Change in the Precipitation Parameter Source and its Effect in Previously Designed Structures

Orlando J. Colón Collazo
Master of Engineering in Civil Engineering
Christian A. Villalta Calderón, PhD.
Civil & Environmental Engineering and Land Surveying Department
Polytechnic University of Puerto Rico

Abstract — *The impact of any development brings with it a series of changes to the environment that must be mitigated; thus, Hydrologic and Hydraulic Studies become necessary to bring solution at the design process. The precipitation-frequency is an important factor to be used in this study. The National Weather Service periodically publishes reports that include the occurrence of precipitation in Puerto Rico. Until 2006, the most recent report was Technical Paper TP-42, published in 1961 until it was reviewed, and the new calculation incorporated in Volume 3 of the NOAA Atlas 14. Owing to this change in mind, we have carried out a comparative study of the TP-42 versus NOAA Atlas 14 and its effect on structures such as bridges that were designed under Technical Paper T-42. This study has proven that there is a significant change in the design parameters obtained from HH Studies based on the use of TP-42 versus NOAA Atlas 14.*

Key Terms — *Bridges, Hydraulic, Hydrologic, Precipitation*

INTRODUCTION

Evidence indicates both observational and from model projections, that changes to the climate are taking place. Although the magnitudes of these changes rely on innumerable uncertainties, the fact that our climate is changing is unquestionable. To ensure a functionality of our daily life, it is therefore important to study the potential impacts on infrastructure due to climate change. Considering that bridges have a long service life, it is of direct significance to find out their reliable operation against climate change risks. On 2006, the NWS released the NOAA Atlas 14 Volume 3 substituting the TP-42 as the precipitation-frequency estimate source to conduct a hydrologic study. The primary difference between Atlas 14 and TP-42 is: the inclusion of 54 years of daily precipitation data, and the number of stations included in the analysis.

With that in mind, we gathered a series of HH Studies from the Puerto Rico Highway and Transportation Authority (ACT, for its Spanish Acronym) that were conducted from 1999 to 2006, and used them to compare the impact in flow using the new precipitation data obtained from the NOAA Atlas 14 Volume 3. Then, we selected two cases to perform a hydraulics analysis to find the change in elevation and velocities at the bridge section previously designed.

JUSTIFICATION

The change in the precipitation source from TP-42 to NOAA Atlas 14 Volume 3 and the climatic change observation and prediction induced the motivation to develop the study of change in the precipitation parameter source and its effect in structures previously designed, as well as the motivation to improve the safety and the wellbeing of the population and determine ways to improve and create a more resilient Puerto Rico.

LITERATURE REVIEW

In conformance with the engineering, Hydrologic and Hydraulic Study is the study of movement of water, including the volume and rate of flow as it moves through a watershed, basin, channel, or man-made structure. HH studies are completed to ensure that the hydraulics structures have the proper dimensions to handle floodwaters. The studies are performed to quantify the volume flow rate of water draining from a watershed and determine the depth and velocity of flow and forces from flowing water on a surface or at hydraulic structures.

The hydrologic part of a HH Study is an important field of study that rely on the called hydrologic cycle or water cycle. Hydrology is defined as the quantification of flow that is produce by precipitation. The precipitation is being studied for decades and in 1961, the Soil Conservation Services in cooperation with Weather Bureau release the Generalized Estimate of Probable Maximum Precipitation and Rainfall-Frequency Data for Puerto Rico and Virgin Islands called Technical Paper 42 (TP-42). This report present rainfall data for various hydrologic design involving areas up to 400 square miles and rainfall durations up to 24 hours. Included in the report are generalized estimates of probable maximum precipitation (PMP) from the cloudburst and from hurricanes, and rainfall intensity-frequency data for return periods from 1 to 100 years [1].

On 2006, the National Oceanic and Atmospheric Administration (NOAA) released the NOAA Atlas 14 Volume 3, Precipitation-Frequency Atlas of the United States, Puerto Rico and the US Virgin Islands. NOAA Atlas 14 Volume 3 contains precipitation frequency estimates for Puerto Rico and the U.S. Virgin Islands. The Atlas supersedes precipitation frequency estimates contained in Technical Paper No. 42 “Generalized estimates of probable maximum precipitation and rainfall-frequency data for Puerto Rico and Virgin Islands” and Technical Paper No. 53 “Two- to ten-day rainfall for return periods of 2 to 100 years in Puerto Rico and Virgin Islands.” The updates are based on more recent and extended data sets, currently accepted statistical approaches, and improved spatial interpolation and mapping techniques [2]. NOAA Atlas 14 Volume 3 precipitation frequency estimates for Puerto Rico and the U.S. Virgin Islands are available via the Precipitation Frequency Data Server at http://hdsc.nws.noaa.gov/hdsc/pfds which provides the additional ability to download digital files.

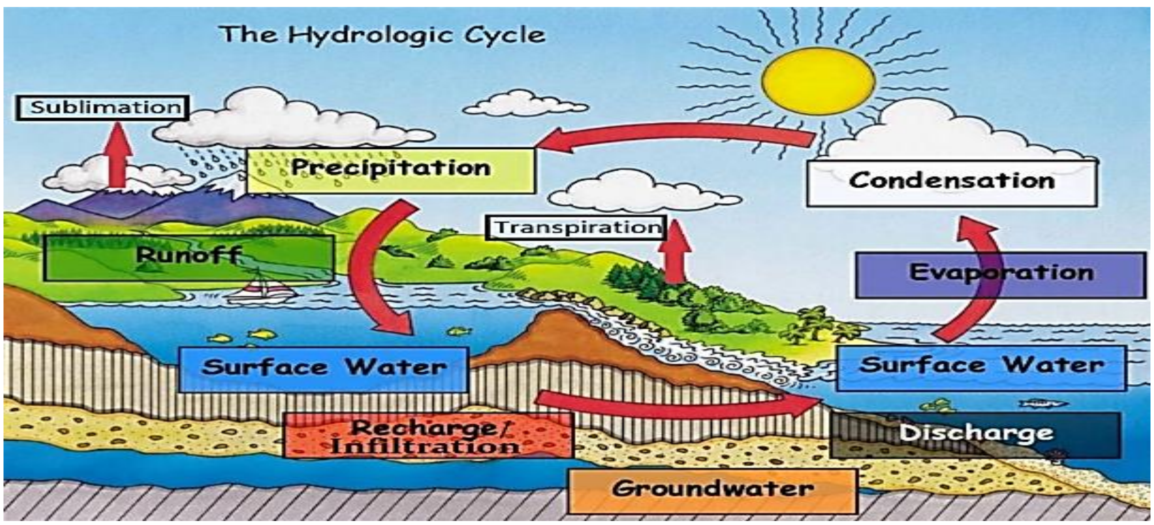

Figure 1: Hydrologic Cycle

The NOAA Atlas 14 Volume 3 brought with it the inclusion of the most recent 54 years of daily precipitation, and the number of stations included in the analisis. Without doubt, all storm precipitation has increased in depth compared to those on the TP-42.

On the other hand, climate change and the discussion on the news and other world organizations as a potential impact to public structures; on the article: “A review of the potential impact of climate change on the safety and performance of bridges,” the authors relate the projected increase in precipitation with 18 directly risk to bridges, and seems to be the most attention-worthy climatic parameter [3].

Having in mind the change to the new NOAA Atlas 14 Volume 3 and climate change, it seems to be necessary to perform a research and a study of the change in the precipitation parameter source, and it effect in structures previously designed.

METHODOLOGY

Hydrologic and Hydraulic Studies are an essential study to establish the flood hazards and mitigate against flood loss in the future. HH Study is divided into hydrology and hydraulics. Some aspect of hydrology involves hydraulics.

Hydrology is defined as the quantification of the flow that is produced by precipitation combined with evaporation, infiltration, surface runoff, among others. In terms of stormwater engineering, hydrology refers to the rate of precipitation, amount of water, surface runoff and time of concentration. For this research, the hydrologic modeling was performed using the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS). The HEC-HMS is designed to simulate the complete hydrologic processes of watershed systems. The software includes many traditional hydrologic analysis procedures [4]. Using a Type 2 hypothetical storm, Curve Number (CN) as a loss method, a Unit Hydrograph and the area, each basin was modeled to obtain the peak discharge (Q). This data was obtained using the gathered information from HH Studies provided by the ACT. Each HH Study was reviewed and the information needed was collected to model the watershed using the precipitation obtained from the TP-42 (the one used in the original study) and NOAA Atlas 14 Volume 3.

In contrast, hydraulics is defined as the study of the mechanical behavior of water in a physical system. In engineering terms, is the analysis of how surface flows move from one point to the next. Hydraulics analysis is used to evaluate flow in rivers, streams, storm drain, water aqueducts, among other. For this research, the hydraulics modeling was performed using the Hydrologic Engineering Center's River Analysis System (HEC-RAS). This software allows the user to perform one-dimensional steady flow, one and two-dimensional unsteady flow calculations, sediment transport, movable bed computations, and water temperature/water quality modeling [5]. Using the HEC-RAS models created by the Federal Emergency Management Agency (FEMA) and creating two new flow profiles for the 100 year 24 hours precipitation, one for the precipitation values obtained from the TP-42 and one for the NOAA Atlas 14. The modeling provided information about the water surface elevation and channel velocities for the study area, which were used to compare both precipitation frequency estimates in terms of water surface elevation and velocities.

CASE STUDIES

Hydrological modeling

Ten hydrologic and hydraulic studies were selected in order to compare the peak flow generated using the TP-42 precipitation-frequency and NOAA Atlas 14 Volume 3 precipitation-frequency. The basins considered on each study were analyzed by HEC-HMS. For each study the area, curve number, and time of concentration were gathered, and input into the HEC-HMS modeling software. For each case, the modeling was run using both the 100 years 24 hours TP-42 precipitation depth and the 100 years 24 hours Atlas 14 precipitation depth. The results from this series of modeling are detailed on table 1. As the original software used to run the modeling on the study were no necessary available to run the model, the peak discharge was not used on the comparison but it is included on the table as Q HH.

As it can be seen, the difference in peak flow goes from 8.56% to 84%. Clearly, the precipitation on Atlas 14 for all storm event's definitions have increased in depth as figure 2 shows, consequently, the peak discharge has increased too.

Table 1
HEC-HMS Modeling Results

HH Study ATC	TP-42 100/24	NOAA Atlas 14 100/24	Basin	Q HH (CMS)	Q TP-42 HMS (CMS)	Q Atlas HMS (CMS)	Dif %
AC-012201	13	16.3	1	841.973	771.7	973.3	26.12%
AC-086112	11	13.4	1	130.00	146.10	191.40	31.01%
AC-000019	10	11.6	1	1174.1	1199	1360.8	13.49%
Ac-000093	11	13.4	1	87.00	90.00	115.00	27.78%
AC-00132	11	14.6	1	636	558.4	804.1	44.00%
AC-00661	13.88	16	1	12.12	35.60	41.80	17.42%
AC-003069	12	15.5	1	453	443.5	598.1	34.86%
AC-005319	12.5	16.3	1	325.22	718.20	978.30	36.22%
AC-010250	11.5	15.6	1	144.642	134.9	192.9	42.99%
	11.5	16	2	182.445	172.6	265.2	53.65%
	11.5	16	3	155.346	140.4	200.8	43.02%
AC-010925	9.3	15.1	1	137.34	110.60	203.50	84.00%
	9.3	10.7	2	99.22	100.70	119.60	18.77%
	9.3	9.95	3	58.47	56.10	60.90	8.56%

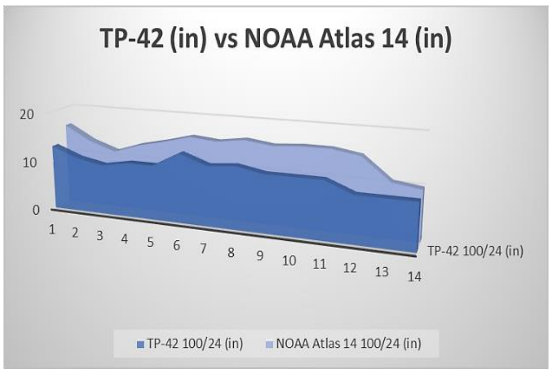

Figure 2
Precipitation Depth TP-42 vs Atlas 14

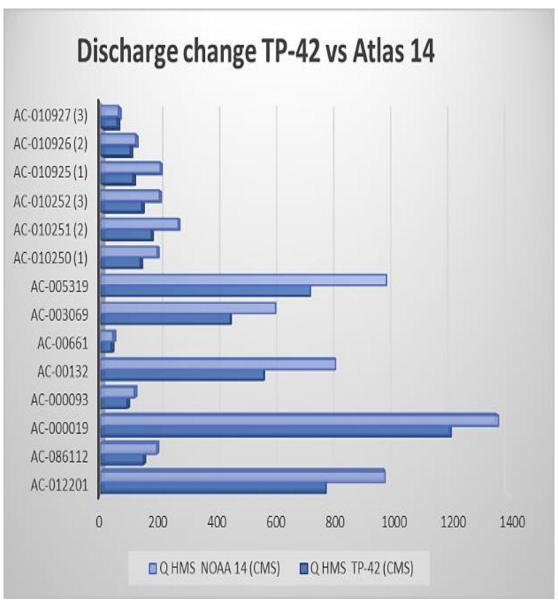

Figure 3
Discharge change TP-42 vs Atlas 14

Figure 3 shows the difference between the TP-42 and Atlas 14, in terms of peak flow generated by those

Hydraulic Modeling

From the ten hydrological cases modeled, two case studies were selected to perform a hydraulics modeling. The H-H Study (AC-010250) for Replacement Bridge at PR-102 at Mayagüez, performed on April 2004, and the H-H Study (AC-00132) for New Bridge Parallel to Road PR-1 at Guaynabo, performed on April 2002, were the selected ones.

Using the peak discharge generated by the HEC-HMS modeling for both precipitation depth sources (TP-42 and Atlas 14), a hydraulic modeling analysis was performed in HEC-RAS using the FEMA models for the rivers in both cases. As with the hydrology modeling, the original software used to run the modeling on the study were no necessary available to run the model, the elevation, and velocities used to design the structures were used on the comparison and these results are included on the tables as W.S. Elev Design and Vel Chnl Design respectively.

Case Study 1: The H-H Study (AC-010250) for Replacement Bridge at PR-102

The modeling results obtained from the HEC-RAS modeling are show on table 2. The water surface elevation as well as the channel velocities were tabulated both before and after the bridge.

Table 2
Hec-Ras Modeling Results Case Study 1

Replacment Bridge at PR 102	River Sta	Profile	Q Total (cfs)	Min Ch El (ft)	W.S. Elev (ft)	W.S. Elev (m)	W.S. Elev Design (m)	Vel Chnl (ft/s)	Vel Chnl Design (ft/s)
	Before Bridge	TP-42 HMS	15817.45	0.71	15.41	4.70	4.02	6.99	5.58
		Atlas 14 HMS	23268.86	0.71	18.68	5.69		8.1	
	Bridge								
	After Bridge	TP-42 HMS	15817.45	0.69	9.65	2.94	3.16	14.4	12.04
		Atlas 14 HMS	23268.86	0.69	12.36	3.77		14.92	

From HH Study, the bridge was designed with the elevation of 4.02 meters before bridge and 3.16 meters after bridge as the water surface elevation design parameters. Using the new peak discharge generated by the HEC-HMS both the TP-42 and the Atlas 14, elevations results are 4.70 and 5.69 before bridge and 2.94 and 3.77, respectively. The Figure 4 show a contrast of the elevations on perspective for the design, the TP-42, and the Atlas 14 elevations. The elevation was significative increased compared to the design parameter used.

As for the channel velocities, an increase on the velocities were heavily noticed as shown on figure 5.

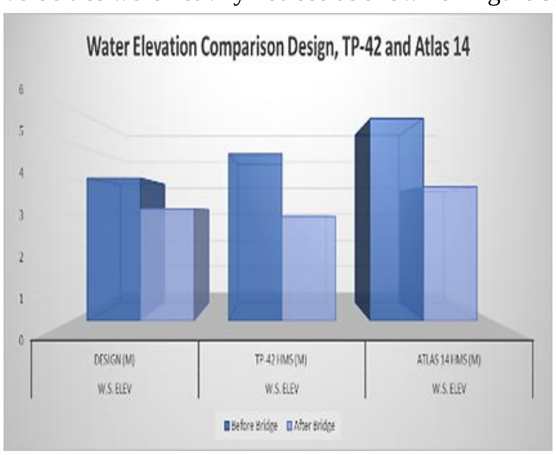

Figure 4
Water Surface Elevation Design, TP-42 and Atlas 14 for Case Study 1

As for the channel velocities, an increase on the velocities were heavily notice as show on the figure 5.

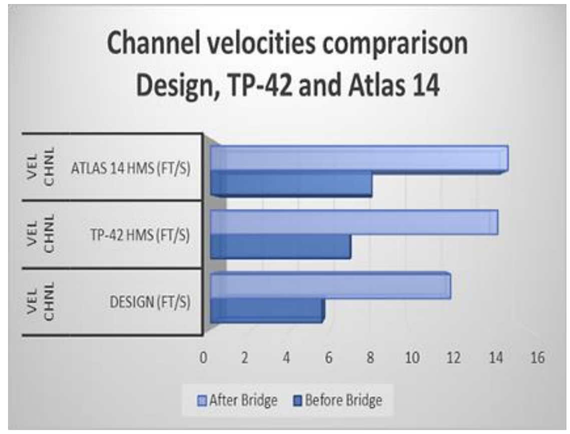

Figure 5
Channel Velocities: Design, TP-42, Atlas 14 for Case Study 1

Case Study 2: H-H Study (AC-00132) for New Bridge Parallel to Road PR-1

Table 3 shows the results obtained from the HEC-RAS modeling for case 2. The water surface elevation as well as the channel velocities were tabulated both before and after the bridge.

Table 3
Hec-Ras Modeling Results Case Study 1

New Bridge PR 1 La Muda	River Sta	Profile	Q Total (cfs)	Min Ch El (ft)	W.S. Elev (ft)	W.S. Elev (m)	W.S. Elev Design (m)	Vel Chnl (ft/s)	Vel Chnl Design (ft/s)
	Before Bridge	TP-42 HMS	19719.73	222.95	245.52	74.83	74.75	9.72	8.99
		Atlas 14 HMS	28396.55	222.95	249.86	76.16		10.72	
	Bridge								
	After Bridge	TP-42 HMS	19719.73	221.26	244.71	74.59	74.66	9.29	7.45
		Atlas 14 HMS	28396.55	221.26	249.07	75.92		10.09	

From HH Study, the bridge was design with the elevation of 74.75 meters before bridge and 74.66 meters after bridge as the water surface elevation design parameters. Using the new peak discharge generated by the HEC-HMS both the TP-42 and the Atlas 14 elevation results are 74.83 and 76.16 before bridge and 74.59 and 75.92, respectively. The Figure 6 shows a contrast of the elevation on perspective for the design, the TP-42, and the Atlas 14 elevations. As with case 1, the elevation was significantly increased compared to the design parameter used.

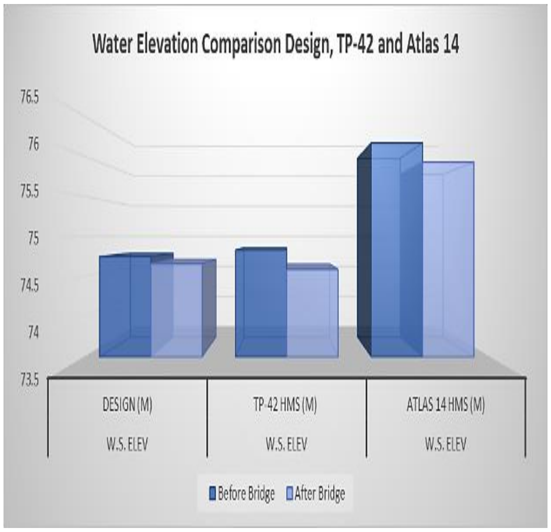

Figure 6
Water Surface Elevation Design, TP-42 and Atlas 14 for Case Study 2

Channel velocities, as it was expected, increased too, both before and after the bridge. Figure 7 shows the velocities on perspective.

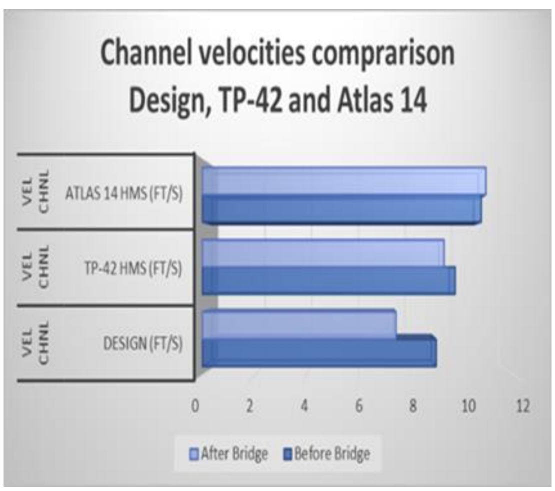

Figure 7
Channel Velocities: Design, TP-42, Atlas 14 for Case Study 2

Conclusions and Future Work

The National Weather Services (NWS) NOAA Atlas 3 Volume 14 replacing the Technical Paper 42 on 2006 was without doubt a huge change in terms of hydrology. Including the most recent 54 years of precipitation data and incrementing the numbers of stations included in the analysis bring with it more precise precipitation depth data easily to obtain from a website. The fact that all storm events definitions have increased in depth, open the window to an imperative need for the creation of a system to review the public structures designed under the Technical Paper 42.

Structures such as bridges and culvert are designed for a long period of service and this research has proven that the lifespan has been reduced or, in the worst case, they did not comply with the code, even for the time in which they were designed. Bridges and culverts have been designed assuming stationarity in rainfall records, meaning that there will be no significant changes in rainfall intensities. The evidence that the climate is changing, and the fact that this issue will result in different rainfall intensities and patterns suggested that is time to incorporate a dynamic precipitation analysis on the hydrologic studies and structure design or at least use our engineering judgment into designs to balance risk across a structure’s lifespan, meaning a more resilient study and design.

Despite the fact that this study has shown that there is a change in the water surface flow and elevation, affecting the safety and lifespan of structures, it is essential to review other parameters such as scour and other studies on structures, which combined to change in flow and elevation of the surface water, can derive on a reduced lifespan of structures.

References

[1] Cooperative Studies Section Hydrologic Services Division U.S. Weather Bureau, “Technical Paper No. 42. Generalized Estimates of Probable Maximum Precipitation and Rainfall-Frequency Data for Puerto Rico and Virgin Islands for Areas to 400 Square MIles, Durations to 24 Hours, and Return Periods from 1 to 100 Years,” US Dept. Of Commerce, Washington, D.C. Technical Paper No. 42., 1961. [Online] Available: https://www.nws.noaa.gov/oh/hdsc/Technical_papers/TP42.pdf

[2] G. M. Bonnin,, D. Martin, B. Lin, T. Parzybok, M. Yekta, D. Riley; “Precipitation-Frequency Atlas of the United States. Volume 3 Version 4.0: Puerto Rico and the U.S. Virgin Islands,” US Dept. Of Commerce, et al, Silver Spring, Maryland, NOAA Atlas 14, 2008.

[Online] Available: https://www.nws.noaa.gov/oh/hdsc/PF_documents/Atlas14_Volume3.pdf

[3] Nasr, A., Björnsson, I., Honfi, D., Ivanov, O. L., Johansson, J., & Kjellström, E., “A review of the potential impacts of climate change on the safety and performance of bridges,” *Sustainable and Resilient Infrastructure*, 2019. [Online] Available: doi: 10.1080/23789689.2019.1593003

[4] *Hydrologic Modeling System HEC-HMS User’s Manual*, Version 3.5, US Army Corps of Engineers, Davis, CA, 2010. [Online] Available: https://www.hec.usace.army.mil/software/hec-hms/documentation/HEC-HMS_Users_Manual_3.5.pdf

[5] *HEC-RAS River Analysis System Hydraulic Reference Manual*, Version 5.0, US Army Corps of Engineers, Davis, CA, 2016. [Online] Available: http://www.hec.usace.army.mil/software/hec-ras/documentation/HEC-RAS%205.0%20Reference%20Manual.pdf.