,241 mosquitoes collected, 1,807 mosquito pools tested, and 20 education/outreach sessions. Recovery activities of 3 additional education/outreach events continued through October while surveillance and control activities returned to routine status.

KEY WORDS   Disaster, flooding, Hurricane Harvey, mosquito surveillance, mosquito control

INTRODUCTION

Harris County Public Health (HCPH) serves as the county health department for Harris County, TX, the 3rd most populous county in the USA, by providing comprehensive health services through its annual budget of $100 million and a workforce of >700 public health professionals. The HCPH jurisdiction includes approximately 2.2 million people within Harris County's unincorporated areas and >30 municipalities located in Harris County (not including the City of Houston). However, public health services provided by the Mosquito and Vector Control Division (MVCD) encompass the entirety of the county, including the City of Houston, providing services to >4.7 million people. The MVCD's mission is to protect county residents from mosquito-borne diseases through environmental surveillance, control measures, education and outreach, research, and technology. The division conducts surveillance, sampling, and testing for several vector-borne diseases, including West Nile virus (WNV), St. Louis encephalitis (SLEV), dengue (DENV), chikungunya (CHIKV), and Zika (ZIKV) viruses. As an integrated vector management (IVM) program, MVCD is expected to respond during natural disasters, monitoring the environment for vector-borne diseases and applying the necessary control measures for mitigation.

Mosquito-borne diseases have rarely increased following a natural disaster in the USA, which may be due in part to active surveillance practices and effective IVM programs (Lehman et al. 2007, Harrison et al. 2009). However, after the passage of Hurricane Katrina in 2005, it was noted that West Nile neuroinvasive disease (WNND) incidence doubled in some counties in Mississippi and Louisiana that were directly impacted by the storm (Caillouët et al. 2008b). Because WNND complications occur in a very small proportion of WNV infections, this increase represented a significantly larger increase in WNV transmission to humans in the area (Caillouët et al. 2008b). This increase in WNV cases was most likely due to an increase in mosquito oviposition sites and human exposure since homes were destroyed and individuals were out in the open environment for days waiting to be evacuated (Caillouët et al. 2008a, 2008b). Domestic cats and dogs from the hurricane-impacted areas were also found to have elevated levels of WNV and other pathogens of zoonotic importance (Levy et al. 2011).

Hurricane Harvey made a landfall on the Texas Gulf Coast south of Houston near Corpus Christi on August 25, 2017, and moved slowly inland and north as a tropical storm before remaining stationary over Harris County and surrounding areas for 4 days. During this period, Harris County received >121.92 cm of rainfall, which is about the same amount of rain received, on average, annually (Blake and Zelinksy 2018). One location in Baytown, directly east of Houston, recorded 104.34 cm rainfall/day (van Oldenborgh et al. 2017). The flooding associated with this event caused >80 deaths and damaged >100,000 homes on the Gulf Coast (van Oldenborgh

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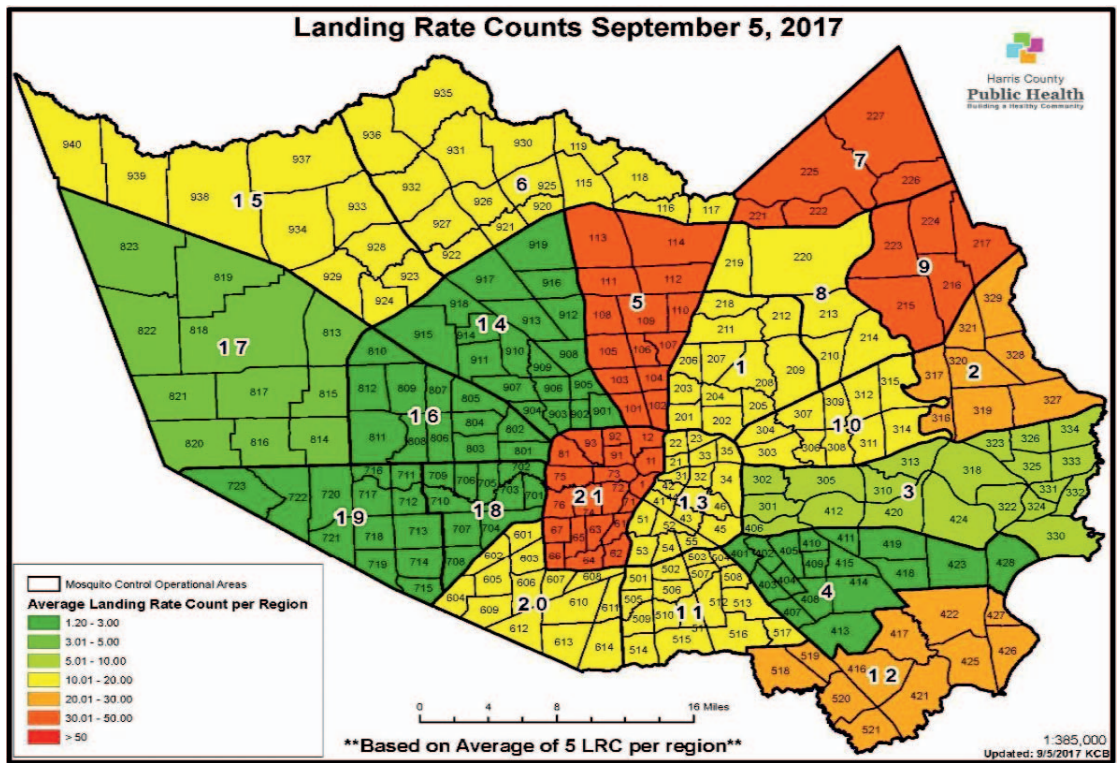[3] To whom correspondence should be addressed.

Fig. 1.   Landing rate counts by regions after Hurricane Harvey in Harris County, TX, in 2017.

et al. 2017). Tens of thousands of individuals were displaced from their homes, and many people were living in unsanitary or unsafe conditions (Ortiz et al. 2017). The amount of water that inundated the Harris County area increased the amount of mosquito oviposition sites, placing the population at a higher risk for mosquito-borne diseases (Breidenbaugh et al. 2008, Ortiz et al. 2017).

Mosquito habitats that were immediately impacted during and after the flooding included groundwater, surface runoff retention ponds, debris-clogged drainage arteries, containers, tires, and abandoned swimming pools, all of which were potential oviposition sites for numerous mosquito species capable of transmitting viruses (Nasci and Moore 1998, Foppa et al. 2007, Caillouët et al. 2008a, Kouadio et al. 2012, Harris et al. 2014). Hurricane Harvey made landfall in the month of August, during the period of highest disease transmission risk of mosquito-borne diseases in Harris County. Taking into consideration the increased potential for mosquito-borne disease transmission, the department activated its staff to respond to the possible threat. The HCPH Office of Public Health Preparedness and Response activated the Emergency Operations Center on August 23, 2017, and the health department began various public health emergency response activities on August 25, 2017. Here, we discuss vector-borne emergency

response measures taken by HCPH post–Hurricane Harvey landfall in 2017.

MATERIALS AND METHODS

Due to the inaccessibility of areas as a result of extensive flooding, MVCD ground response activities did not commence until September 3, 2017. The initial focus was to conduct human landing rate counts (LRCs) to assess the abundance of the mosquito populations throughout the county. All available MVCD personnel received training on the correct procedures for conducting LRCs and were provided with educational handouts, larvicides, and human LRC recording data sheets. Staff were also instructed to wear long pants and a light-colored long-sleeved shirt both for their protection and to increase effectiveness of the LRC. For those who did not have light-colored clothing, disposable laboratory coats were provided. The county was divided into 21 LRC regions, with a team of 2 staff members per region. Teams were expected to conduct at least 5 LRCs per region in areas that were easily accessible, with vegetation and/or shaded, around parks, cemeteries, and wooded areas within proximity of residents (Fig. 1).

The primary human LRC surveillance method used was a 1-min LRC (Schmidt 1989). One member of the LRC team would stand still near the selected

location with arms extended for 1 min, while the other team member moved around that individual, slowly counting the mosquitoes that had landed. The necessary caution was taken to not disturb the mosquitoes. Two human LRCs were conducted at each site, and an average of the number of mosquitoes observed was recorded. For the purpose of this emergency response effort, a human LRC of >30 mosquitoes/min was set as the action threshold to apply control measures.

As the effects of the disaster continued to impact Harris County, HCPH was forced to prioritize its response efforts. In order to accomplish this, staff were reassigned to other areas of need as required such as medical shelters, water sampling, etc. This reassignment reduced the staff available to cover all 21 regions.

A new plan was developed to accommodate the staff shortage. Moving forward, LRCs were conducted using the established Mosquito Control Operational Areas (MCOAs), based on historical data for mosquito abundance and disease risk as well as rainfall data and area accessibility. During the planning phase for the aerial treatment, it was decided that human LRCs would be conducted in targeted areas pre- and posttreatment to determine the treatment efficacy. Maps depicting completed treatment and human LRCs throughout the county were created by the ArcGIS team daily.

The MVCD conducts routine arbovirus disease surveillance in both avian and mosquito populations in Harris County annually. Avian surveillance included live bird trapping using mist nets that are erected in county parks before sunrise and maintained until 9:30 a.m. (Wilkerson et al. 2017). Dead bird collection is dependent on resident reports. Mosquito specimen collection involved utilizing 3 different trap types: the modified Centers for Disease Control and Prevention (CDC) miniature light trap, the modified CDC Reiter gravid trap (J.W. Hock and Co., Gainesville, FL), and the Biogents Sentinel (BG) trap (Biogents Inc., Regensburg, Germany). The CDC light traps were baited with carbon dioxide (CO_2) in the form of dry ice, gravid traps with a modified Reiter-medium (fermented hay infusion made by adding 1.3 kg hay in 166 liters of water in a covered plastic garbage bin for 7 days) (Reiter 1991), and BG traps used a proprietary BG lure (Biogents Inc.) enhanced with CO_2. The CDC light and gravid traps were utilized to maximize the collection of Culex quinquefasciatus Say, thereby increasing the probability of detecting WNV, while BG traps were expected to provide a greater opportunity for the collection of Aedes aegypti (L.) and Ae. albopictus (Skuse), which were tested for the presence of DENV, CHIKV, and ZIKV. Trapping activities were concentrated every day of the week (i.e., Monday to Sunday) in high-risk areas, depending on access to that area. As the situation slowly returned to a degree of normalcy, trapping activities

increased until the surveillance section was able to cover all 268 MCOAs.

Mosquito species collected from the field were sorted, sexed, identified to genus and species, placed in cryovials, issued laboratory unique identification numbers, and placed in cold holding at −80°C. The frozen vials were then received by the MVCD Virology Laboratory for virus testing. The MVCD Virology Laboratory operates in accordance with CDC guidelines in executing specific methodologies to analyze and screen mosquitoes that pose a threat to human health. Current testing procedures focus on isolating the following arboviruses: WNV, SLEV, DENV, CHIKV, and ZIKV.

Routine collections and testing of mosquito samples were suspended due to the passage of the storm; however, these activities were resumed 1 wk post–Hurricane Harvey. Each sample was initially screened using the enzyme-linked immunosorbent assay (ELISA) test for WNV and SLEV. Samples testing positive for WNV received a confirmatory rapid analyte measurement platform ramp test (Response Biomedical Corporation, Vancouver, BC, Canada) (Randle et al. 2016). Samples containing Ae. aegypti or Ae. albopictus were further tested using DENV ELISA, CHIKV VectTor test (VecTOR Test Systems Inc., Newbury Park, CA), and reverse transcriptase–quantitative polymerase chain reaction for ZIKV. Samples were tested and recorded according to unique identifier, which corresponded to the exact location where they were collected. This aided in control efforts if test results indicated that a sample tested positive for an arbovirus.

The HCPH-MVCD is authorized to use adulticides when one of the following conditions is met: a confirmed positive mosquito pool, avian sample or epidemiology report for mosquito-borne disease (normal operations), or a declared emergency in which nuisance mosquito populations are interfering with response and recovery efforts. Upon declaration of an emergency, MVCD followed the protocol of Federal Emergency Management Administration (FEMA) recovery policy 9523.10—Eligibility of Vector Control. The declaration allowed treatment protocols targeting nuisance mosquito populations to be enacted.

The 1st steps were to prioritize larval and adult surveillance regions based on the amount of water, road conditions, and safety in the declared impacted flood areas, and communications with Public Health Preparedness staff and emergency managers. When thresholds from the human LRCs were determined, areas meeting the threshold were scheduled for ground-based ultra-low volume (ULV) spraying to reduce both nuisance and vector mosquito populations. The proposed treatment areas were loaded into the MVCD geographic information system and posted on the HCPH website to notify residents of treatment activities.

Ground-based ULV was conducted with either truck-mounted, London Fog 18-20 sprayers (London

Table 1. Education and Outreach schedule for community events after Hurricane Harvey in 2017.

Time	Activity[1]
0700 h	Meet at central location
0700–0800 h	Load supplies and plan for event
0800–0900 h	Transport MVU and SSB to venue
0900–1000 h	Set up for event
1000–1700 h	Provide information, mosquito repellent, Mosquito Dunks
1700–1800 h	Pack up from event
1800–1900 h	Transport MVU and SSB to storage facility

[1] MVU, Mosquito and Vector Control Division (MVCD) Mobile Vector Unit; SSB, MVCD Skeeter School Bus.

foggers, Minneapolis, MN) or ADAPCO Guardian 180SS sprayers (ADAPCO, Sanford, FL). Adulticides applied were either Permanone (permethrin) 31-66 (Bayer Environmental Science, Cary, NC) at 50.598 ml/ha (6.720 g AI/ha) or Fyfanon (malathion) ULV (FMC Global Specialty Solutions, Philadelphia, PA) at 50.598 ml/ha (61.599 g AI/ha) at 16.09 km/h. The products were rotated on a weekly basis to mitigate the risk of insecticide resistance developing in mosquito populations. All application data were recorded using the ADAPCO Monitor 4 system, which allowed real-time tracking of vehicle location, flow rate, speed, and spray status (spray on/off).

Aerial treatments are normally contracted. However, in the case of Hurricane Harvey this was accomplished in collaboration with the Texas Department of State Health Services (DSHS) and the Air Force Aerial Spray Flight of the US Air Force Reserve via the State of Texas Assistance Request (STAR) system. Aerial adulticide applied during Hurricane Harvey was Dibrom (naled) (AMVAC Chemical Corporation, Newport Beach, CA) at 54.76 ml/ha.

The Education and Outreach Team within MVCD began its Hurricane Harvey community outreach prior to Hurricane Harvey making landfall on the Texas Gulf Coast. Public education messages were crafted for both social and traditional media focusing on hurricane preparations and posthurricane actions related to mosquito breeding site elimination and personal protective measures. These messages were provided to the Harris County Regional Joint Information Center (JIC) and the HCPH Office of Communications, Education, and Engagement (OCEE). Providing these messages to the JIC in advance of the storm ensured that our community had the information needed prior to the hurricane and after the storm had passed. In the week following the storm, the MVCD Education and Outreach Team provided just-in-time training for employees who would be working outside of their usual job responsibilities and talking points for media interviews. Company donations of OFF! mosquito repellent (SC Johnson and Son Inc., Racine, WI) and Mosquito Dunks® (Summit Chemical Company,

Baltimore, MD) were accepted to be distributed to impacted communities. These operational plans and donations proved to be integral in connecting with impacted communities moving forward.

Community outreach activities began on September 5, 2017, with the activation of the HCPH Mobile Health Village composed of health educators and operational staff from across HCPH, including the MVCD Mobile Vector Unit and the MVCD Skeeter School Bus. During a 12-h workday (Table 1), a team of 6 individuals provided educational tours of the Mobile Vector Unit, and distributed mosquito repellents, Mosquito Dunks, and informational materials at various locations throughout Harris County.

In addition to the HCPH Mobile Health Village, MVCD participated in 6 additional Hurricane Harvey–related community recovery events during September and October 2017.

RESULTS

The countywide human LRCs began on September 5, 2017, once MVCD employees were able to travel the roads safely, and continued through September 22, 2017, with a total of 741 LRCs conducted. The entire MVCD staff was utilized for LRCs on the 1st day, while later during the response, fewer staff were available due to reassignment and returning to their normal duties (virology, surveillance, and ULV spraying). Furthermore, all 21 MVCD LRC regions (totaling 101 MVCD operational areas) were investigated on the 1st day of response, and fewer regions and operational areas were investigated during the following days. From September 5–8, 2017, the highest average LRCs meeting the action threshold were recorded with 50 MCOAs meeting the threshold while 30 MCOAs met the action threshold through the rest of the response period. Figure 1 shows an example of LRCs that were conducted daily during the emergency response. During the response, 31 operational areas recorded LRCs above 50. In the northeastern corner of the county (Kingwood, Huffman, and Crosby areas), LRCs above 50/min were consistently observed. The southwestern portion of the county along Interstate I-10 was also of special concern as the Addicks and Barker reservoirs released water shortly following the storm, flooding the area, making it inaccessible to traffic and LRCs. Each of the LRC sites were geocoded and those that were treated by air were then revisited as the posttreatment count sites to evaluate treatment efficacy.

Table 2 shows avian surveillance activities before and after the passage of the storm. A total 10 dead birds from 7 different species were collected before the storm, and 6 dead birds from 5 different species were collected within the 4 wk following the storm. Of the 10 dead birds reported before Hurricane Harvey, 2 (20%) were positive for WNV, while 1 of 6 (17%) reported after Hurricane Harvey was positive for WNV. All positive birds were blue jays,

Table 2. Number of dead birds collected 4 wk before and 4 wk after Hurricane Harvey in Harris County, TX, in 2017.

Species	31	32	33	34	35—Hurricane Harvey	36	37	38	39
American robin	0	1	0	0	0	0	0	0	0
Black vulture	1	0	0	0	0	0	0	0	0
Blue jay	0	2	1	0	0	1	0	0	0
Cooper's hawk	0	1	0	0	0	0	0	0	0
Eastern screech-owl	0	0	0	0	0	1	0	0	0
Great-tailed grackle	0	0	1	0	0	0	0	0	0
Mourning dove	1	0	1	0	0	0	0	0	0
Rock dove	0	0	1	0	0	0	0	0	0
Sora	0	0	0	0	0	0	0	0	1
White-winged dove	0	0	0	0	0	0	2	0	0
Yellow-breasted chat	0	0	0	0	0	0	1	0	0
Total	2	4	4	0	0	2	3	0	1

Cyanocitta cristata (L.). Live bird trapping before the storm yielded 103 live birds from 12 different species while 89 birds from 16 species were trapped following the storm. These included the American redstart (*Setophaga ruticilla* (L.)), black-and-white warbler (*Mniotila varia* (L.)), common yellowthroat (*Geothlypis trichas* (Cabanis)), downy woodpecker (*Picoides pubescebs* (L.)), gray catbird (*Dumatella carlonensis* (L.)), indigo bunting (*Passerina cyanea* (L.)), Nashville warbler (*Vermivora ruficapilla* (Wilson)), Swainson's thrush (*Catharus ustulatus* (Nuttal)), and yellow-breasted chat (*Icteria virens* (L.)) (Table 3).

Prior to epi-week 35, i.e., before the hurricane made the landfall, 30 different species of mosquitoes had already been part of the collection.

Trapping activities following the storm produced 32 different species of mosquitoes. Increases in floodwater mosquito species were observed, including *Ae. taeniorhynchus* (Weid.), *Ae. vexans* (Meigen), *Ae. sollicitans* (Walker), *Psorophora ferox* (von Humboldt), and *Ps. columbiae* (Dyar and Knab) while other species followed their usual trend during the fall season. Some species that were present pre–Hurricane Harvey were not collected following the flood, while some that were not present before the storm appeared after (Table 4).

The peak period for WNV-positive isolates at HCPH-MVCD is usually during August. One month prior to Hurricane Harvey, out of 1,915 samples tested for arbovirus activity, 56 mosquito pools were confirmed positive for WNV. During epi-week 32

Table 3. Number of live birds collected 4 wk before and 4 wk after Hurricane Harvey in Harris County, TX, in 2017.

Species	31	32	33	34	35—Hurricane Harvey	36	37	38	39
House sparrow	19	21	9	0	0	0	8	19	12
Blue jay	3	14	3	1	0	1	4	2	1
Northern mockingbird	6	5	2	0	0	1	4	1	1
Northern cardinal	4	3	0	3	0	0	2	4	10
Mourning dove	0	0	2	0	0	0	2	3	0
Nutmeg mannikin	0	0	0	1	0	0	0	1	1
White-winged dove	0	2	0	0	0	0	0	0	0
Carolina chickadee	1	0	0	0	0	0	0	0	0
Carolina wren	0	0	0	1	0	0	0	0	0
Tufted titmouse	0	1	0	0	0	0	0	0	0
European starling	1	0	0	0	0	0	0	0	0
Red-vented bulbul	1	0	0	0	0	0	0	0	0
American redstart	0	0	0	0	0	0	0	0	1
Black-and-white warbler	0	0	0	0	0	0	0	0	1
Common yellowthroat	0	0	0	0	0	0	0	0	1
Downy woodpecker	0	0	0	0	0	0	0	0	1
Gray catbird	0	0	0	0	0	0	0	0	2
Indigo bunting	0	0	0	0	0	0	0	0	2
Nashville warbler	0	0	0	0	0	0	0	0	1
Orange-crowned warbler	0	0	0	0	0	0	0	0	1
Swainson's thrush	0	0	0	0	0	0	0	0	1
Yellow-breasted chat	0	0	0	0	0	0	0	0	1
Total	35	46	16	6	0	2	20	30	37

Table 4. Mosquito collection by species before and after Hurricane Harvey in Harris County, TX, in 2017.[1]

Mosquito species	Week 31	Week 32	Week 33	Week 34	Week 35	Week 36	Week 37	Week 38	Week 39	Total before Hurricane Harvey	Total after Hurricane Harvey	Delta
Aedes aegypti	745	810	1,745	863	0	1,303	1,190	363	1,004	**4,163**	3,860	−303
Ae. albopictus	1,819	1,583	1,716	1,594	0	1,773	1,845	806	1,195	**6,712**	5,619	−1,093
Ae. atlanticus	1	6	24	1	0	**143**	**223**	3	**64**	32	430	**398**
Ae. fulvus pallens	0	0	0	0	0	0	12	3	0	0	15	**15**
Ae. hendersoni	0	0	0	0	0	0	2	2	0	0	4	4
Ae. infirmatus	0	3	67	9	0	**219**	**126**	19	**111**	79	**475**	**396**
Ae. sollicitans	7	44	79	9	0	**387**	76	1	3	139	**467**	**328**
Ae. taeniorhynchus	169	1,192	478	148	0	2,904	**2,213**	15	148	1,987	**5,280**	**3,293**
Ae. triseriatus	2	1	0	0	0	0	0	0	0	3	0	−3
Ae. vexans	32	30	28	14	0	**938**	**448**	**118**	**382**	104	**1,886**	**1,782**
Anopheles crucians	22	5	4	8	0	5	21	13	**26**	39	65	**26**
An. punctipennis	2	0	1	0	0	0	0	0	1	**3**	1	−2
An. quadrimaculatus	11	15	47	9	0	0	15	25	14	**82**	54	−28
Coquillettidia perturbans	8	4	3	0	0	1	**60**	**17**	**9**	15	87	**72**
Culex coronator	214	259	178	135	0	54	141	73	167	**786**	435	−351
Cx. erraticus	42	235	9	27	0	10	56	100	25	**313**	191	−122
Cx. nigripalpus	226	140	106	106	0	72	284	368	221	578	945	**367**
Cx. quinquefasciatus	21,024	17,665	13,373	14,360	0	7,589	11,959	15,857	21,045	**66,422**	56,450	−9,972
Cx. restuans	0	0	0	0	0	0	**1**	**3**	0	0	4	4
Cx. salinarius	99	65	227	10	0	2	76	**388**	10	401	476	**75**
Cx. tarsalis	0	0	0	0	0	0	**6**	**4**	0	0	10	**10**
Mansonia titillans	89	63	92	93	0	17	21	116	23	**337**	177	−160
Orthopodomyia signifera	0	0	1	1	0	0	0	0	0	**2**	2	−2
Psorophora ciliata	0	4	39	2	0	11	4	0	4	**45**	19	−26
Ps. columbiae	46	195	602	82	0	**817**	**1,227**	20	**680**	925	2,744	**1,819**
Ps. cyanescens	2	2	35	0	0	**71**	6	0	**47**	39	124	**85**
Ps. ferox	7	2	974	92	0	**1,755**	**1,152**	18	272	1,075	3,197	**2,122**
Ps. horrida	0	0	5	0	0	5	0	0	1	5	6	1
Ps. howardii	2	3	53	10	0	31	5	0	52	68	88	**20**
Ps. longipalpus	0	0	151	34	0	85	10	1	9	**185**	105	−80
Ps. mathesoni	0	0	8	0	0	**11**	0	0	0	8	11	3
Toxorhynchites rutilus septentrionalis	2	1	2	1	0	0	2	**3**	2	6	8	2
Uranotaenia lowii	0	1	0	2	0	0	2	**3**	2	3	7	4
Ur. sapphirina	1	0	0	0	0	0	1	0	1	1	1	0
Totals	24,572	22,328	20,047	17,610	0	19,506	19,865	18,336	25,518	84,557	83,225	

[1] Values in bold indicate the increase in collection of the mosquito species after the flood event. These are mainly floodwater mosquitos. Numbers show emergence after the event.

Table 5. Weekly mosquito collection in Harris County, TX, in 2017.[1]

Week	Traps	Females collected	Females tested	Pools tested	WNV	WNV MIR
1	133	1,143	721	73	0	0
2	272	11,801	5,548	189	0	0
3	160	5,021	3,086	108	0	0
4	271	5,515	3,125	162	0	0
5	244	3,885	2,331	166	0	0
6	248	5,541	2,111	191	0	0
7	239	6,581	3,194	158	1	0.313
8	212	9,352	4,880	161	0	0
9	252	10,324	4,631	216	0	0
10	195	12,789	4,760	181	0	0
11	259	8,739	4,764	226	0	0
12	231	22,348	6,544	217	0	0
13	258	20,634	7,159	243	0	0
14	218	17,023	6,066	207	0	0
15	177	15,791	4,768	149	0	0
16	213	12,736	5,611	195	0	0
17	261	18,358	7,926	251	0	0
18	262	22,632	7,820	250	0	0
19	135	18,057	4,524	131	0	0
20	273	23,231	8,086	259	0	0
21	152	10,001	4,249	143	0	0
22	241	16,993	6,935	239	0	0
23	403	28,689	13,699	552	2	0.146
24	414	33,047	13,887	548	3	0.216
25	437	30,701	12,768	539	3	0.235
26	397	26,532	11,159	499	3	0.269
27	214	12,707	6,277	289	3	0.478
28	438	27,186	12,281	531	10	0.814
29	417	23,741	12,231	543	20	1.635
30	419	26,100	12,989	546	8	0.616
31	441	24,572	11,522	521	18	1.562
32	418	22,328	11,626	542	24	2.064
33	383	20,047	9,422	484	9	0.955
34	295	17,610	7,973	368	5	0.627
35	0	0	0	0	0	0
36	314	18,204	6,442	381	0	0
37	412	21,183	8,500	510	**1**	0.118
38	404	18,336	8,819	429	0	0
39	398	25,518	11,120	487	**1**	0.09
40	371	29,045	10,704	466	0	0
41	418	46,261	14,702	555	0	0
42	412	37,045	12,811	540	**1**	0.078
43	419	30,040	11,936	527	0	0
44	374	35,875	11,138	468	0	0
45	347	19,557	7,529	400	0	0
46	153	11,172	4,438	207	0	0
47	83	4,435	1,816	102	0	0
48	131	10,579	2,923	163	0	0
49	153	6,568	1,778	104	0	0
50	153	3,511	2,011	139	0	0
51	88	1,580	1,010	68	0	0
52	0	0	0	0	0	0
Total	14,212	890,664	362,350	15,623	112	0.309093

[1] WNV, West Nile virus; MIR, minimum infection rate.

(week of August 10), the virology laboratory had already isolated 24 WNV-positive pools. In the month following the storm, 1,807 mosquito samples were tested for WNV and only 2 *Cx. quinquefasciatus* pools were confirmed positive: one in week 37 (September 14), and the other in week 39 (September 28) (Table 5). None of the samples submitted pre– and post–Hurricane Harvey tested positive for SLE, CHIKV, DENV, or ZIKV.

The MCOAs that reached the action threshold were scheduled for treatment by ground-based ULV application unless they were in the designated aerial treatment zone. The ULV operations were conducted over multiple days to account for a reduced licensed
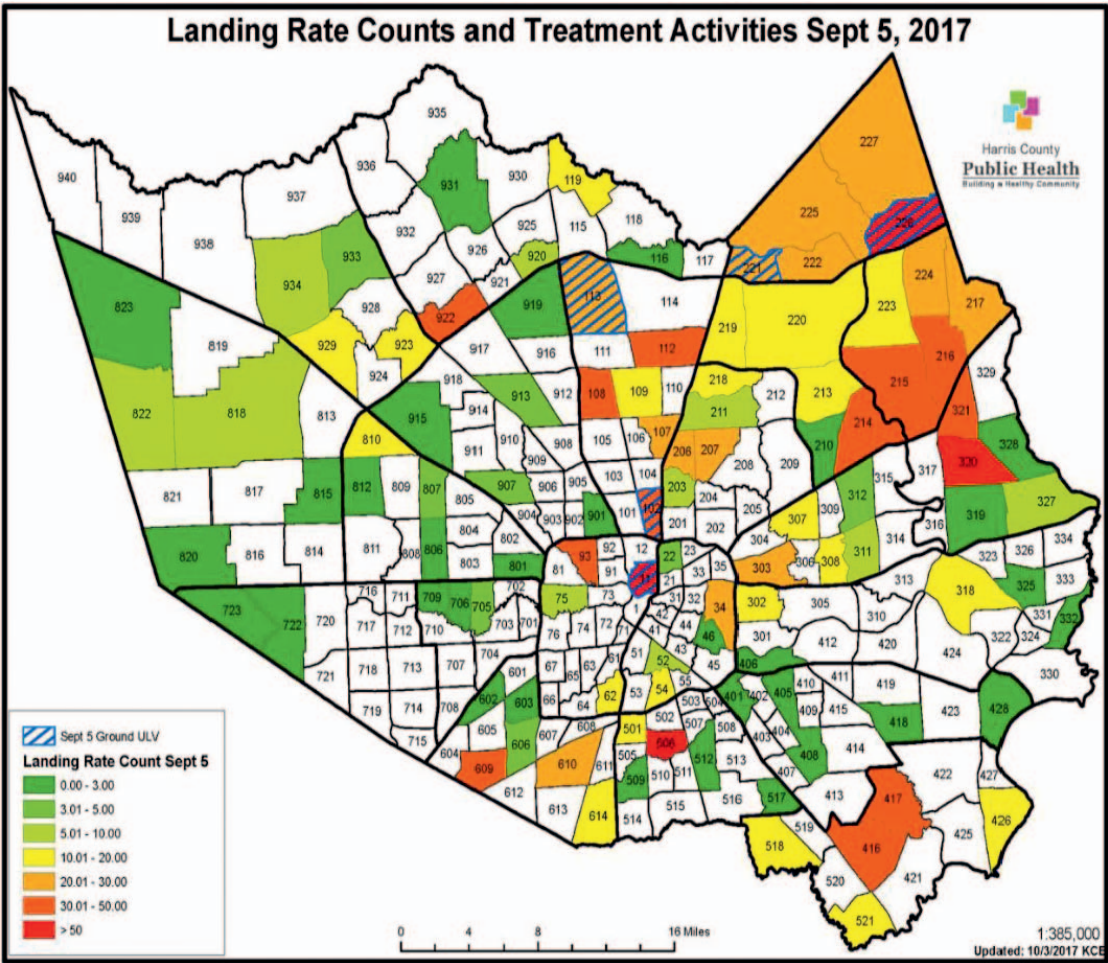
Fig. 2.   Landing rate counts and treatment activities after Hurricane Harvey in 2017.

ULV spraying staff as several drivers were reassigned. The ULV operations began on Sunday, September 3, 2017, in response to a request received through the HCPH incident command. A mosquito inspector was dispatched to Sam Houston Race Park in MCOA 918 to a staging site for electrical linemen and other responders. An LRC of 50 was recorded. Therefore, the area was treated by truck-mounted ULV to allow for recovery activities to resume.

Areas proposed for treatment (ground-based ULV) were prioritized by the highest LRC followed by the time elapsed from LRC high counts. For instance, MCOAs with the highest LRC would be prioritized first, then any areas remaining from the previous day's treatment list would take priority over the current day's LRC of the same amount. Highest LRCs were always top priority (Fig. 2).

A total of 49,342 ha were treated by ground-based ULV applications encompassing 101 MCOAs (Table 6). Of the 101 areas treated, 38 were treated by Fyfanon (17,236 ha) and 62 were treated with

Permanone (32,039 ha). A maximum of 4,961 ha (9 MCOAs) were treated on September 12 and a minimum of 67 ha (1 MCOA) was treated on September 3. There were no treatments on September 17–20 due to weather or the areas meeting treatment threshold falling into the aerial treatment zone (Fig. 3). Aerial treatments were conducted as part of the STAR request to DSHS in collaboration with FEMA and the Department of Defense. The aerial treatment zone was determined through extensive discussions between HCPH leadership and DSHS (Fig. 4). The treatments totaled approximately 242,811 ha, with a maximum of 51,740 ha on September 17 and a minimum of approximately 12,141 ha on September 19. Since we did not know the nightly proposed aerial treatment zones, MVCD did not schedule MCOAs that were in the aerial spray block with high LRCs as a precaution to prevent the possibility of overapplication of insecticides to an area, i.e., an MCOA being treated by air and ground on the same night. Aerial adulticide spray blocks were not

Table 6. Daily ground-based ultra-low volume applications after Hurricane Harvey in Harris County, TX, in 2017.

Date	Chemical	Hectares treated	No. of areas
Sept. 3	Fyfanon	67.2	1
Sept. 5	Fyfanon	2,308.3	5
Sept. 6	Fyfanon	3,372.6	6
Sept. 7	Fyfanon	4,050.5	11
Sept. 8	Fyfanon	3,220.2	9
Sept. 9	Permanone	2,184.1	7
Sept. 10	Permanone	3,326.1	6
Sept. 11	Permanone	4,006.4	7
Sept. 12	Permanone	4,961.2	9
Sept. 13	Permanone	3,906.9	4
Sept. 14	Permanone	2,707.2	6
Sept. 15	Permanone	276.3	2
Sept. 16	Fyfanon	762.0	1
Sept. 21	Fyfanon	3,522.3	6
Sept. 24	Permanone	4,062.6	8
Sept. 25	Permanone	1,802.1	5
Sept. 26	Permanone	3,707.6	4
Sept. 27	Permanone	1,098.8	4
Totals		49,342.5	101

completed in one night, instead over a series of nights in irregular patterns complicating LRC timing for evaluation and, on occasion, resulting in delays of ULV applications (Fig. 5). Aerial spray zones were examined the morning after application to determine LRC sites that were in treatment zones for follow-up/ postspray LRC counts. The final aerial application occurred on September 20 as the mosquito populations had returned to levels that were manageable by ground-based ULV treatments. A review of the pre- and posttreatment LRCs revealed a satisfactory result of the aerial treatments (Table 7).

The MVCD Education and Outreach Team provided information, mosquito repellent, and Mosquito Dunks throughout Harris County poststorm. In September and October 2017, the team provided information and supplies to 27 locations and educated 5,311 Harris County residents. A total of 4,392 cans of mosquito repellent and 878 packages of Mosquito Dunks were provided to the community. An additional 3,500 cans of mosquito repellent and informational materials were provided to the Meals on Wheels program.

DISCUSSION

The extent of flooding experienced in Harris County after the passage of Hurricane Harvey was unprecedented. The HCPH-MVCD initiated a response by putting measures in place that would mitigate the possibility of the imminence and spread of mosquito-borne diseases. One of the key components that contributed to the decision-making process was the human LRCs. The LRCs proved to be invaluable in that they provided real-time data on the biting burden faced by residents and for the concentration of ULV treatment. Conducting human LRCs also updated MVCD on road closures, high-water locations, provided pertinent information for aerial application of adulticides, and assisted in directing the decision for locating mosquito collecting devices. The data collected from LRCs also assisted the Air Force in prioritizing aerial insecticide
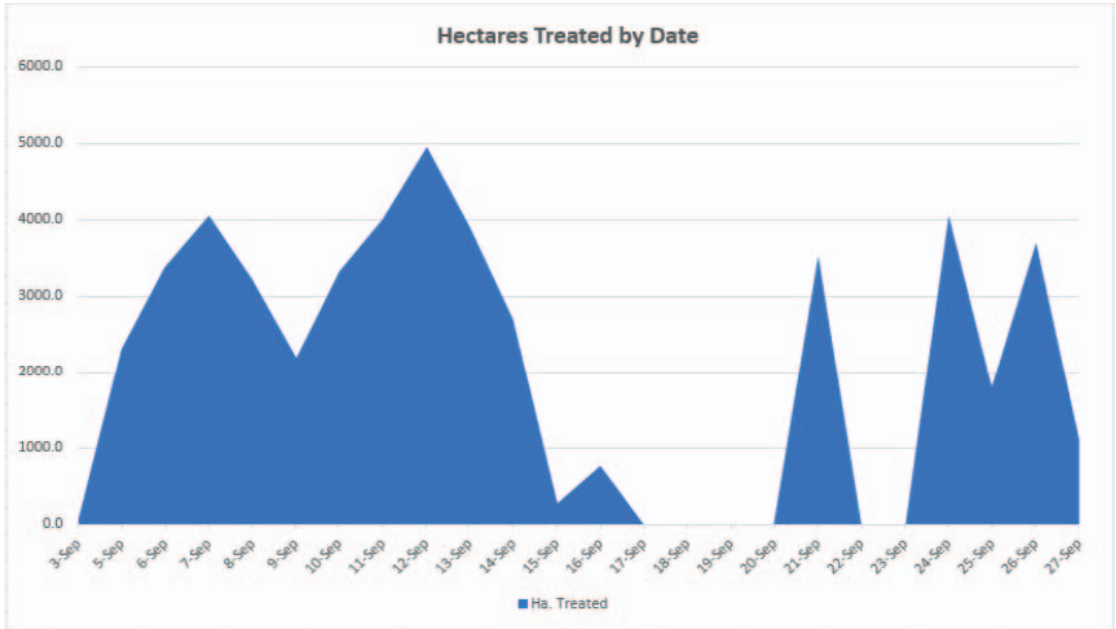

Fig. 3. Hectares treated by ground-based ultra-low volume (ULV) treatment each night after Hurricane Harvey in 2017.
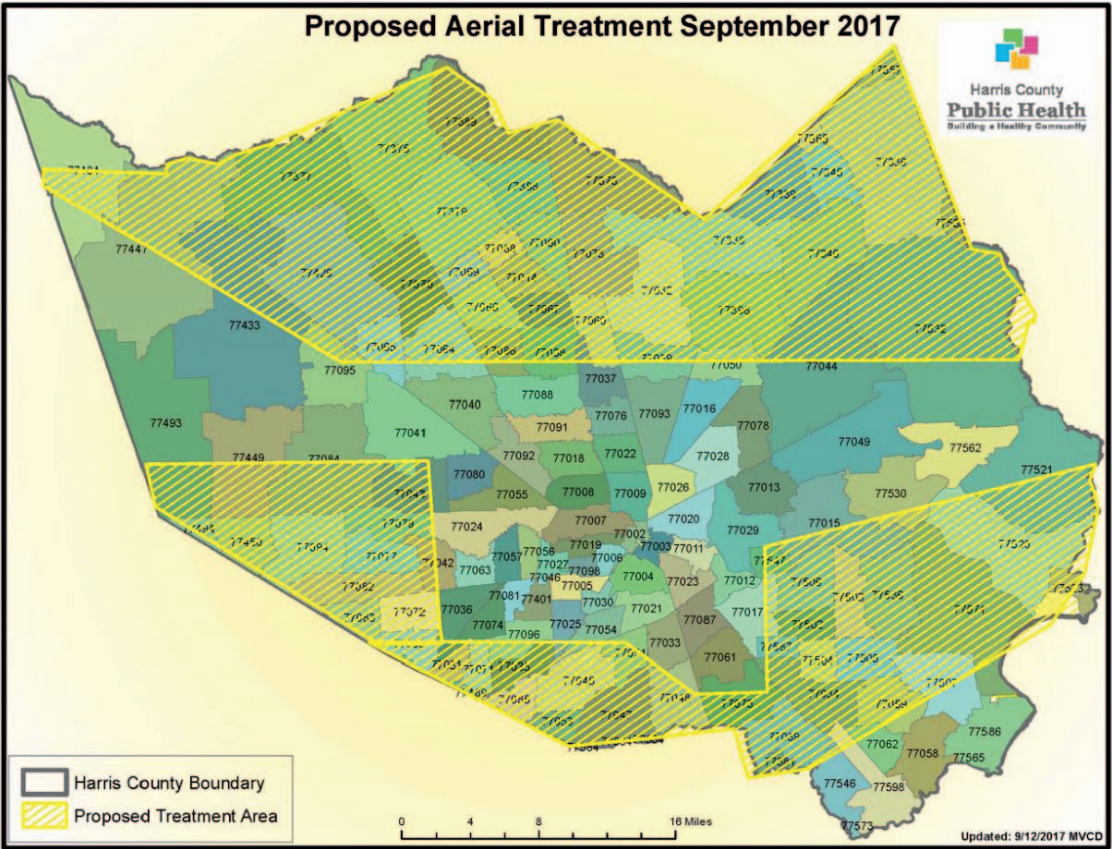
Fig. 4. Aerial treatment zone agreement between Texas Department of State Health Services (DSHS) and Harris County Public Health Mosquito and Vector Control Division (HCPH-MVCD) after Hurricane Harvey in 2017.

application over Harris County. As the LRC numbers dropped, and roads became more accessible, the Air Force was able to cease operations over Harris County and direct the distribution of resources to other areas along the Texas coastline. This left MVCD with approximately 242,000 ha to be covered by ground-based ULV treatments.

Mosquito and avian surveillance resumed approximately 10 days after the storm as roads and trap sites became more accessible. It has been reported that hurricanes can be disruptive to avian communities, causing increased mortality and changes to the ecosystem (Dionne et al. 2008, Rittenhouse 2010). The flooding effected by Hurricane Harvey had a little effect on the avian community in Harris County. There were no increases in the number of dead birds reported, and the species composition remained typical for the sample size and time of year. The number of permanent-water mosquitoes collected in CDC light traps was drastically reduced as the excessive flooding had washed away any mosquito larvae from the storm sewers. However, an increase in floodwater mosquitoes was observed from the aboveground collections. Data collected agree with prior studies which state that there was an increase in

the relative abundance of some mosquito species that develop in receding waters and pockets of standing water after hurricanes (CDC 1993, Brown 1997, Nasci and Moore 1998, Simpson 2006, Breidenbaugh et al. 2008, Harris et al. 2014). Mosquito species collected were submitted to the MVCD virology section for virus testing in order of importance for arbovirus disease transmission.

Testing procedures were carried out in accordance with the CDC protocol for screening mosquitoes that transmit disease-causing pathogens. No outbreak of mosquito-borne disease was detected; however, the virology laboratory did identify and detected ongoing transmission through 3 WNV-positive mosquito pools. This agrees with previously published documents (Nasci and Moore 1998, Kondo et al. 2002), which state that the incidence of arboviral infections rarely increases after natural disasters such as floods and hurricanes.

As no disease outbreak was reported by the virology laboratory, concentration was directed to reduction and control of adult nuisance mosquitoes that affected the residents of Harris County. The extensive flooding that occurred left several ULV drivers stranded. Those that made it in were initially
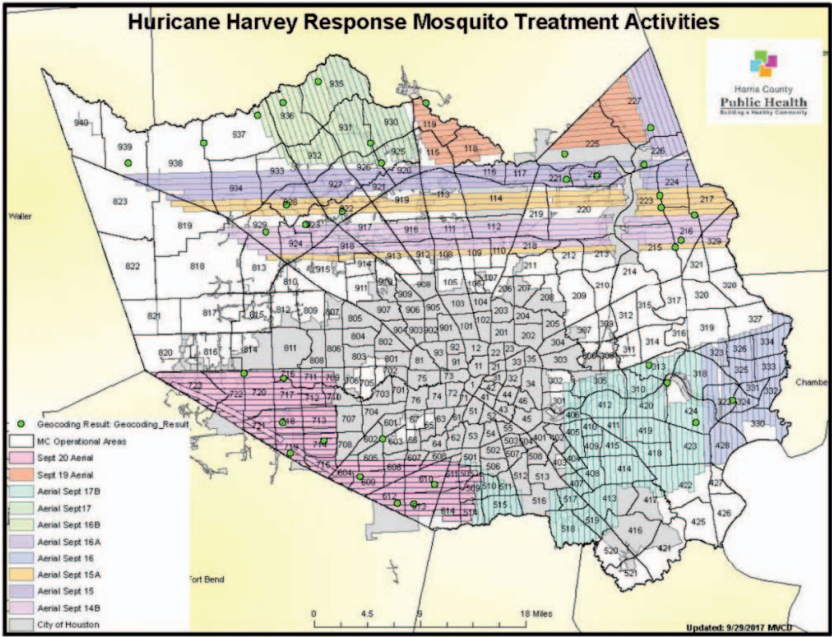
Fig. 5.　Nightly aerial treatment after Hurricane Harvey in Harris County, TX, in 2017.

Table 7.　Landing rate counts conducted pre– and post–aerial treatment by Mosquito Control Operational Area (MCOA) after Hurricane Harvey in Harris County, TX, in 2017.[1,2]

MCOA	Landing rate counts								
	Sept. 14	Sept. 15	Sept. 16	Sept. 17	Sept. 18	Sept. 19	Sept. 20	Sept. 21	Sept. 22
119	7	7	0	—	0	—	0		1
215	100	**75**	75	—	0	—	7	6	—
216	**42**	1	0	—	0	—	3	5	—
217	**50**	0	0	—	0	—	2	0	—
221	10	**12**	2	—	0	—	1	0	—
222	60	**60**	4	—	0	—	0	0	—
223	75	**0**	0	—	0	—	5	3	—
224	50	**0**	0	—	0	—	0	0	—
226	12	**20**	4	—	0	—	2	0	—
227	40	30	**10**	—	0	—	1	2	—
322	9	6	**6**	—	0	—	0	2	—
609	50	0	0	—	0	—	**0**	0	—
610	25	4	4	—	0	—	**5**	0	—
612	50	0	0	—	0	—	**5**	1	—
613	30	5	0	—	3	—	**0**	0	—
714	12	0	2	—	0	—	**0**	0	—
717	2	2	4	—	0	—	**0**	0	—
718	10	10	3	—	1	—	**3**	0	—
719	7	7	5	—	0	—	**0**	0	—
720	15	20	1	—	0	—	**0**	0	—
925	13	15	0	—	4	—	2	—	3
929	**120**	1	3	—	5	—	0	—	1
930	3	2	0	—	0	—	0	1	0
935	20	5	**4**	—	0	—	0	0	2
936	3	3	**5**	—	0	—	0	0	0
937	20	27	**11**	—	0	—	0	0	0

[1] —, none.
[2] Values in bold indicate the increase in collection of the mosquito species after the flood event. These are mainly floodwater mosquitos. Numbers show emergence after the event.

assigned to conducting LRCs. As data came in on improved travel accessibility, ULV drivers were deployed. Coverage was concentrated to selected MCOAs as the number of certified pesticide applicators was limited. The fact that much of the county was covered with water increased travel times to and from treatment areas. This forced the drivers to carry out treatment over several nights to effect full coverage of the MCOA. Once the staff increased to 11 drivers on September 14, more areas were added for treatment, making the process more effective. The widespread nature of the response efforts, coupled with the number of areas meeting the treatment thresholds, signaled the need for aerial treatments. The STAR request was filed through HCPH Office of Public Health Preparedness and Response. The ULV ground treatments continued until the aerial application treatment zones were decided. Aerial application began as soon as the STAR request was received and processed. Once the aerial treatments commenced, the mosquito populations began to decline as the applications were not obstructed by debris piled on roadsides or closed roadways. The most significant drop in mosquito populations were observed following the 1st aerial treatment; LRCs dropped from 120/min on the previous morning to 0 mosquitoes the following morning. On some nights, there were 2 United States Air Force planes applying insecticides over a large area of the county, increasing the coverage area.

A tremendous amount of collaboration went into coordinating aerial and ground treatment to ensure that there was not an overapplication of insecticides. This accounted for the discrepancy in the amount of each adulticide used, i.e., 836.58 liters of malathion versus 1,559.6 liters of permethrin since malathion fell on a week when areas meeting treatment thresholds fell in an aerial treatment zone. Following the cessation of aerial treatment on September 20, ground-based ULV treatment continued as areas that were initially inaccessible became passable. This was concentrated in areas that met the treatment threshold and one area where a positive WNV pool was isolated.

Projected rainfall totals indicated that Hurricane Harvey would have a severe impact on historically low-lying areas, bayou and other waterway levels, and would stress reservoir capacities. This advance warning afforded MVCD the opportunity to craft public education messages for pre- and poststorm and to provide those messages to the Harris County JIC and HCPH OCEE.

Following the storm and resulting catastrophic flooding experienced throughout Harris County, resources were taxed both in terms of staffing and mobility. The crafting and providing public education messages in advance proved to be incredibly useful for getting the information to the community as quickly as possible. It also saved the valuable resource of time as HCPH prepared to launch the Mobile Health Village in storm-impacted communi-

ties. Assisting our community in response to this public health emergency was important to the overall mission of public health, which is to meet people where they are to positively impact their health, well-being, and protect them from vector-borne diseases.

Despite the considerable amount of rainfall, flooding, and increase in mosquito vector habitats, the incidence of mosquito-borne disease occurring after the storm did not increase due to a combination of factors, including the robust vector control response and unfavorable environmental factors limiting vector populations. In conclusion, the HCPH-MVCD demonstrated its organizational competency in all aspects of public health recovery and response efforts after Hurricane Harvey, especially in preventing vector-borne disease outbreaks and reducing nuisance arthropod populations to manageable levels. The vector control emergency response after Hurricane Harvey in Harris County and the City of Houston included an IVM approach consisting of human LRCs, mosquito and avian surveillance, arbovirus testing, ULV ground-based and aerial adulticide spraying, and community engagement through education and outreach awareness.

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