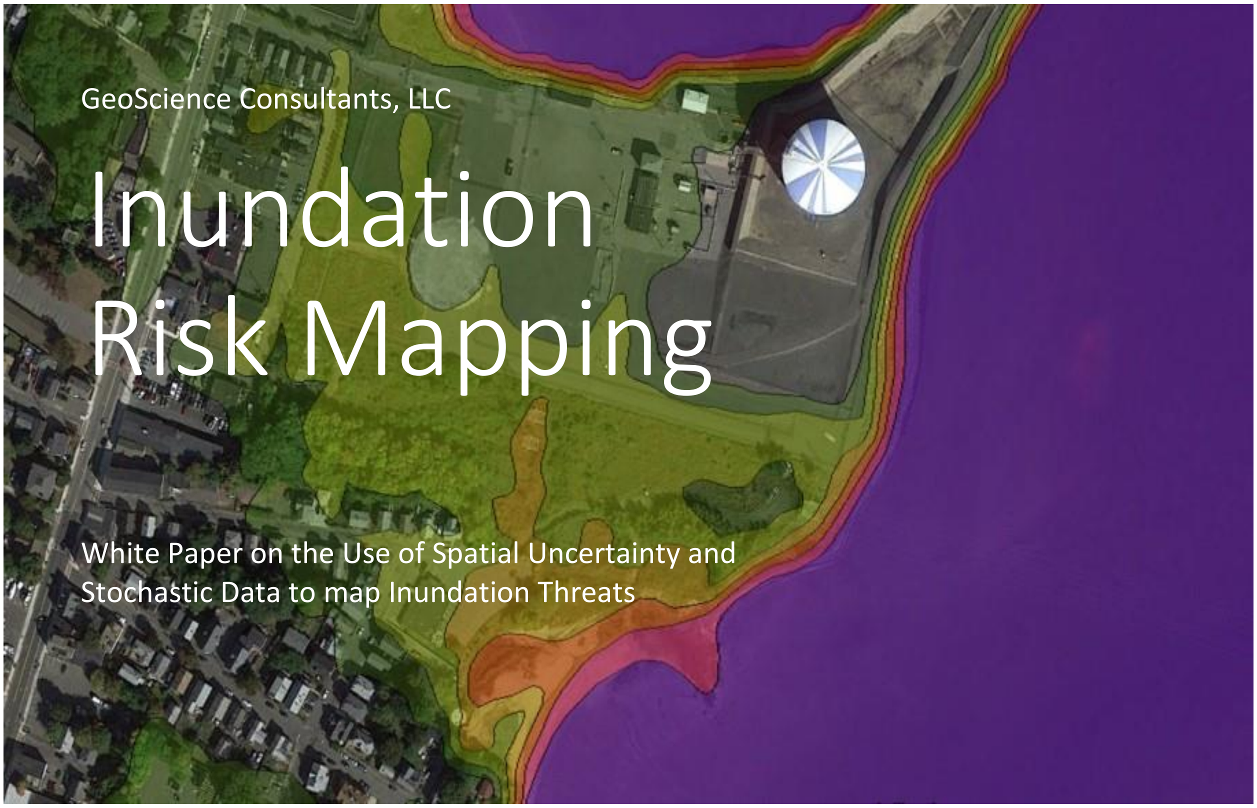


GeoScience Consultants, LLC

Inundation Risk Mapping

White Paper on the Use of Spatial Uncertainty and Stochastic Data to map Inundation Threats

Table of Contents

Needs of the Coastal Community

The Geoscience risk mapping technique addresses the needs that come largely from government agencies. NOAA clearly stated on the first page of the US National Climate Assessment report on Global Sea Level Rise Scenarios[1].

> "At present, coastal managers are left to identify global SLR estimates through their own interpretation of the scientific literature or the advice of experts on an ad-hoc basis."

And the USACE's report on risk informed decisions "Decision Making Under Uncertainty" provides a more emphatic opinion on the needs for probabilistic risk in decision making[2].

> "In contrast to probabilistic risk and decision analysis, ad-hoc methods and intuition are unlikely to provide a defensible basis for decision making. This is particularly true in cases where decision makers hold the public trust, which is the case when potential losses would be distributed across a population that may have had little or no input into a decision process.
>
> Probabilistic risk and decision analysis is the most (and some would say "the only") rigorous engineering approach to difficult decision-making problems involving uncertainty."

These opinions highlight the need for risk-based information for the US. As it relates to sea level rise (SLR) projections, people, municipalities, states, and the federal government have a difficult time

---

[1] NOAA, 2012. Global Sea Level Rise Scenarios for the United States National Climate Assessment, NOAA Technical Report OAR CPO-1., National Oceanic and Atmospheric Administration, Silver Spring, MD.

[2] USACE, 2010. Decision Making Under Uncertainty. Schultz, M., Bridges, T., Mitchell, K., and Harper, B. ERDC TR-10-12. US Army Corps of Engineers, Washington DC.

agreeing on a single (deterministic) SLR value to help define risk[1]. Uncertainty in SLR projections is a large factor, among other physical processes, in forecasting future coastal hazard risks. As a result mapping of areas with wet/dry symbols, as is the norm in most SLR mapping, can make for flawed governance, as the modeled outcomes are not likely to be correct.

The outputs from Geoscience's risk technique address these issues by including the fundamental aspect of time and it's relation to uncertainty in future Sea Level Change (SLC) scenarios using ensemble members from modelled SLR. For example, the uncertainty in the 2018 SLR risk assessment is extremely small as compared to 2075; the developed maps honor that fundamental aspect of time.

The evolution of coastal hazard mapping has been advanced significantly in the US. Further advances in the state of the art are, however, needed as understanding of SLR begins to transition to action along the coastal regions of the US. This new risk mapping technique provides these important improvements to the existing techniques:

a. Time is a component and is risk-based in nature
b. Results are based on probabilities, which allows different parties to select levels that are consistent with their own ability to handle risk, e.g., hospitals cannot tolerate the same level of risk as a private residence.
c. Maps provide a Risk % for all mapped areas – even those that are not within the present limits of inundation.
d. Mapping outputs can be combined with other ancillary data to provide regional summaries or focused results for specific decisions.

Geoscience's Risk Based Inundation Mapping Overview

The general mapping principals of the method follow the processes outlined in Schmid and others[3]. The technique's approach takes advantage of the normal or Gaussian nature of the natural system and large data sets. Data errors and the natural data are modeled using Gaussian functions; and the final outputs provide a spatial representation of those functions in the form of risk of inundation from SLR and/or water levels (storms) through time.

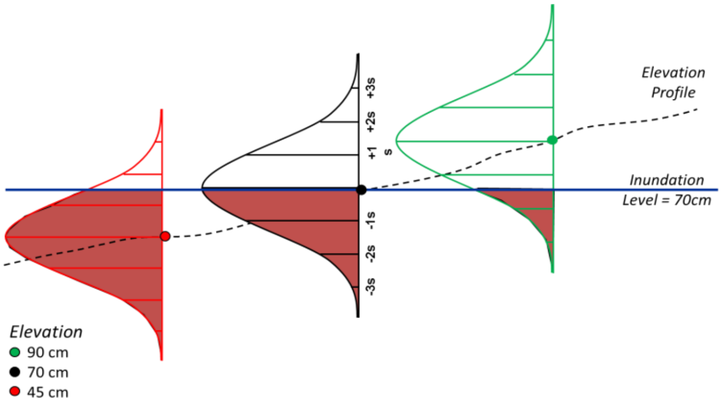
The primary aspect of this method is the treatment of errors/uncertainty as a normal population and the use of Z-scores as intermediate mapping outputs. In natural systems the normal distribution is the expected behavior, and was found to be the case with water level data[4]. In fact, in most systems the distribution tends toward a normal population as the sample number increases[3].

---

[3] Schmid, K.; Hadley, B., and Waters, K., 2014. Mapping and portraying inundation uncertainty of bathtub-type models. Journal of Coastal Research: Volume 30, Issue 3: pp. 548 – 561.

[4] Kriebel, D.L. and Geiman, J.D., 2014. A coastal flood stage to define existing and future sea-level hazards. Journal of Coastal Research: Volume 30, Issue 5: pp. 1017 – 1024.

Simple representation of mapping principal. Each location's normal curve may vary depending on inputs but the intermediate output is a Z-score representing the area under the curve that would be 'inundated' as depicted in this figure (Schmid et al., 2014).



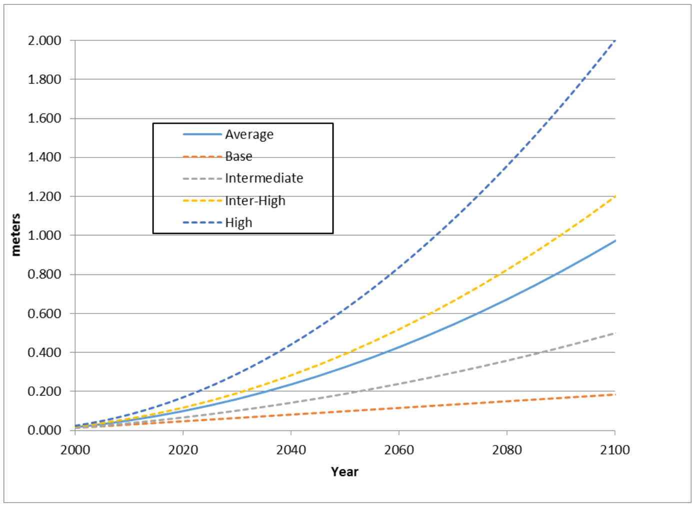
The approach leverages the mean and standard deviation of the populations to calculate a Z-score for each result (i.e., pixel value) based on the modelled water level and elevation. The resulting Z-scores can then be converted to percentages and represented in various ways in the final mapping outputs

The second important aspect is the treatment of the maximum cumulative uncertainty (MCU) of the system using techniques similar to those employed in VDatum's Estimation of Vertical Uncertainty[5]. The measurements and conversions involved in assessing SLR and water levels follow a similar treatment to those in tidal errors. The result is a compound mean (i.e., the deterministic value of SLR + Tide + Modeled Water Level) and an MCU representing the spread of error. The MCU is substituted for the STD in the calculation of the Z-score[3].

Components

The primarily factors/data, depending on product, include:

- the global SLR projections (NOAA, 2012) and uncertainty in the predictions;
- the rate of local SLR ;
- the existing land (elevation) and errors in modelling the elevation;
- the tides (water elevation) and errors in VDatum computations;
- historical water level analysis from nearby stations;
- and/or modeled water surfaces and statistics from ensemble runs; e.g., Sea and Lake Overland Surge from Hurricanes (SLOSH) outputs and variance.



Example of SLC curves through time and increases in variation through time

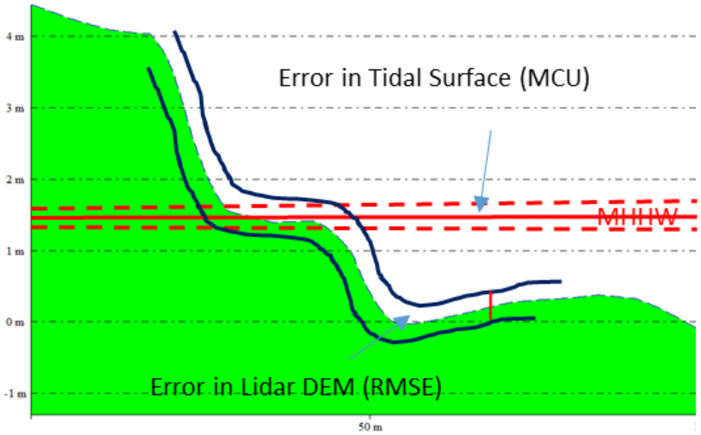
Use of these data sources, their variability, and the techniques referenced above translate into an uncertainty assessment, which is the unique aspect of this method for determining SLR and water level risks. The method essentially estimates the spread of potential values above and below the means (deterministic value) using the 'uncertainty' in the model components. The model itself is deterministic;

---

[5] http://vdatum.noaa.gov/docs/est_uncertainties.html

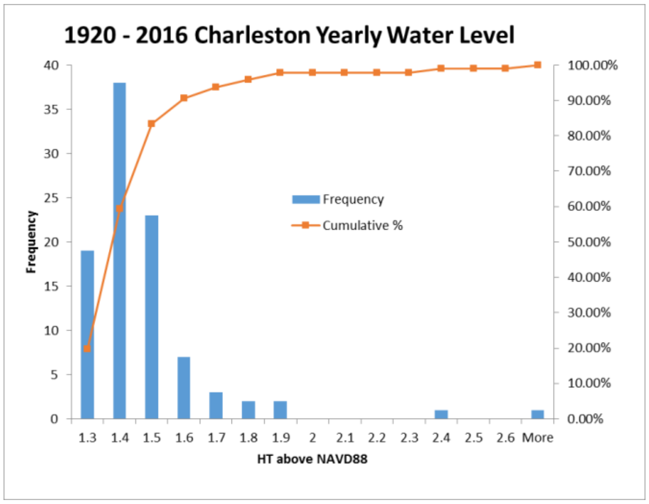
it does not vary; for example a SLR of 1 meter will always produce the same mapping results. It is the input data, however, that has the natural variation.

The probabilistic treatment of time in the inundation scenarios highlights the fact that as the length of time into the future increases so does the spread of the potential outcomes. This is inherently handled in the mapping such that probabilities are less tightly spaced around the mean as the forecast period is extended. For example, the map of tidal inundation risk for 2018 would look very similar to a deterministic wet vs. dry map since the spread in potential outcomes is very small and driven mainly by errors in the data; but as projections move toward 2100 any similarity to a wet vs. dry output will be much less prevalent given the increase spread in potential outcomes.

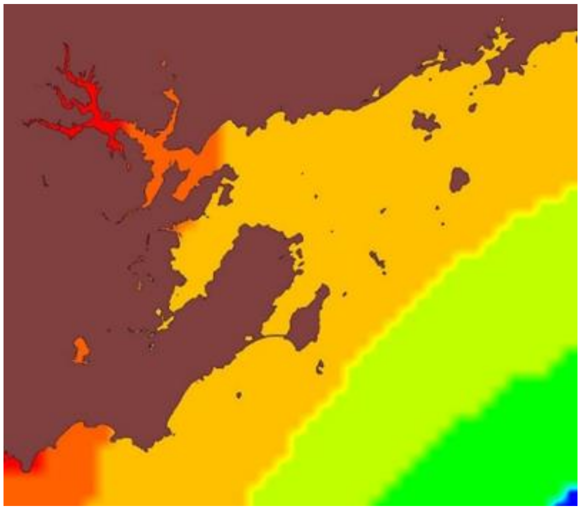


Time zero data and error schematic

With regards to the above example, it is important to note that this technique and outputs also include the uncertainty in the existing time zero data. Uncertainty in both tidal levels and the underlying elevation data are incorporated into the outputs in all present and future maps.



Still water (surge) data used to calculate yearly inundation and statistics

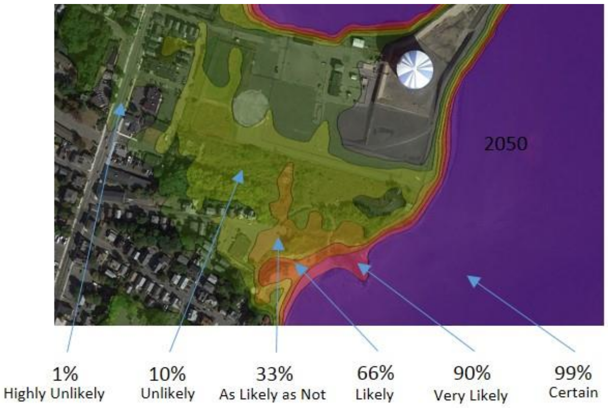


Example of modeled water surfaces

The model incorporates these various inputs and is run in either a ‘connected’ or ‘unconnected’ mode depending on the flooding duration. Event driven inundation is run so that inland areas require a connection to the source of flooding and will not flood beyond the % risk of the source connection. In a longer-term inundation regime, e.g., SLR, the duration can facilitate inland, so in this case the model can be run in an unconnected mode.

Example Risk Mapping Products

The following are examples of the typical products that are developed for communities or counties. The products are available in common web and GIS formats including KMZ's and vector and raster GIS layers. The risk categories shown in the following example products have been generated to coincide with IPCC "likeliness" terminology; however, representation can be tailored to the customer's needs. The range of outputs extends from present to 2100 at 10-yr intervals.



Example risk categories of stochastic inundation modeling for 2050

Tidal Inundation Risks

Tidal inundation – i.e., mean higher high water – products are derived primarily for habitat or restoration work. The maps depict chance of tidal inundation and are produced from: 1) Global Sea Level Curves; 2) High Resolution Elevation; 3) VDatum Tidal Surfaces; and 4) Local Sea Level Corrections. Like all of the examples here, mapping outputs portray the percent chance of inundation at the chosen tidal level from 0 to 99%.

Tidal (MHHW) inundation risk in 2040

Threshold Inundation Risks

Threshold inundation is computed similarly to the tidal inundation product but for specific threshold tidal levels. For example shallow coastal flooding is a set tidal elevation that has been shown to impact infrastructure and transportation and typically occurs several times a year. These products highlight areas that risk inundation from set thresholds (e.g., shallow coastal flooding, king tides, or highest astronomical tides (HAT)). The products are computed using the same layers used in the Tidal Inundation analysis.

Shallow coastal flooding risk in 2040

Still Water (Surge) Inundation Risk

Still water or surge inundation products are similar to FEMA flood maps in their presentation and highlight the risk of a yearly inundation event based on still water levels. As a result they differ from FEMA flood maps in areas with significant wave action (open coastal coasts) and where riverine input is a significant flooding component. Risks, however, are portrayed from 0 to 99%, thus providing more specificity than FEMA flood maps. The products are developed from the analysis of local NOAA station's historical still water levels in addition to the risk components from the tidal inundation analysis and can be treated as 1 or 2D surfaces.

Still water surge risk in 2040

Hurricane/2D Modeled Surface Inundation Risks

Hurricane risk products – an example of a 2D modeled water surfaces with ensemble members – are developed to be used for planning purposes. Individual storms have very specific outcomes that cannot be forecasted, so an ensemble approach is used. The outputs represent specific categories of storms (i.e., 1 to 5) and the population of modeled inundation levels from potential storms. The variable inundation levels in the SLOSH modelled outputs are driven by the different forward motion speeds and directions of potential storms impacting the area of analysis. The inundation extents are handled as a population of potential outcomes, much like the SLR analysis, for each category of storm. The other variables employed include the four components in the tidal flooding as well as a an analysis of the tide ranges. Stochastic analysis of tide levels is required to cover the equally likely event of a quick moving storm hitting during the lower or higher half of the tidal cycle.

Outputs are similar to the other products but have more spread in the risk values; they are less constrained to a ‘wet vs dry’ appearance because the number and magnitude of potential outcomes is significantly wider. Like the others, however, the maps portray a risk of being inundated. Each storm category has its own unique output.

Model water surface (SLOSH) risk output for a category 1 hurricane

Risk Mapping Development

Development of the mapping products includes modeling potential future morphology (landform) changes. This would include vertical accretion of marshes as well as erosion of beaches and dunes. These morphologic components can be integrated into the stochastic framework of the technique and can be developed using historic data or modeling outputs.

In regards to modeling outputs, the technique is not limited to the example products above. This technique can be employed with ensemble models or historical data of a variety of different inputs and goals. The stochastic mapping outputs can be tailored to ecological/habitat studies or other hazard/natural spatial phenomenon easily as long as the relationships between the variables are understood.

Inundation Risk Mapping Benefits

The benefits of the technique extend beyond the efficacy of visualizing the rich information developed from varied and complex inputs. The common output formats help facilitate leveraging the information with other spatial data (i.e., roads, parcels, structures) to analyze impacts from the potential modeled outcomes. Coupling the risk outputs with additional GIS layers is particularly useful when assessing individual structures, transportation routes, or calculating shoreline resilience metrics.

Example of a parcel analysis with a continuous risk scale.

GeoScience Consultants, LLC.

GeoScience Consultants (GSC) is a small business providing consulting and research services for coastal engineering, environmental, cultural, and geologic projects. GSC excels in the use of and development of remote sensing data to address littoral, riverine, and marine environmental and engineering problems. GSC also provides a full suite of LiDAR QA and post-processing services to help organizations maximize their understanding and application of the data.

Geoscience Consultants, LLC
453 Mt Royall Drive
Mount Pleasant, SC 29464
keil@geosciconsultants.com

843-513-443
www.geosciconsultants.com