

Vertical Datum Used for Flood Mapping in Puerto Rico An Application in the Bayamon River Basin

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Abstract — *Inconsistencies in the use of different datums used for the creation of the Bayamón River basin flood maps force some land surveyors, cartographers, and other professionals working with flood maps, to use the USGS MSL of 1927 datum, while others use the NGS PRVD 02 datum as a vertical reference surface. The objective of this study is to explain the current situation in addition to promote a better understanding of which vertical datum should be used when working with the flood maps of the Bayamón River basin. A methodology is established that could aid the professionals working with the current FEMA flood maps in the Bayamón River basin.*

Key Terms — *Datum, flood insurance rate map, flood insurance study, mean sea level.*

BACKGROUND

A precise vertical reference surface is needed to creation and use flood maps. The vertical reference surface, which is also known as a vertical datum, is essential for infrastructure design, flood prevention, mitigation, and insurance purposes in flood plain areas. In order to research floodways, design infrastructure and develop land, surveyors, land planners, cartographers, and other professionals use the elevation of a benchmark, which is referenced to a specific datum.

Vertical datums in Puerto Rico are referred to the mean sea level, which is the height of the oceans water level, registered and averaged over long periods of time, using tide gauges (mareographs.) [4]

The mean sea level at each tide gauge changes over time according to different tidal epochs. In Puerto Rico there are 2 main official government

datums, each created at a different time using a different tidal epoch. The datums are:

- Mean Sea Level of 1927 (MSL of 1927) datum created by the United States Geological Survey (USGS).
- Puerto Rico Vertical Datum of 2002 (PRVD 02) created by the National Geodetic Survey (NGS) and the government of Puerto Rico.

Interviewed land surveyors agree that the difference in elevations between these datums is somewhere from 15 to 30 centimeters. This means that using the wrong vertical datum when working with flood related elevations could place a property in the wrong flood hazard area, at times forcing the property owners to pay flood insurance, higher insurance premiums or potentially endanger their lives.

The Flood Insurance Rate Maps (FIRMS) are the official maps of a community on which the Federal Emergency Management Agency (FEMA) has delineated both the special hazard areas and the risk premium zones applicable to the community. The FIRMS contain the base flood elevations of the Flood Insurance Study (FIS) which present flood risk data for specific watercourses, lakes, and coastal flood hazard areas within a community. The current flood map for the Bayamón River basin is the 2009 FEMA FIRM. This map refers to the NGS benchmarks which are on the PRVD 02 datum and state the vertical datum of the map to be the mean sea level.

It should be noted that both datums, the MSL of 1927 and the PRVD 02, are referred to as a “mean sea level”. The difference is the tidal epoch of the mean sea level. The MSL of 1927 datum is referred to the mean sea level of the 1927 tidal

epoch. The PRVD02 datum is referred to the mean sea level of the to the 2001 tidal epoch. This means these datums are different and would provide a different elevation on the same point.

The FIS for the community in Bayamón, states that new studies were done for the 2005 revision of the FEMA flood maps. The restudy area was the stream by detailed methods, from PR-2 to the river mouth, approximately 0.25 kilometer upstream towards PR Highway 824. The data for the study was obtained from field surveys and 7.5-minute USGS quadrangle maps. The hydrologic and hydraulic analyses from the data obtained in the field surveys were completed in 1999. [1]

The 2009 FEMA FIRM references the PRVD02 datum, but contrary to this, FIS for the 2009 FEMA FIRM references the USGS quadrangles as a source of data. The USGS quadrangle maps were created on the MSL of 1927 datum. Referencing different datums on the same map is the main cause of confusion when working with the flood maps of the Bayamón River basin.

The PRVD02 datum and its geoid model were completed in 2012. It is therefore probable that it was not used for the FEMA flood studies which concluded in 1999. The FIS and FEMA flood studies appear to have been developed on the USGS Mean Sea Level Benchmarks of 1927.

REVIEW OF LITERATURE

The literature related to vertical datums in Puerto Rico was mostly published by United States Federal Government agencies such as the National Geodetic Survey (NGS), the Federal Register, Federal Emergency Management Administration (FEMA,) and the United States Geologic Survey (USGS).

The research of the events related to the creation of Flood Maps is crucial to determine which vertical datums were available when the flood maps were made.

- **National Geodetic Survey:** one of the authors that have published the most information regarding Puerto Rico vertical datums is David

Doyle, a retired Senior Geodesist for the NGS. His paper “Development of a Comprehensive Vertical Geodetic Datum and Control Network for Puerto Rico”, the author gives us a historical background of the vertical datums in Puerto Rico. David Doyle was the project manager of the Puerto Rico Vertical Datum of 2012. [2]

- **The Federal Register:** is a repository of substantive actions carried out by the executive branch and Congress of the United States of America. The Federal Register published on Monday, July 23, 2012 the announcement of the decision of the NGS to acknowledge the Puerto Rico Vertical Datum of 2002 (PRVD02) as the official civilian vertical datum for surveying and mapping activities for the islands of the Commonwealth of Puerto Rico, which include Culebra, Mona, and Vieques. [3]
- **Federal Emergency Management Administration:** the study for the flood maps of the Bayamón River basin is compiled in a series of five papers called Flood Insurance Study (FIS), Commonwealth of Puerto Rico and Municipalities. These documents contain some technical information about the flood studies used for the flood maps and the river profiles of the major rivers of Puerto Rico. We obtained the dates when the flood studies were made and the source of the data used from the FIS.
- **United States Geologic Survey:** the only available official published source found for the Puerto Rico Mean Sea Level datum is the 1978 publication by the USGS called, “Mean Sea Level Datum of 1927.” These documents were written by the USGS in an effort to find the benchmarks and republish the data for the 1927 Mean Sea Level Benchmarks. This was the last official published documents regarding the USGS 1927 Mean Sea Level Datum.

There are currently two federal agencies creating flood maps of the Bayamón River basin;

FEMA and USGS. The USGS flood maps for the Bayamón River basin show the extents of floods in a particular event. The FEMA FIRM maps show the flood hazard and its related elevations.

EXPERIMENT

Objectives

The object of this study is to clarify the vertical datum used in the flood maps of the Bayamón River basin and make recommendations to professionals working with the current FEMA flood maps of the Bayamón River basin.

In order to know which datum to work with when using the FEMA Flood maps of the Bayamón River basin a timeline will be created. The timeline will be created using information from the relevant literature reviewed, as well as the available FEMA and USGS maps. The object of this first phase of the study is to develop an estimation of what is the correct vertical datum for the flood map of the Bayamón River basin.

The second objective is to develop and test a methodology that allows land surveyors to use dual frequency GPS to certify elevations in Bayamón for FEMA.

Methodology

1. Obtain relevant published information regarding the Bayamón River basin floods. The main sources of information are FEMA, USGS, and NGS.
2. Create a timeline which shows the creation of vertical datums in Puerto Rico and the FEMA FIRM.
3. Find the benchmarks used for the Flood Insurance Study. The main sources are FEMA and USGS.
4. Measure the difference between the currently published NGS vertical datum (PRVD 02) and the datum used for the flood maps. The measurements will be obtained using differential leveling and/or GPS observation.
5. Make recommendations to those using the flood maps and their elevations.

Timeline

The timeline shows the dates of significant events regarding FEMA FIRM vertical datums used in Puerto Rico.

In the timeline we can see that the Hydrologic and Hydraulic (HH) analyses that are used to determine flood elevations for the 2005 FEMA FIRM were finalized in 1999. Previously, the only vertical datum available was the MSL of 1927. [1]

The work of placing benchmarks for the PRVD 02 datum began in 2002 and was made official on 2012. It is therefore not likely that the 2005 FEMA FIRM is in the PRVD02 datum, rather in the MSL of 1927 datum.

Figure 1
Timeline of Significant Events

1 9 2 ~	<p>MSL 1927 USGS creates mean sea level datum. Benchmarks used in this study dated 1941.</p>
1 9 9 ^	<p>HH Analysis for FEMA FIRM flood maps Hydrologic and hydraulic analyses for the 2005 FEMA Flood Map finished in 1999.</p>
2 0 0 ^	<p>PRVD 02 project begins The NGS began setting benchmarks for the PRVD 02. Benchmarks in Bayamon County were published in 2003.</p>
2 0 0 ~	<p>2005 FEMA FIRM flood map FEMA published a revised map on April 19, 2005. This map was created with the analyses which ended on 1999.</p>
2 0 0 ^	<p>2009 FEMA FIRM flood map FEMA published a revised map and FIS on November 18, 2009. The same map as the 2005, but with different benchmarks.</p>
2 0 1 ~	<p>PRVD 02 & Geoid 12A Federal Register announces the NGS decision to acknowledge the PRVD02 vertical datum. The NGS announced the release of a geoid model for Puerto Rico</p>

USGS BENCHMARKS

The benchmarks in the MSL datum of 1927 were installed by the USGS and are shown on the USGS 7.5 Minute Series Topographic Quadrangles. Of the benchmarks found in these quadrangles 24 benchmark sites were identified and visited. Only 3 benchmarks were recovered. Of those benchmarks that were found two are brass disks and one is a chisel square. According to our recovery effort sample, nearly 88% of the original benchmarks belonging to the MSL of 1927 no longer exist.

A second group of benchmarks which are not part of the original MSL of 1927 benchmarks were also recovered. These were installed by both the USGS and private contractors and were used for the USGS for the Investigations Report of the flood of September 10, 1996 in Bayamón, Puerto Rico. These benchmarks are reported by the USGS to be in the Mean Sea Level Datum and not part of the original level run of the MSL of 1927 and therefore are less accurate.

ANALYSIS TECHNIQUES

A Leica SR5330 Dual Frequency Geodetic GPS receiver, LEICA 502 Dual Frequency Geodetic Antenna and a two meter fixed height tripod unit was used for static observation on benchmarks found. In some cases the location of the benchmarks found was not suitable for GPS observation. An offset benchmark was set in these unsuitable locations and the difference in elevation was measured using a Leica Sprinter digital level. Although the level used is not of geodetic precision, the distance leveled was short, which has a low margin of error.

The raw data gathered by the GPS receiver was converted to RINEX (Receiver Independent Exchange) format using Leica Ski Pro software. The raw data in RINEX format was processed using the Online Positioning Service (OPUS.)

Opus is a service offered by the NGS which provides access to high accuracy National Spatial Reference System (NSRS) coordinates and is used to process and adjusts GPS observations.

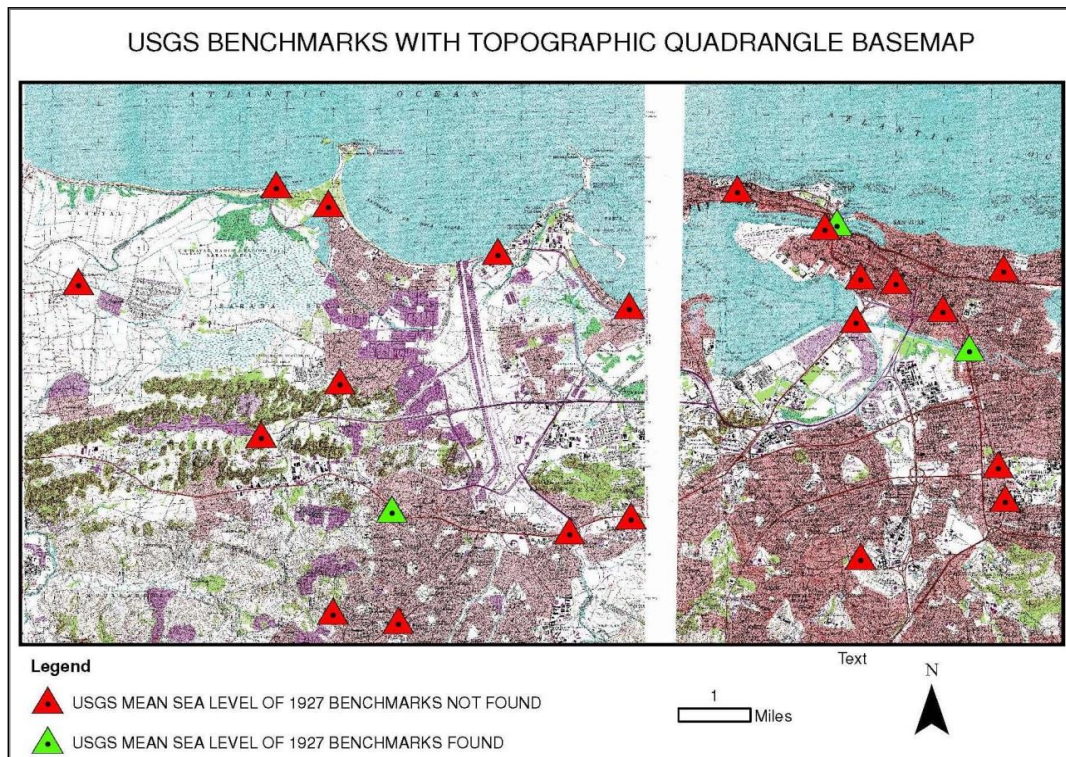


Figure 2
Map of Benchmarks Found

The OPUS solution provides elevations in the PRVD 02 datum with centimeter accuracy when appropriate GPS observation sites are chosen, enough observation time allowed and GPS reference stations are within tolerable range.

Table 2
GPS Observation Results

<i>Mean Sea Level of 1927 Datum Benchmarks</i>				
Name	1927 MLS Elev.	OPUS RMS	PRVD02 Elev.	Difference
31 R 1939	4.395			
Offset point	2.912	0.019	2.702	0.21
Chisel Square	3.85			
Offset point	3.408	0.019	3.187	0.221
7 JIB 1954	45.62			
Offset point	45.79	0.027	45.548	0.243
<i>Benchmarks Used by the USGS, Flood of September 10, 1996 in the MSL of 1927 Datum</i>				
Name	1927 MLS Elev.	OPUS RMS	PRVD02 Elev.	Difference
RM 4	16.42	0.018	16.069	0.351
RM 7	25.25			
Offset	26.62	0.401	26.497	0.121

RESULTS

A comparison was made between the elevation of the benchmarks of the MSL of 1927 datum and the elevation of that same benchmark in the PRVD 02 datum. The elevation of the benchmark in the PRVD 02 datum was obtained by GPS observation and processing the GPS data using OPUS.

The results obtained from the GPS measurements on the original MSL of 1927 benchmarks show that difference in elevation between these datums is approximately 22 centimeters with a standard deviation of 1.7 centimeters. The elevation of the MSL of 1927 is

greater than the elevation of the PRVD02. RMS values for the GPS observations are lower than 3 centimeters for the GPS observation and therefore suitable according to FEMA Certifications. FEMA allows for a vertical precision of less than 10 centimeters in Puerto Rico for their certifications.

The second set of benchmarks measured was placed by both the USGS and private contractors and were used by the USGS for the map of the September 10, 1996 flood. The results from measurements on these benchmarks show that the difference in elevation between these and the PRVD 02 datum elevation is approximately 24 centimeters on average. The elevation of the MSL of 1927 is greater than the elevation of the PRVD 02 datum. RMS values range from 0.018 to 0.401 meter in the GPS observation. The observations with RMS of 0.401 meter should be repeated with a longer observation period or an alternative GPS site should be used with less obstruction to allow a more accurate result. Confirmation of these preliminary results with further field study would suggest that these secondary benchmarks are not suitable for FEMA elevation certifications since the error within these is not within the allowed range.

Figure 3
GPS Equipment Used on an Offset Point



DISCUSSION

Measurements made of the original benchmarks showed that there is an elevation difference between the MSL of 1927 datum and the PRVD 02 datum of approximately 22 centimeters or 8.6 inches.

This difference in elevation between datums is substantial. The consequences of using the PRVD 02 datum instead of the MSL 1927 datum are:

- Real estate located above base flood elevations which are not required to purchase flood insurance might have to purchase flood insurance. If the elevation of a property is certified lower than it actually is because of using an incorrect datum, might lead to a property falling below base flood elevation, forcing the owner to purchase flood insurance for their mortgagee.
- The general population will pay higher flood insurance premiums because the elevation of their real estate being certified to be lower than it actually is. Any real estate located on lower elevations is at higher risk of flooding and will therefore pay a higher insurance premium.
- Lower appraisal value of real estate. Interviews with real estate appraisers confirmed that real estate with a higher risk of flooding has a lower market value than real estate with a lower risk of flooding.
- Infrastructure built on the wrong elevation. Land surveyors, architects, and engineers use the elevations of flood maps in order to design infrastructure and develop land. Infrastructure built on the wrong elevation could place the general population at risk. For example an apartment building or road is at a higher risk of flood because it was built at a lower elevation than originally designed. The Automobile Association states that just 6 inches of flowing water could knock a person off their feet and one foot of flowing water could be enough to move an average family car.

LIMITATIONS

This research was limited by the available information and the need for further fieldwork. Some of the limiting factors for this project are:

- Access to the field data and studies done for the creation of the FEMA FIRM.
- The project's timeframe limited the field work regarding finding benchmarks and GPS observation time.
- Reliability of this research is limited by the reliability of the sources (FEMA, USGS, and NGS)

CONCLUSION

The conclusion of this study is that the FEMA flood maps of the Bayamón River basin were created in the Mean Sea Level Datum of 1927. This means that the current 2009 FEMA FIRM map should be revised by:

- Removing the benchmarks referenced to the PRVD 02 datum and replacing them with existing benchmarks of the Mean Sea Level datum of 1927.
- Removing the reference to the NGS as the government agency responsible for the vertical datum and replacing it with the USGS.

The use of GPS equipment with the Mean Sea Level Datum of 1927 is limited due to the lack of a geoid model that is referenced to this datum. The suggested methodology to work with GPS is:

The MSL 1927 datum is to develop a local constant between the MSL 1927 and PRVD 02 datum. This constant is then added to the results obtained using GPS in the PRVD 02 datum.

The use of the correct datum when referring to flood hazard and the recommendations made in this conclusion will save the population money on flood insurance, potentially help increase the market value of their real estate and most importantly, keep them safe by providing a more precise flood risk data.

REFERENCES

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