Flooding impacts on Maryland's transportation system and users

Illustrative analysis of highway flooding incidents in Maryland

By Cassandra (Snow) Bhat, Angela Wong, Maeve Givens, and Christopher Snyder, ICF

Flooding regularly affects our nation's communities and infrastructure. Transportation infrastructure is no exception. Flood water can overtop roads, leading to a range of impacts from lane closures and traffic slow-downs to road closures and travel disruptions or loss of access to key destinations. It can even damage the roadway itself or supporting drainage infrastructure like pipes and culverts.

ICF conducted an analysis to begin to understand the toll that roadway flooding takes on the transportation system and its users.

We focused the analysis on available roadway flooding incident data from the Maryland Department of Transportation (MDOT) State Highway Administration (SHA).[1]

Key findings from this analysis include:

- Flooding affects roadways regardless of whether they are located in a FEMA-designated flood zone. In fact, of the analyzed flood incidents, 78% are located outside FEMA 500-year floodplains.
- Flood incidents occur in both inland and coastal areas. On average, MDOT SHA-maintained roads experience 196 roadway flooding incidents per year.
- On average, there are 41 days each year in Maryland with flood-related disruptions on the state highway system.
- Cumulatively, flooding on the Maryland state highway system typically results in 1,582 hours of total disruption time per year, on average. Flooding incidents on the system are estimated to affect over 480,000 people per year.[2]
- Estimated road user delay costs from flooding incidents on the system average approximately $15 million per year. While significant, user delays only represent a fraction of the cost associated with flooding incidents. Costs of remediation from the damage, vehicle repairs, emergency services, and other costs from flooding are not captured in this analysis.
- Several locations appear to be "clusters," with repeated flooding in the past 15 years and typically have longer incident durations than other isolated locations.

This paper summarizes the key takeaways from ICF's analysis of roadway flooding, as well as information on the data, methods, and limitations of the analysis. For example, the dataset underlying this analysis summarizes flood incidents on roads within the maintenance responsibility of MDOT SHA, which represent over 20% of the roadway lane-miles in Maryland (see footnote 1). Thus, these figures underrepresent the overall effects of flooding on the transportation system.

Although this paper identifies the frequency of flooded roads, it is important to note that Maryland is a leader among states in scientifically assessing coastal vulnerability to address places that repeatedly flood. For example, MDOT SHA has used the best available climate projections to perform an assessment of the vulnerability of over 8,500 bridge structures to sea level change, storm surge, and precipitation change, and a statewide road flooding vulnerability assessment that provided a comparative risk value for road segments to sea level change and storm events of varying probabilities of occurrence. Additionally, since 2015, Maryland's Coast Smart program has developed resources such as its 2020 Coast Smart Construction Program guidelines, which outline design criteria for state-funded capital projects that improve climate resilience. Maryland's approach to flood preparation represents its commitment to planning for the full range of threats including sea level rise.

The Pew Charitable Trusts commissioned ICF to conduct this research but does not necessarily endorse the findings or conclusions.

[1] Flood incidents are defined as instances where a roadway is reported blocked, in whole or in part, due to high water. The dataset analyzed is based on only flood incidents on roads within the maintenance responsibility of MDOT SHA from 2006 through August 17, 2020. MDOT SHA manages over 20% of lane-miles in Maryland (14,932 of 69,045 total lane-miles) according to the MDOT SHA 2019 Mileage Reports. The analysis excludes toll roads that are owned and maintained by the Maryland Transportation Authority; roads without a number which are maintained by a county or municipality; and interstates, numbered routes, and local roads within the City of Baltimore which are maintained by the city. Throughout this document, the MDOT SHA roadway system is referred to as the state highway system.

[2] This annual average excludes data from 2020.

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Findings

1. **The majority of flood incidents are located outside of the FEMA-designated flood zones for 100-year or 500-year events.** (See Table 1 and Figure 1)
   - This indicates that flooding is not limited to mapped flood zones.[3]
   - Most flooding incidents outside FEMA-designated flood zones are relatively close (averaging about 0.31 miles from the flood zone).

Table 1: Number of incidents located in and out of FEMA-designated flood zones (excluding the 176 incidents without geospatial data).

Total incidents	Incidents in FEMA floodplain	Incidents outside FEMA floodplain	Average distance from floodplain (if outside)
2,771	600 (22%)	2,171 (78%)	0.31 miles

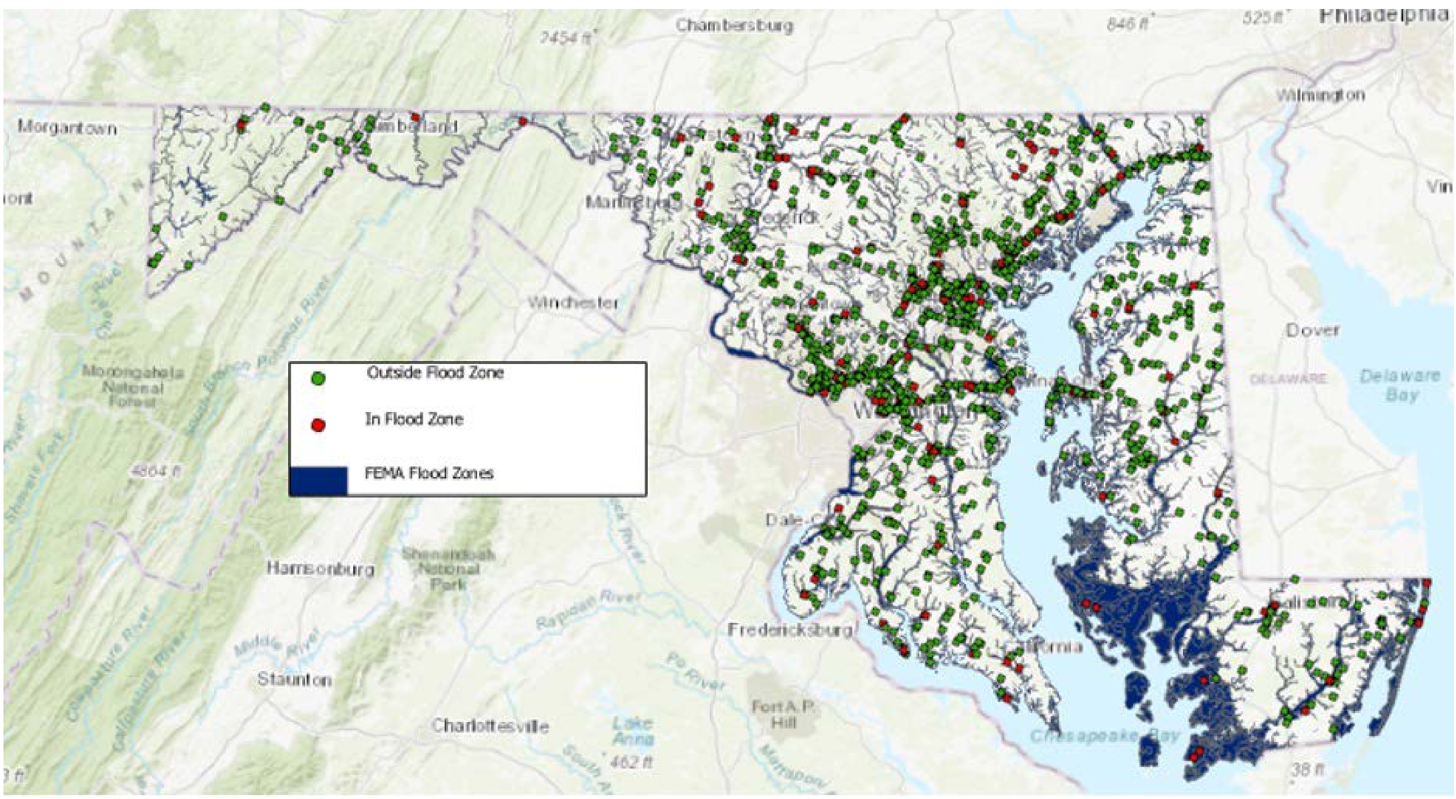

Figure 1. Flood incident locations within and outside the FEMA floodplain.

[3] The purpose of FEMA flood maps is not to predict the full extent of where flooding will occur, but to provide a resource that states and communities can use when assessing risk and making decisions about where and how to build.

2. Flood incidents occur all across the state, in both inland and coastal areas.

- On average, MDOT SHA experiences 196 reported roadway flooding incidents per year, which are distributed across both inland and coastal areas (see Figure 2 and Figure 3). The greatest number of incidents occurred in 2011 and 2018. However, note that reporting of the number of incidents in MDOT SHA's Coordinated Highways Action Response Team (CHART) has improved over time, particularly between 2006 and 2011.
- Incident frequency does not show any strong trends over time.

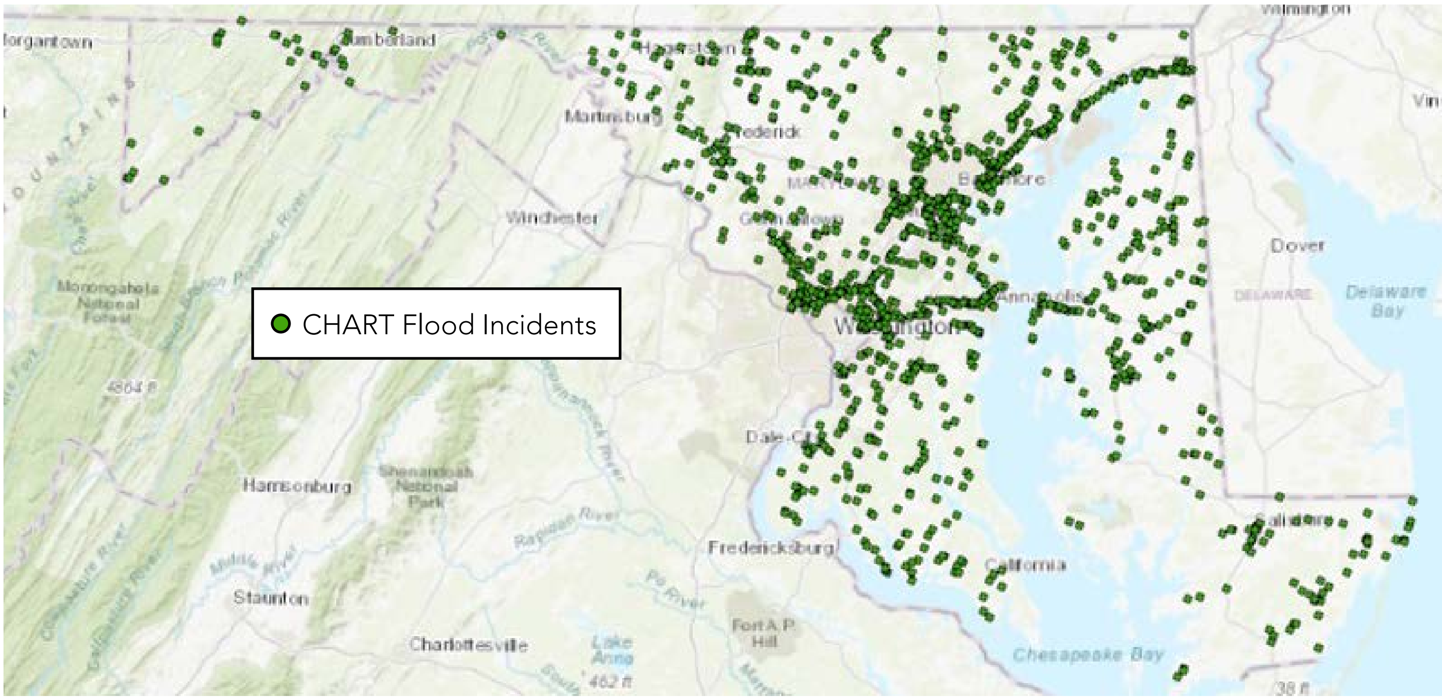

Figure 2: CHART flood incident locations throughout Maryland, 2006-2020.

Incidents by year

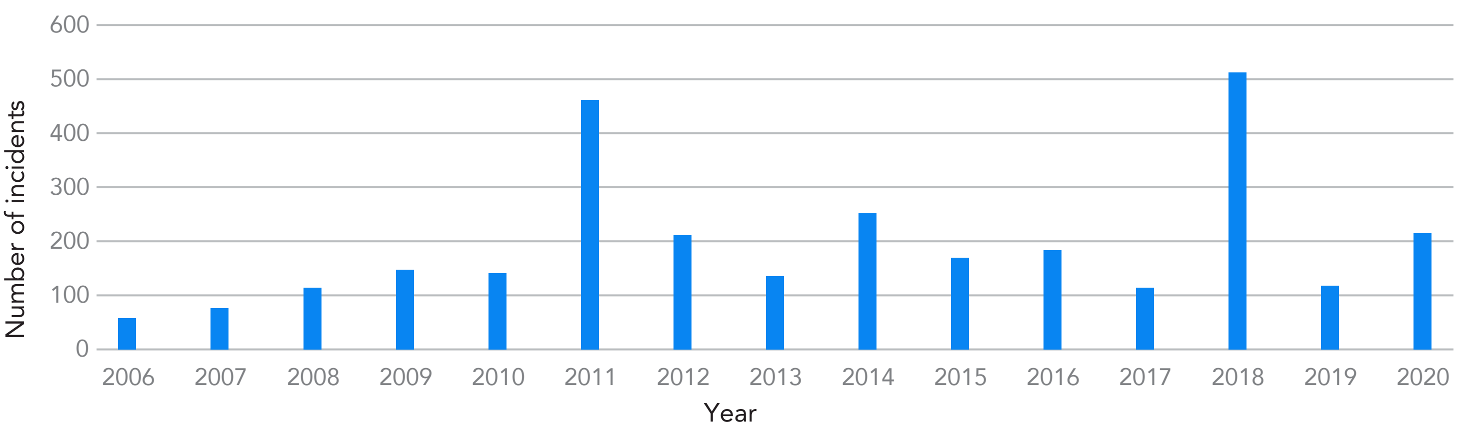

Figure 3. Number of incidents by year.

3. **Cumulatively, flooding on the Maryland state highway system typically results in 1,582 hours of disruption time per year, on average.**[4] (See Figure 4)

- The average duration of lane closures across all incidents was just over eight hours (see Table 2).
- On average, 41 days with flood-related disruptions occur annually. Between 2006 and 2020, there were 612 days in total with flood incidents (see Table 3).

Total combined duration of all incidents by year (hours)

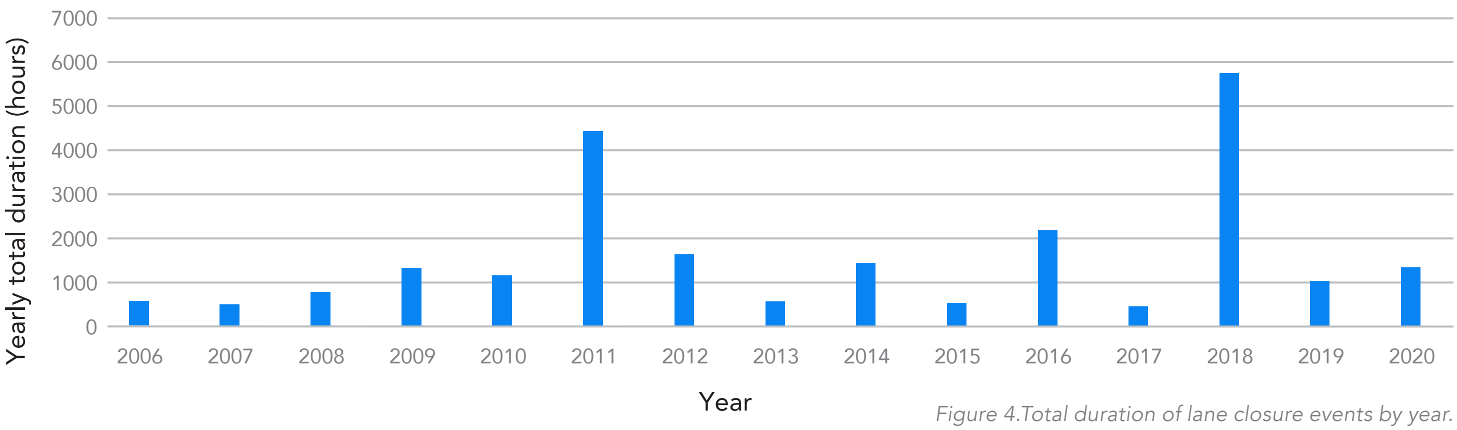

Figure 4.Total duration of lane closure events by year.

Table 2: Average and median duration of flood incidents.

Year	Average duration(hours)	Median duration(hours)
2006	9.0	4.0
2007	6.4	2.5
2008	6.7	4.5
2009	8.8	3.5
2010	8.0	3.4
2011	9.6	4.3
2012	7.6	3.5
2013	4.1	2.1
2014	5.7	2.8
2015	3.1	1.8
2016	11.8	2.3
2017	3.9	2.0
2018	11.2	2.3
2019	8.6	2.7
2020*	6.2	2.5
Total	**8.1**	**2.8**

*Partial year – data through 8/17/20.

[4] The average disruptions per year was derived by summing the total duration across all incidents in a year, and then averaging the total duration of incidents by year.

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Table 3: Annual number of days with flood incidents.

Year	Annual number of days with flood incidents
2006	19
2007	32
2008	29
2009	35
2010	30
2011	52
2012	41
2013	44
2014	37
2015	40
2016	48
2017	27
2018	87
2019	55
2020*	36
Total	**612**
Average	**41**

*Partial year – data through 8/17/20

4. Estimated road user delay costs from flooding incidents average about $15 million per year.
(See Table 4, Figure 5, and Figure 6)

- Flooding incidents are estimated to affect over 480,000 people per year. This estimate excludes incidents in 2020 as only partial data for the year was available.
- Total user delay costs, including passenger and freight delays, from 2006 to 2020 exceed $230 million dollars ($2019). The year with the most delays was 2018, in which estimated user delay costs exceeded $55 million dollars.
- Total user delays since 2006 surpass 14.4 million person-hours, with auto vehicle users delayed by 14.0 million person hours and truck vehicle users delayed by 384.8 thousand person-hours.
- The Data, Methods, and Limitations Section explains the methodology for calculating user delays.

Table 4: Total and average annual user delay cost by year.

Year	Total persons affected (in cars)	Total user delay costs	Average user delay costs by incident
2006	90,554	$5,232,410	$134,164
2007	127,130	$3,046,690	$64,823
2008	147,296	$7,590,841	$96,087
2009	209,597	$7,312,990	$58,040
2010	200,140	$7,753,908	$76,771
2011	612,966	$41,238,348	$90,833
2012	487,925	$18,279,497	$87,045
2013	288,004	$5,761,754	$42,057
2014	581,679	$20,694,556	$81,155
2015	667,205	$8,062,716	$46,605
2016	699,101	$20,236,923	$110,584
2017	458,339	$7,356,065	$62,872
2018	1,857,860	$55,172,311	$107,758
2019	393,857	$7,910,436	$65,376
2020*	661,931	$15,098,701	$69,579
Total	**7,483,583**	**$230,748,146**	**$83,273**

*Partial year – data through 8/17/20

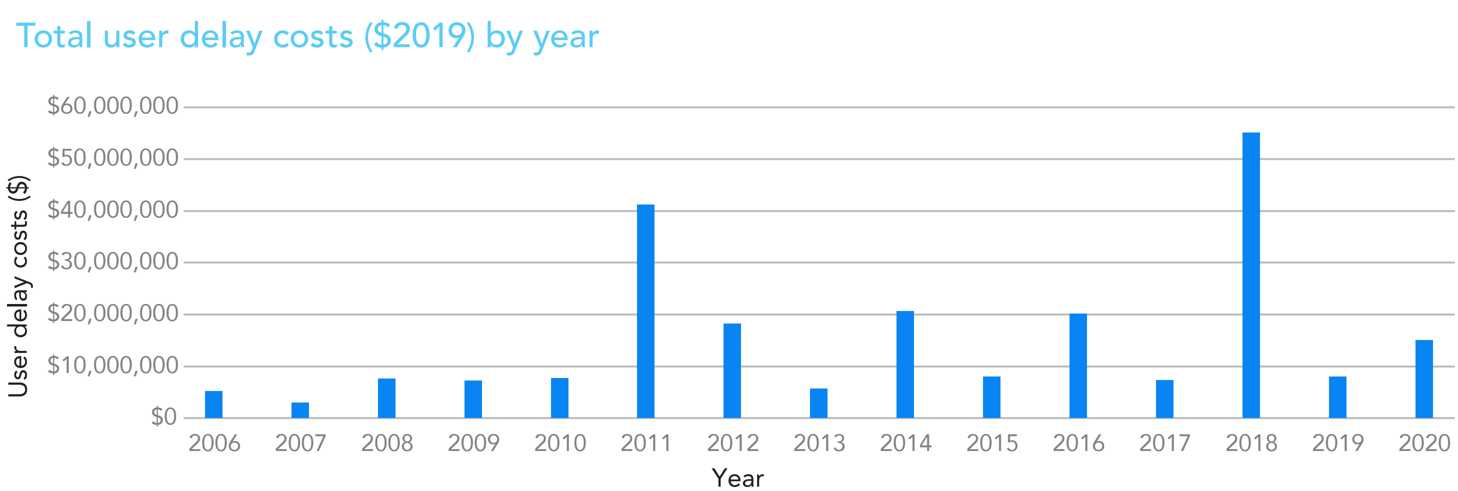

Figure 5. User delay costs from lane closures by year.

Average user delay costs ($2019) per incident

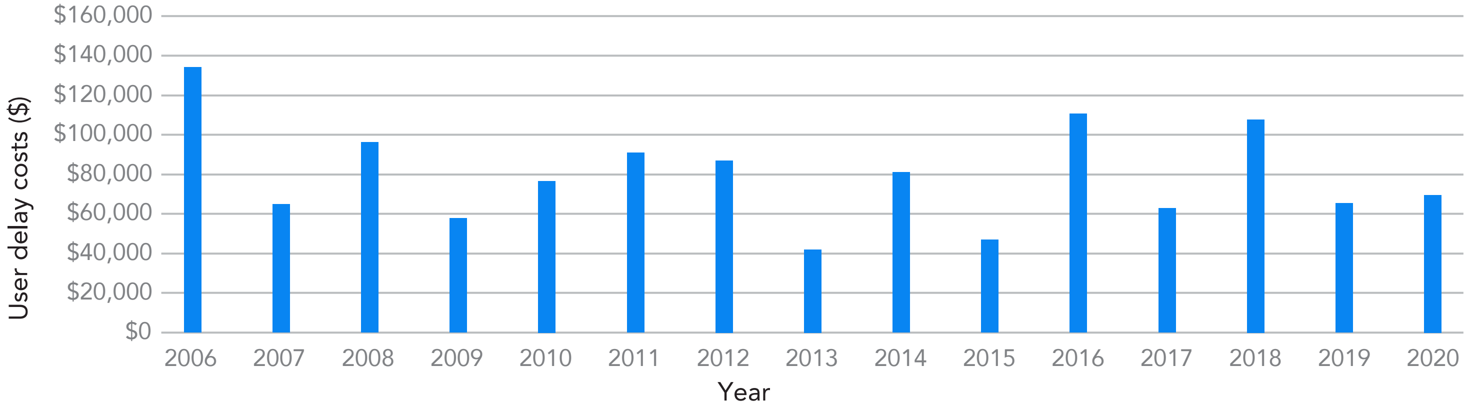

Figure 6. Average user delay costs from lane closures by year.

Total user delay costs were highest in 2011 and 2018. On the other hand, average user delay costs are similar across multiple years including 2006, 2008, 2011, 2012, 2014, 2016, and 2018. The difference between years with the highest total user delay costs and average user delay costs is most likely the number of incidents per year. For example, in 2011 and 2018 there were 462 and 512 incidents respectively, while in 2016 there were only 185 incidents.

5. Several locations appear to be "clusters" with repeated flooding in the past 15 years—and typically longer incident durations than other incidents.

- Over 100 locations demonstrate at least five flood incidents within 1,000 feet of each other (see Figure 7). There are 116 locations with at least five flood incidents within 5,000 feet (see Figure 8).
- Seven locations show at least 30 flood incidents in the past 15 years (see Figure 9).
    - At six of these locations, average incident durations ranged from over 7 to 21 hours, which is longer than in locations with fewer flood incidents or incidents not in a cluster.
- At least nine of the 112 frequent flooding locations with incidents within 1,000 feet of each other appear to have been resolved over time; these locations showed clusters of flooding earlier in the dataset but no flood incidents since at least 2015.[5] For example, one location had 20 flood incidents between 2009 and 2014, but none since.

[5] Upon review of the nine locations, MDOT SHA identified various operational and project-specific activities that likely contributed to the reduction in flood events over time. Among these activities are routine maintenance (e.g., clearing debris out of existing stormwater drainage structures), replacement or rehabilitation of existing structures, and associated roadway improvements.

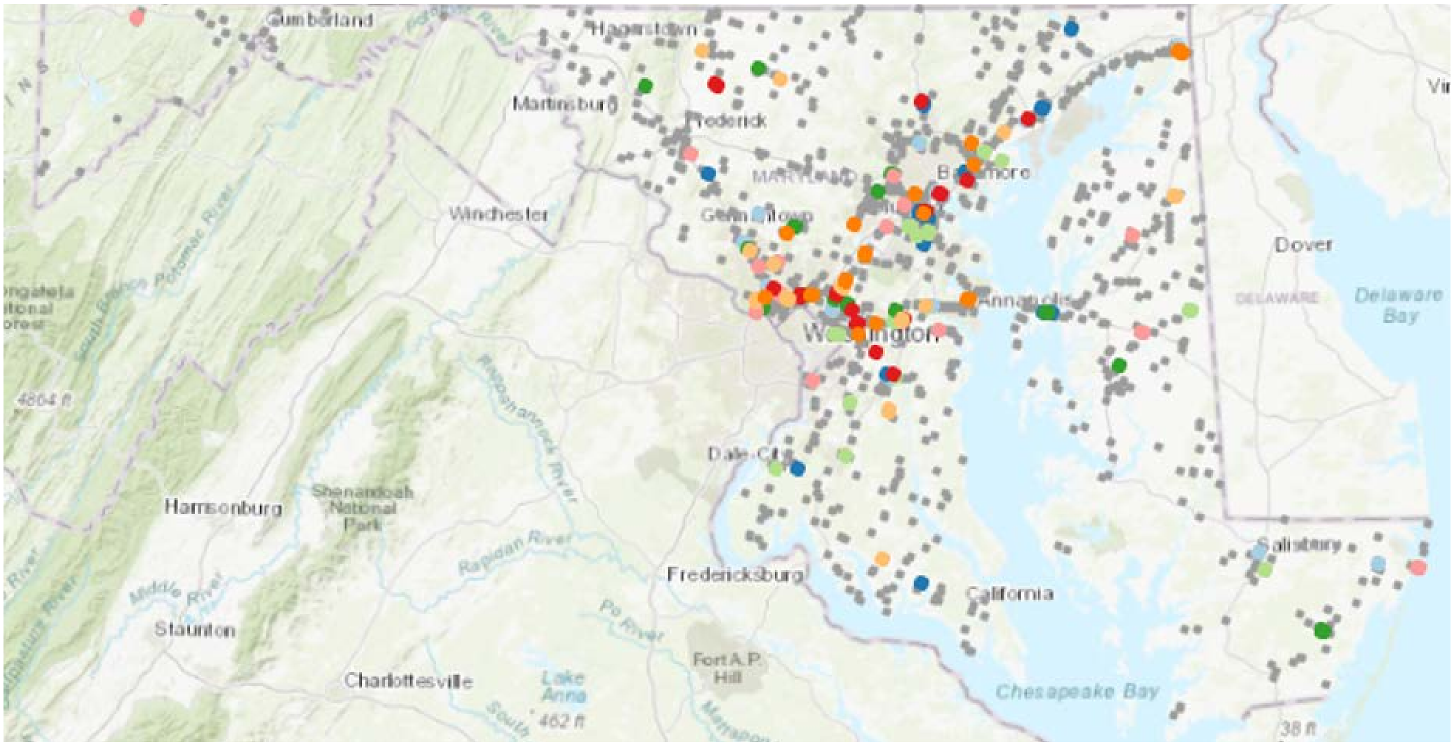

Figure 7. Flood incident clusters indicating locations with at least five events within 1,000 feet of each other. Each individual colored dot represents a single cluster; however, colors repeat. For example, two green dots are separate clusters. Gray dots are incidents that were not grouped within a cluster.

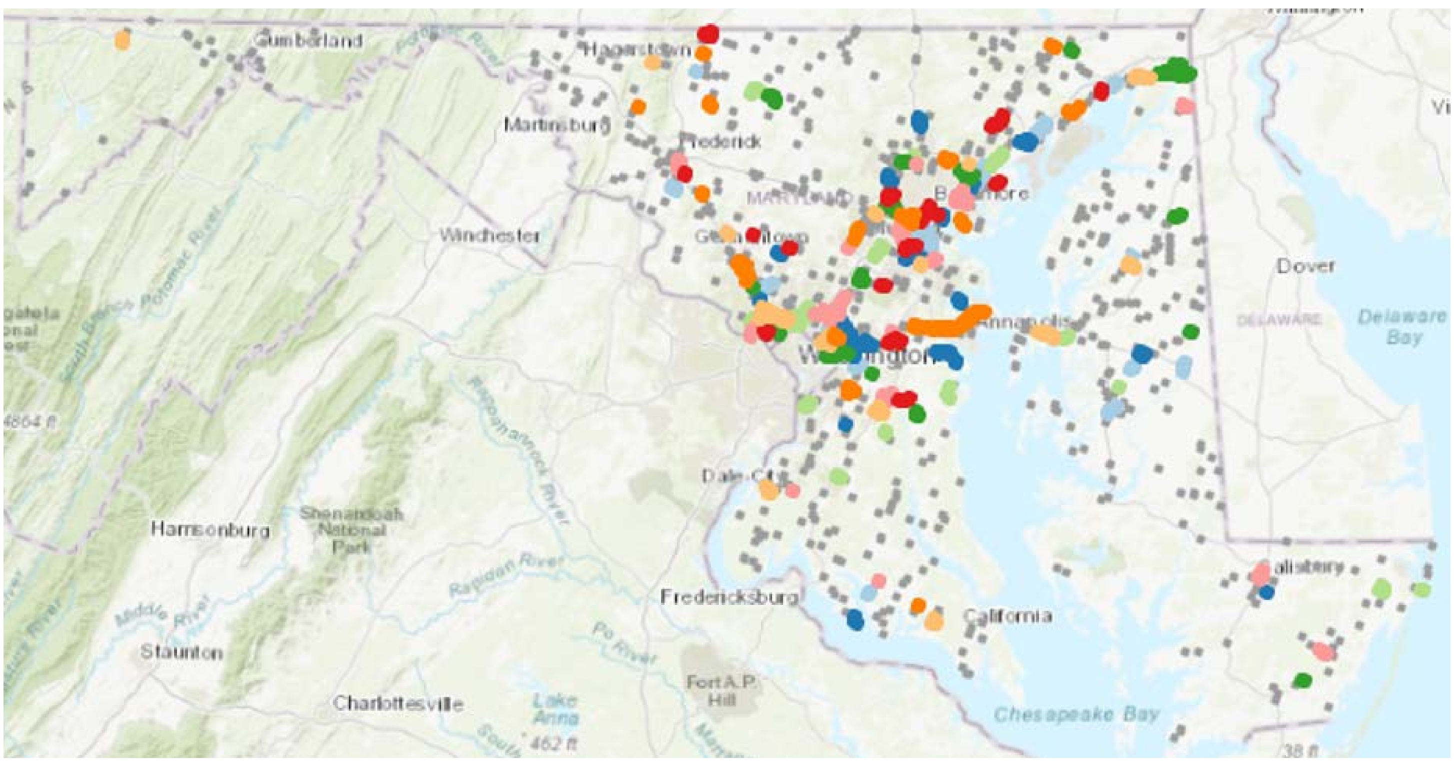

Figure 8: Flood incident clusters indicating locations with at least five events within 5,000 feet of each other. Each individual colored dot represents a single cluster; however, colors repeat. For example, two green dots are separate clusters. Gray dots are incidents that were not grouped within a cluster.

Incidents per flooding location cluster (1,000 ft clusters)

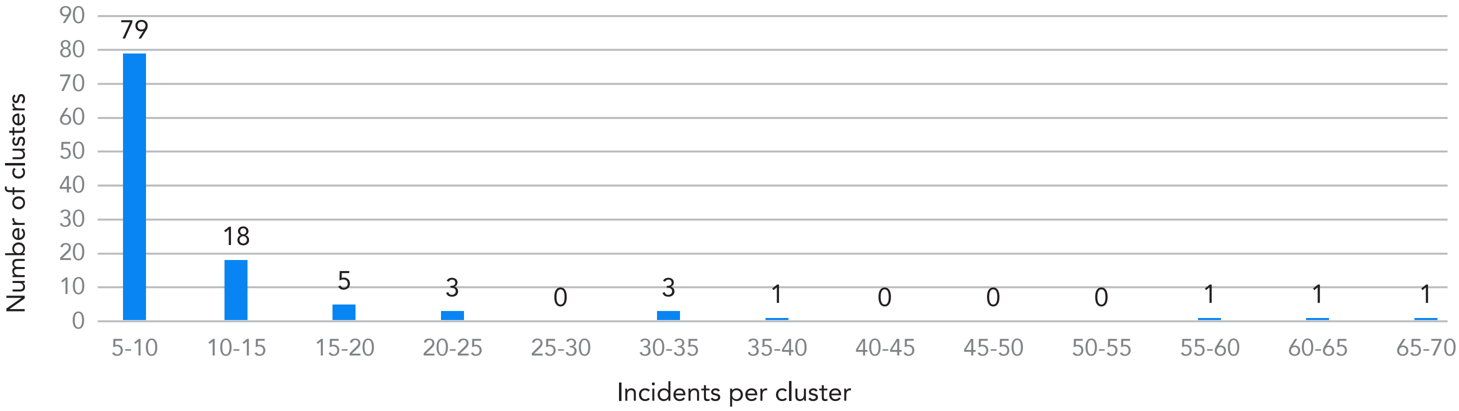

Figure 9: Incidents per flooding location cluster (1000-ft clusters).

6. Nearly 25% of incidents last 8 or more hours.

- Sixty percent of all flood incidents lasted less than four hours in duration and 25% lasted less than one hour (see Table 5). ICF found no clear signals in the data indicating whether event frequency or location (see Figure 10) were associated with longer durations. Longer duration events could be associated with the severity of flooding, extent of damage, capacity of the drainage system, response time, or the length of the precipitation event.

Table 5: Number of incidents by duration (all years).

Incident duration (hrs)	Incidents	Percentage	Cumulative percentage
0 to 0.5	458	16%	16%
0.5 to 1	272	9%	25%
1 to 2	458	16%	40%
2 to 4	569	19%	60%
4 to 8	475	16%	76%
8 to 12	229	8%	84%
12+	486	16%	100%
Total	**2,947**	**100%**	

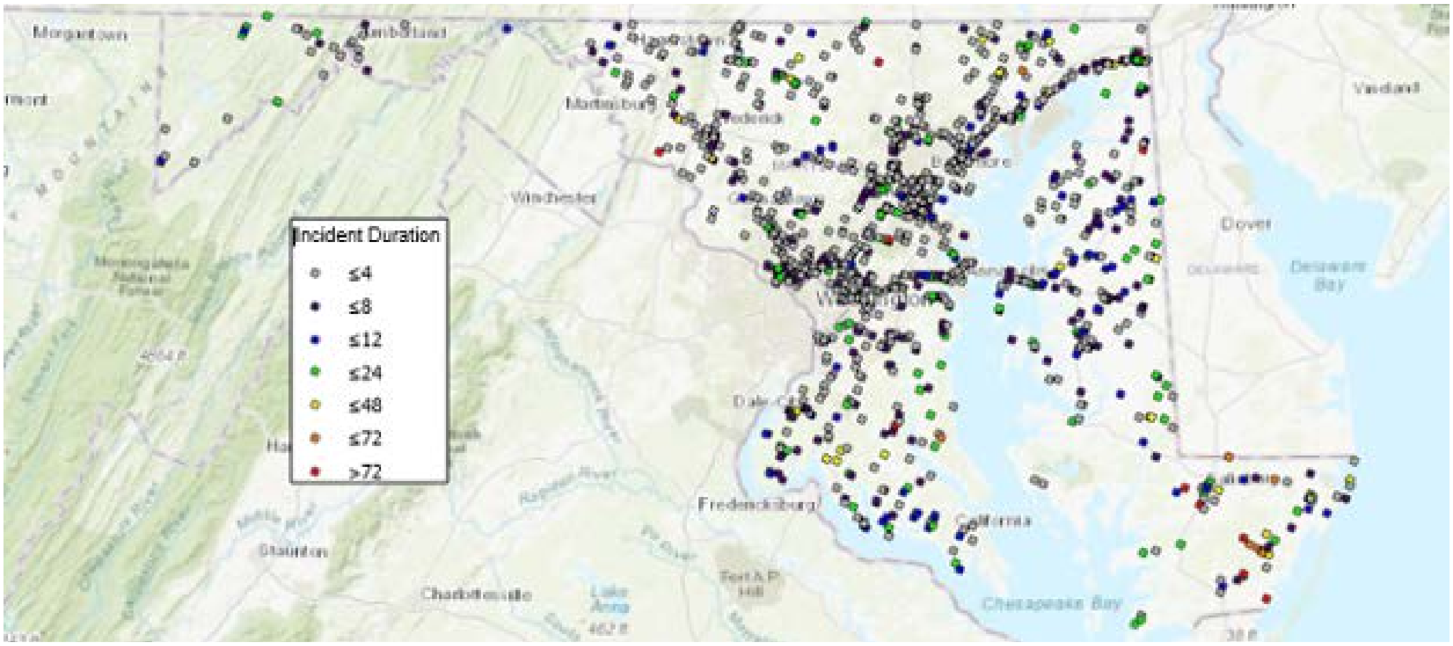

Figure 10: Map of flood incidents by duration.

7. **The greatest number of flooding incidents have occurred in the summer, and in the afternoon and evening.** (See Table 5 and Table 6)
   - In the years with the greatest number of incidents, 2011 and 2018, more incidents occurred between the hours of 12:00 PM to 3:00 PM and 6:00 PM to 9:00 PM. The same trend holds for total incidents (see Table 7).

Table 6: Incidents from 2006 to 2020 by season.

Season	Number of incidents	Percent of total incidents
Winter (DJF)	381	13%
Spring (MAM)	644	22%
Summer (JJA)	1097	37%
Fall (SON)	825	30%
Total	**2,947**	**100.00%**

Table 7: Incidents by time of day.

Time of day	Number of incidents	Percent of total
12:00 AM — 03:00 AM	473	16%
03:00 AM — 06:00 AM	189	6%
06:00 AM — 09:00 AM	315	11%
09:00 AM — 12:00 PM	107	4%
12:00 PM — 3:00 PM	655	22%
03:00 PM — 06:00 PM	456	15%
06:00 PM — 09:00 PM	591	20%
09:00 PM —12:00 AM	161	5%
Total	**2,947**	

Data, methods, and limitations

Flood incident dataset

MDOT SHA logs traffic incident data through CHART. The dataset covers highways that fall under the maintenance responsibility of MDOT SHA, which includes all non-toll, numbered roads. As discussed in the dataset limitations section below, the MDOT SHA highways represent only a portion of the whole roadway network in Maryland.

ICF accessed CHART data through the Regional Integrated Transportation Information System hosted at the University of Maryland. ICF downloaded all recorded "flood incidents" in Maryland from 2006 through August 17, 2020 (inclusive).

According to CHART, a "flood incident" is one that is reported to have blocked a roadway, in whole or in part, due to high water. CHART also collects data of "weather service events." These are another incident type that indicates events where there was water on the roadway (requiring action from CHART such as high water signs or emergency drainage clearance) but the road remained passable. These data were collected but ultimately not used in the analysis.

Reporting in CHART has improved over time since establishment of the reporting system. As such, the number of incidents consistently reported through CHART has increased over time, especially prior to 2012.

The incident data includes the geospatial location (latitude and longitude), location (provided as road names, intersection cross streets, exit numbers, etc.), county, start date, end date, lane closure duration, response time, and the maximum number of lanes closed.

The flood incident dataset totaled 2,947 recorded incidents over the time period of analysis, exclusive of an outlier. ICF removed one outlier incident from the dataset, assumed to be erroneous: the event duration lasted almost three years from June 30, 2012 to June 17, 2015. All but 176 incidents included latitude and longitude coordinates. Most analyses include all 2,947 incidents. Geospatial analyses that depend on incident location include just the 2,771 incidents with latitude and longitude data.

Flood incident dataset limitations

The research team evaluated the scope and magnitude of flooding impacts to the transportation system. The team also analyzed the number of incidents, lane closures, and duration of incidents. In addition, the research team mapped incident locations to identify areas with repeat flooding locations and analyzed incident locations with respect to FEMA floodplains.

However, since the scope of data includes only roads within the maintenance responsibility of MDOT SHA, the analysis excludes: toll roads (e.g., I-95) that are owned and maintained by the Maryland Transportation Authority; roads without a number that are maintained by a county or municipality; and interstates, numbered routes, and local roads within the City of Baltimore that are maintained by the city. This gap in the scope of data is notable, since roadway flooding on some of the busiest routes and in the largest city in Maryland is not captured in the analysis.

Cluster analysis methodology

The cluster analysis used ArcGIS Pro's Find Point Clusters tool to group flood incidents into clusters based on their distance from each other. There are two different point cluster layers: a 1000 feet layer and a 5000 feet layer. Each analysis used the following parameters:

- The default clustering method: the density-based spatial clustering of applications with noise (DBSCAN) method.
- A minimum of five features per cluster.

The difference between the two layers is their search distance parameters (1000 feet and 5000 feet). The 1000 feet cluster layer captures "intersection" level granularity for flood incident clusters whereas the 5000 feet cluster captures "road segment" or "route" based flood incident clusters.

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User delay cost methodology and limitations

The research team also summarized flooding impacts in terms of number of vehicles and people affected by flood incidents. The research team calculated user delays for each flood incident through the following formula[6]:

User delays (person-hours) = Hourly traffic[7] × Closure duration (hours)[8] × Delay per vehicle per hour[9] × Persons per vehicle[10]

Lastly, to monetize user delays into approximate economic costs, the research team utilized average value of passenger time factors through the following formula:

User delay costs = (Automobile user delays × Average cost per person per hour (automobile)[11]) + (Truck user delays × Average cost per person per hour (truck)[12])

The research team recognizes that this is a highly simplified approach. Actual delays will vary based on size of highway, time of day of the incident, traffic patterns, and other factors. The intention of this exercise is simply to illustrate the range and rough order of magnitude of delays that flooding incidents can cause. User delays also only represent a portion of flood-related costs; for example, costs of infrastructure damage from flooding are not captured in this analysis.

Expert external reviews

Expert insight on this report was provided by two external reviewers: Elizabeth Habic, an environmental protection specialist at the Federal Highway Administration of the U.S. Department of Transportation, and Sevgi Erdogan, assistant research professor at the National Center for Smart Growth Research and Education and an affiliate of the Maryland Transportation Institute of the University of Maryland. Neither they nor their organizations necessarily endorse the report findings.

[6] The methodology to calculate user delays was derived from FHWA's methodology to value vehicle occupant's travel time. Source: FHWA. 2015. Appendix A: Highway Investment Analysis Methodology. U.S. Department of Transportation. Available at: https://www.fhwa.dot.gov/policy/2015cpr/appendixa.cfm#_Toc464549618

[7] Hourly traffic is derived from Annual Average Daily Traffic (AADT) and Annual Average Daily Truck Traffic (AADTT) data for the segment. Traffic per hour is calculated as AADT(T)/24. The research team did not use hourly traffic data for each segment since the data were not available. AADT and AADTT data were provided by MDOT SHA.

[8] Closure duration is based on the duration data provided for each incident.

[9] Delay per vehicle per hour is based on an approximate hours of delay per vehicle based on the percentage of lane closures. This was calculated using the formula: Delay (minutes) = 60 minutes × % of lanes closed.

[10] Persons per vehicle is based on a national average vehicle occupancy factor of 1.53 people per automobile and 1.02 people per truck (assuming an average 5+ axle combination truck). Source: FHWA. 2015. Appendix A: Highway Investment Analysis Methodology. U.S. Department of Transportation. Available at: https://www.fhwa.dot.gov/policy/2015cpr/appendixa.cfm#_Toc464549618

[11] $15.60 (in 2019 dollars). Source: FHWA. 2015. Appendix A: Highway Investment Analysis Methodology. U.S. Department of Transportation. Available at: https://www.fhwa.dot.gov/policy/2015cpr/appendixa.cfm#_Toc464549618

[12] $31.17 (in 2019 dollars). Source: FHWA. 2015. Appendix A: Highway Investment Analysis Methodology. U.S. Department of Transportation. Available at: https://www.fhwa.dot.gov/policy/2015cpr/appendixa.cfm#_Toc464549618

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For over a decade, Cassie has helped governments and organizations improve their resilience to climate risks. She develops climate vulnerability assessment techniques and adaptation strategies that feed directly into core decision-making processes, allowing clients to incorporate climate resilience into their day-to-day processes and ultimately to manage climate risks internally. Cassie's work has special application in the infrastructure, transportation systems, and community impact fields, where she has done some of her most innovative projects. For example, she created the industry standard suite of transportation vulnerability assessment tools for the United States Department of Transportation, conducted a first-of-its-kind climate risk assessment for the province of British Columbia, and led a groundbreaking analysis of the business case for resilience investments in Miami Beach, Florida.

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