Sea-level rise vulnerability mapping using LiDAR DEMs

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1. Introduction

Decision makers, faced with the problem of adapting to sea-level rise (SLR), utilize elevation data to identify assets vulnerable to potential inundation. High accuracy, high resolution Light Detection and Ranging (LiDAR) Digital Elevation Models (DEMs) are increasingly being used in forming management guidlines. **The purpose of this research is to review technical developments and challenges to conducting research in SLR vulnerability assessments using LiDAR DEMs.**

2. Assessing LiDAR error

National Standards for Spatial Data Accuracy (NSSDA; FGDC, 1998) measure error using Root Mean Square Error (RMSE). NSSDA statistic for reporting error:

NSSDA linear error = 1.96(RMSE)

Validity of NSSDA linear error is based on two assumptions:

1) errors follow a Gaussian distribution so that it is appropriate to use standard normal variable 1.96

2) data have zero bias so it is appropriate to use RMSE instead of standard deviation; see Figure 1 for the linkage and difference between RMSE and standard deviation.

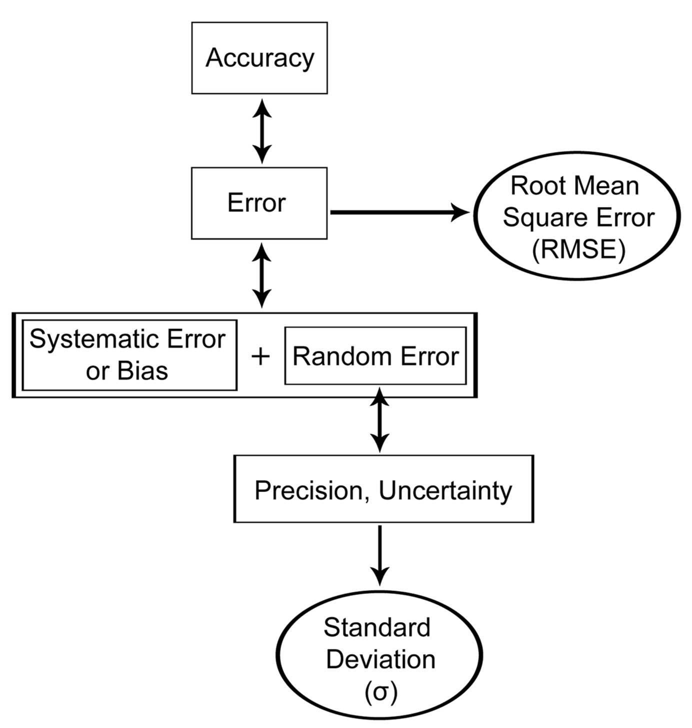


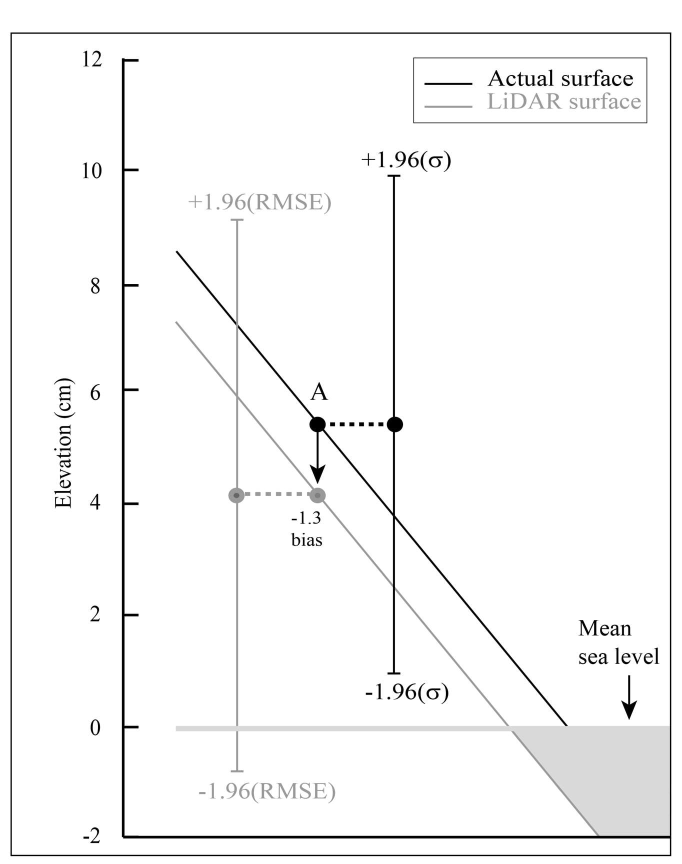
Figure 1. Interrelationship between error measurement terms and statistics. Double arrows denote measurements terms are interchangeable, single arrows denote links with statistics, and ovals denote statistics.

3. Violating normal distribution with zero bias

In a LiDAR quality assessment report (NOAA, 2011), NSSDA linear error for land cover category open terrain assume errors follow a Gaussian distribution with zero bias (Table 1). Although the small skewness (which does not exceed +0.5) indicates errors are normally distributed, they have a systematic negative bias. Replacing standard deviation with RMSE to calculate NSSDA linear error is invalid.

Table 1 LiDAR vertical error descriptive statistics for San Francisco Bay. RMSE = root mean square error; σ = standard deviation; # of points = number of survey checkpoints. Modified from NOAA (2011).

Land cover category	RMSE (cm)	Mean (cm)	Median (cm)	Skew	σ (cm)	# of points	NSSDA Linear error	NDEP/ASPRS 95th percentile
Consolidated	4.7	0.0	-0.3	3.447	4.7	60		6.2 cm
Open terrain	**2.6**	**-1.3**	-0.9	**-0.207**	**2.3**	20	5.1 cm	5.3 cm
Marsh	7.2	2.5	0.4	2.485	7.0	20		15.4 cm
Urban	2.5	-1.0	-0.8	-0.556	2.3	20		4.7 cm



Using LiDAR from Table 1, location 'A' will be mistakenly labled as "inundated" if we 1) assume LiDAR surface has no bias although actually there is -1.3 cm bias, and 2) RMSE is used in replacement of standard deviation to calculate NSSDA linear error (Figure 2). The approach used by National Oceanic Atmospheric Administration (NOAA) Coastal Services Center (CSC) would be less reliable because it "assumes that the RMSE is analogous to the standard deviation (i.e. the data are not biased), which allows for the generation for a type of Z-score or 'standard score' from the data" (NOAA, 2010: 3).

Figure 2 Applying values from Table 1, effect of using root mean square error (RMSE) when LiDAR are negatively biased compared with using standard deviation when LiDAR are not biased.

4. SLR vulnerability mapping case studies using LiDAR

The reliability of statistics used to quantify LiDAR error become increasingly important when used to address uncertainty. A tendency to cause confusion in SLR mapping is that the quality of LiDAR may refer to a measure of uncertainty denoted by standard deviation, RMSE (most commonly reported; see Table 2), or NSSDA linear error.

Table 2 Overview of LiDAR vertical error and relevant attributes in peer reviewed SLR vulnerability mapping case studies. DEM = Digital Elevation Model; SLR = sea-level rise; RMSE = root mean square error; N/A = not available.

Study	Geographic location	Sector	Point spacing (m)	DEM resolution (m)	SLR scenarios mapped (m)	RMSE (cm)
Webster et al., 2004	Prince Edward Island, Canada	Human	≤3	2	0.10 increments up to 4	30
Webster et al., 2006	New Brunswick, Canada	Human & natural	0.6	1	0.5 and 0.7	16
			0.45			12
Poulter and Halpin, 2008	North Carolina, USA	N/A	N/A	6	0.025 increments up to 1.1	16
				15		20
Henman and Poulter, 2008	North Carolina, USA	Natural	N/A	15	0.35, 0.59, 0.82, and 1.38	25
Purvis et al., 2008	Somerset, England	Human	N/A	2 re-sampled to 50	0.48	10
Gesch, 2009	North Carolina, USA	Human	N/A	3	1	14
Chust et al., 2010	Gipuzkoa, Spain	Natural	N/A	1	0.49	15
Zhang, 2011	South Florida, USA	Human & natural	1.5	5	0.5, 1, 1.5	15
Zhang et al., 2011	Florida Keys, USA	Human	1.3	5	0.15 increments up to 5.1	9 and 15
Mitsova et al., 2012	Southeast Florida, USA	Human	N/A	N/A	0.23	N/A
Cooper et al., 2012	Maui Island, Hawai'i, USA	Human & natural	1.3	2	0.75 and 1.9	20
			2			16
Rotzoll and Fletcher, 2012	Honolulu, Hawai'i, USA	Human	N/A	1	0.33 increments up to 1 m	N/A

5. Mapping inundation

Direct marine inundation is often modeled based on assumptions of hydrological connectivity where a grid cell is specified vulnerable if its elevation is below the SLR scenario and hydrologically connected with the ocean (Figure 3).

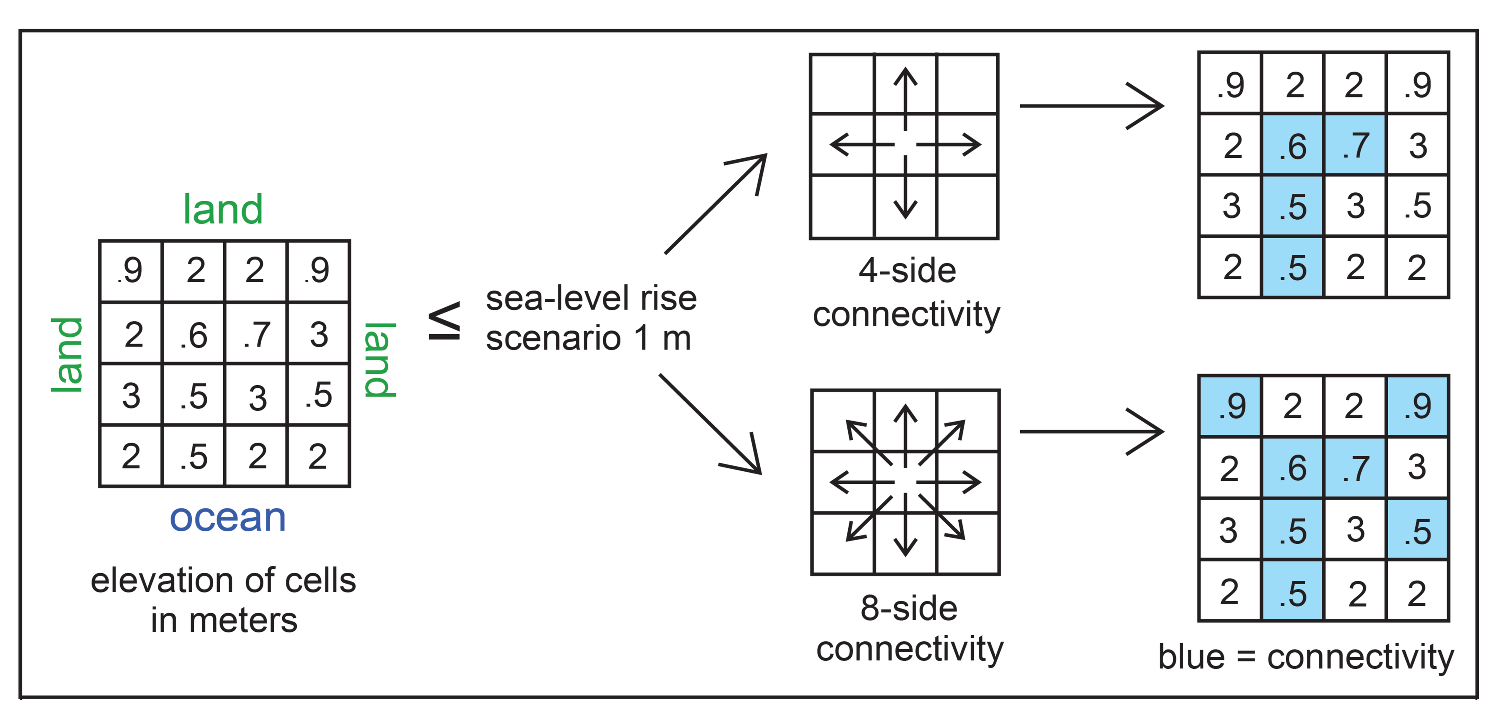
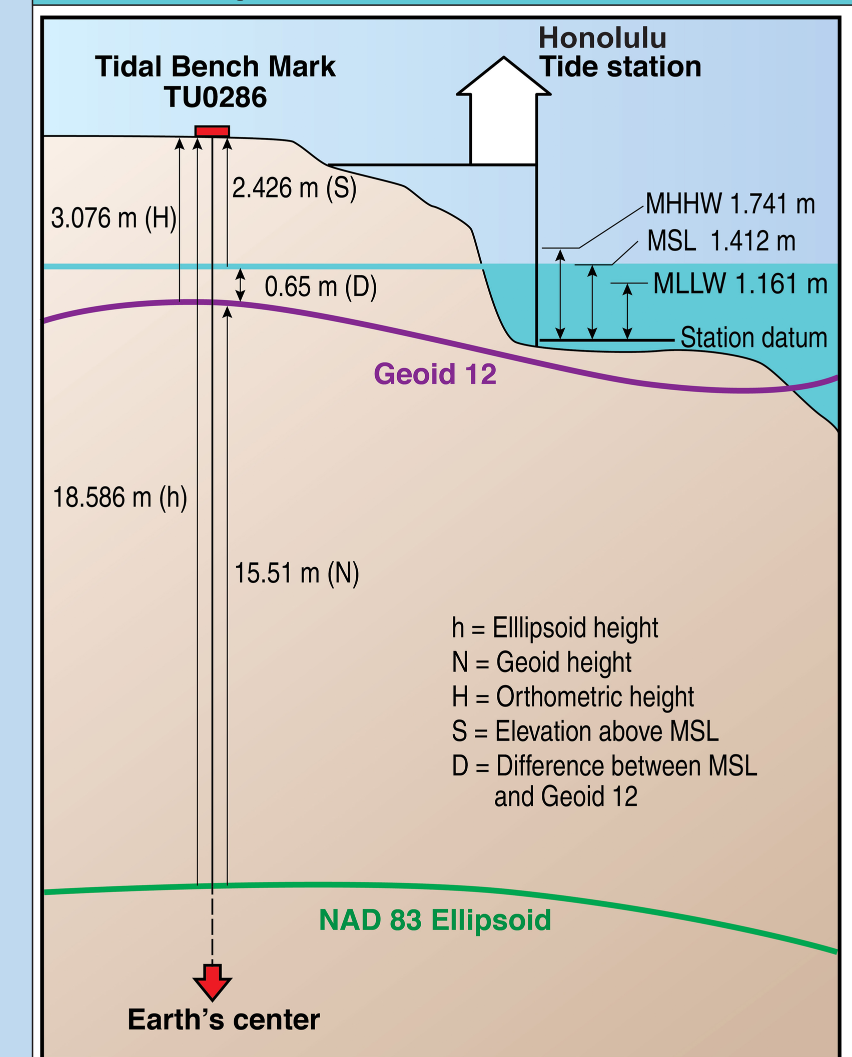


Figure 3 Demonstration of fewer cells connected using 4-side approach compared to many cells connected using 8-side approach.

6. Discrepancies between vertical datums



The location of a National Geodetic Survey and National Ocean Service tidal benchmark near the Honolulu tide station (Figure 4). Increasing sea level 30.5 cm (1 ft) above Geoid 12 at this location results in mapping areas already inundated at Mean Sea Level (MSL) because Geoid 12 is below MSL. Additionally, increasing sea level 30.5 cm above MSL results in mapping areas already inundated at Mean Higher High Water (MHHW). A transformation between tidal datums is necessary because SLR should be mapped above the highest watermark where land is inundated daily.

Figure 4. Example illustration to demostrate the difference between datums using the Honolulu tide station. Elipsoidal datum of NAD 83 = North American Datum of 1983. Tidal datums of MHHW = Mean Higher High Water; MSL = Mean Sea Level; and MLLW = Mean Lowever Low Water (1983-2001 epoch). Station datum is the zero reference for measuring tidal datums.

7. VDatum

VDatum is the industry standard in the US for transforming LiDAR elevations between vertical datums. The Delaware Bay region is used as an example when transforming values that is typical for a SLR mapping project (Figure 5). For short-term SLR planning targets (e.g. 30.5 cm), current VDatum errors may complicate generating accurate inundation maps referenced to MHHW.

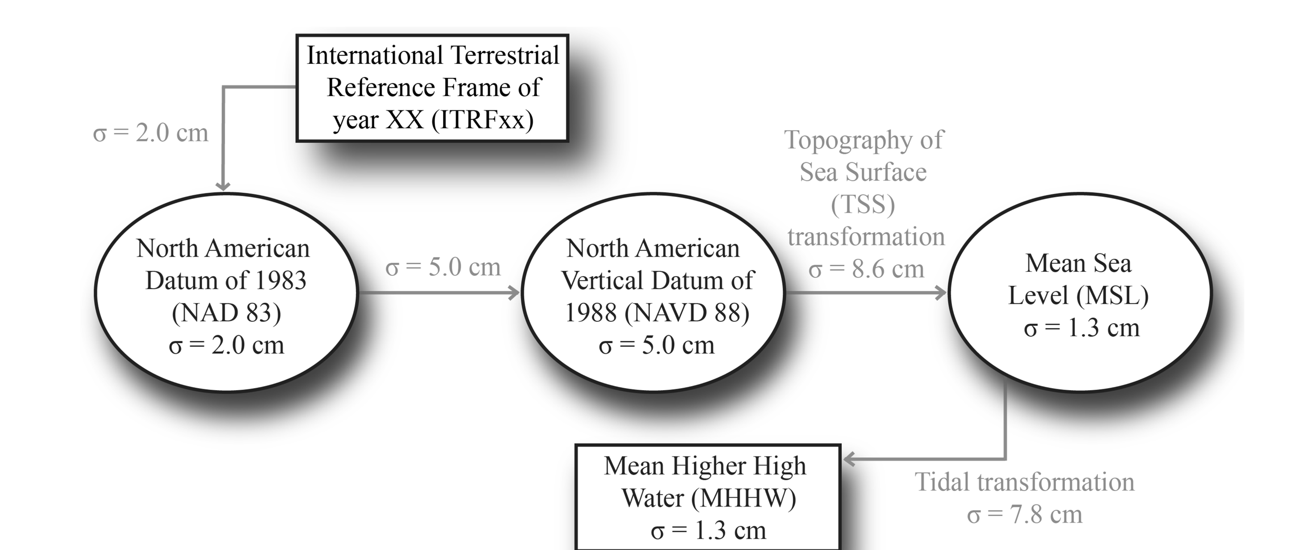


Figure 5. VDatum errors calculated as standard deviation (σ) values for Delaware Bay region. Arrows denote transformation processes, ovals denote core datums, and rectangles denote individual vertical datums.

8. Conslusions

- The most commonly used guideline for reporting LiDAR error, NSSDA linear error, is based on the assumptions that errors follow a normal distribution with zero bias.
- The current practice of SLR vulnerability mapping assumes that LiDAR errors follow a normal distribution with zero bias, which is sometimes violated.
- Mapping a SLR target of 30.5 cm (1 ft) is difficult to achieve based on current LiDAR and VDatum data sets.

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