A Coastal Hazard Assessment with High-Resolution Data: A Pacific Island Case Study

Katie Poston: [0:05] Welcome from the US Fish and Wildlife Service's National Conservation Training Center in Shepherdstown, West Virginia. My name is Katie Poston and I would like to welcome you to our webinar series held in partnership with the US Geological Survey's National Climate Adaptation Science Center.

[0:22] Today's webinar is titled, "A Coastal Hazard Assessment with High Resolution Data -- A Pacific Island Case Study." We are happy to have Dean Gesch with us today. We have Heather Kerkering, who is the Pacific Islands Climate Adaptation Science Center's Science Coordinator, here to introduce our presenter today.

[0:42] Thanks, Heather.

Heather Kerkering: [0:44] Yeah, aloha, everybody. Dean Gesch has been one of our PIs for this project, so we're very excited he was willing to provide this presentation to you.

[0:54] He is a research physical scientist with USGS. Since 1992, he has conducted topographic science research at the Earth Resources Observation and Science Center, EROS, in Sioux Falls, South Dakota, where he is the principal investigator leading the Coastal Changes and Impacts focus area in the Integrated Science and Applications Branch.

[1:15] His research topics are sea-level rise vulnerability assessment, topographic change analysis and monitoring, hurricane storm search mapping, elevation data accuracy assessment, and topographic data development.

[1:27] His academic background includes a bachelor's degree in physical geography from Carroll College, a master's in geoscience from Murray State University, and a PhD in geospatial science and engineering from South Dakota State University. Sounds like you're pretty qualified to keep talking.

[1:40] [laughter]

Heather: [1:42] Thanks, Dean.

Dean Gesch: [1:45] Heather, thanks for the great introduction, also the invite to participate in this webinar series. I'm honored to present this work. It's the work of a lot of people as these kinds of presentations go. Hopefully, I can do it justice.

[2:00] As we've heard, it's sponsored in large part by the PI CASC or the Pacific Islands Climate Adaptation Science Center. We're grateful to that. We'll dive right in and hopefully share some results that are relevant.

[2:17] This is the headline from just last week Friday, day after Thanksgiving. This is the area that we're going to look at as the focus of the case study today. Talking about inundation and all the things associated with that.

[2:34] Just last week, there was an event where there was very high waves. They were peaking at nearly 16 feet. That's a quote right from the article there. You can see some pictures. Direct impacts and some real relevance to the work we're trying to do here and the results that we're having.

[2:54] Realizing that probably not everyone's familiar, maybe a little bit, with Republic of the Marshall Islands or what I'll call RMI. Just got some intro stuff there. This is an aerial shot of the atoll. It's located in the Central Pacific, southwest of Hawaii.

[3:12] The Marshall Islands or RMI are about halfway between Hawaii and Australia as the little inset map shows there. Pretty remote in a lot of ways from other locations that we're used to right down in the central Pacific.

[3:29] Just some aerial shots of parts of the atoll. This one is looking eastward along the southern part of the atoll. In this case, the open ocean is on the right and the lagoon or the atoll lagoon is on the left there.

[3:44] You can see the road and in the distance, the international airport, the coral reef flats, all the things associated with typical atoll landforms. Another one here, farther down the atoll. Again, the ocean on the right and the lagoon on the left.

[4:01] This is the urbanized area at the east end of the atoll. It contains City of Majuro, which is the capital of RMI. Quite built up, quite densely populated residential, commercial, industrial area, that sort of thing. Another one with a lagoon on the foreground in this case, and the open ocean behind the land in the background.

[4:25] Hopefully these shots give an impression of the low-lying nature of the atoll and thus its vulnerability. It's an island location and you can see that it's completely surrounded by water and very thin strip of land, as atolls generally are. We'll have more of these as we move on.

[4:44] Just a shot along the shoreline in one of the islets that's in the northern portion of the atoll. Tropical location, obviously, some beautiful scenery. Just look at that type of thing.

[4:57] From a couple of months ago...This is interesting. Heather, thanks for pointing this out. I think I got this from you. A declaration of a national climate crisis in RMI. This is something that the national legislature in RMI did. It's recognition by the national government of the severity of climate change issues and impacts for the country.

[5:20] Statement here by the president, again, re-emphasizing the severity of the direct climate issues and climate change impacts that the government is facing. Emphasizes the critical needs in this area.

[5:39] That's a brief intro to Majuro. That's our case study, but I want to back up and give a little bit broader context for where some of this work falls. The general topic of integrated coastal elevation models. It's part of a project that we call CoNED, the Coastal National Elevation Database.

[6:02] A primary product there are these high-resolution topographic bathymetric digital elevation models with high spatial resolution and high vertical accuracy. These are merged coastal elevation models. They have the water depth information, nearshore water depth or the bathymetry, and then the land information. It's a seamless topographic surface across that land-water interface.

[6:25] When I say high spatial resolution, these are one-meter spatial resolution models and centimeter level vertical accuracy, so very high vertical accuracy.

[6:35] We'll look at how these models are used for coastal inundation exposure assessment and the Majuro Atoll case study. Then at the end, just a couple of brief examples of some other areas where CoNED is doing work and the type of things we're looking at there.

[6:52] A little bit more about CoNED. I want to acknowledge Jeff Danielson, my colleague, who's the CoNED project's chief here at EROS.

[7:02] As I mentioned already, the two main components of it are development of these high-resolution integrated elevation models, what we call CoNED TBDEMS, and the associated research with that. That's remote sensing research related to different sources of 3D or elevation information and how that can enhance and produce improved elevation models.

[7:28] Some quick screenshots there of some of these areas where we produce these high-resolution integrated models.

[7:35] Under stakeholders, whole list there of folks that are involved or acknowledged. What we call the short name, the USGS Coastal Program. The long name is the Coastal and Marine Hazards and Resources Program. That's a major sponsor of the CoNED activities. Then a lot of the other users, if you will, of CoNED information.

[8:01] A couple different storm surge models, the National Water Model, which is getting a lot of attention, at least within USGS and within NOAA.

[8:09] For instance, they use the CoNED models to provide the symmetry in estuaries. That's useful for coupling together inland hydrologic flow models and coastal water level models. An important use there.

[8:25] There's a number of sea level rise and coastal resiliency tools and viewers that also make use of the CoNED information. That's just really a short list of some of those things CoNED factors in.

[8:37] A map of the current coverage of CoNED models, and then some ongoing work, and then where CoNED has planned to work.

[8:45] This is for CoNEDs in Hawaii. Obviously, it doesn't include Majuro, but that's included as well.

[8:52] The red area along the Northeast Atlantic coast there, that's the Hurricane Sandy impact region. That was a big driver for a lot of CoNED development and a lot of CoNED work.

[9:04] Likewise, in Florida, where you see where we're going to have work starting up fairly soon. These integrated models reproduced for that area, that was subject to the impacts of Hurricane Florence. We're driven by a lot of these ongoing events and coastal hazards.

[9:24] Some examples, more examples. This is a recently completed CoNED TBDEM in the Pacific Northwest. That's a validated high-res model. That's a critical component for what's called CoSMoS. Some of you may have heard of that, the Coastal Storm Modeling System.

[9:43] It's a big USGS activity where sea level rise and effects of storms are modeled along the west coast. CoNED provides the key elevation input for that system.

[9:59] Some current work that's really ramping up right now. It's a major upgrade of the Northern Gulf of Mexico Model or what we call NGOM.

[10:05] We produced a model there, a bit lower resolution, a number of years ago. That's going to be a complete upgrade. That's being upgraded to a one-meter model. There's a whole bunch of new LIDAR data and bathymetry data for that area. Those are being integrated.

[10:19] This is really a key dataset, and a key partner of this work is the Louisiana State Agency. It's called CPRA. It stands for the Coastal Protection and Restoration Authority. That's the state agency that guides all the coastal resiliency work, coastal restoration and protection work.

[10:39] They put out a master plan every five years. This CoNED model is used as a key component of developing that master plan and the strategies for coastal restoration. That's some important work that's taken a lot of time already, and will be of our CoNED staff.

[11:01] There's a brief introduction to CoNED. Now, back to our case study, where we're going to illustrate the development and application of a high res, high accuracy integrated coastal elevation model, in this case for Majuro Atoll in RMI.

[11:15] Just some quick shots at the beginning of the one-meter digital elevation model, or the DEM, that was produced for this area. I'll have a little bit more detail about how that was produced and then a lot more detail about how that was used.

[11:30] We produced this model for what I'll call the "connected portion." By that, I mean a continuous road from the southern half of the atoll that runs a length of about 48 kilometers, or about 30 miles. We've got this one-meter model that covers that area.

[11:50] The aerial shots that I showed you earlier all come from that study area there. We're going to move around the atoll from the northeast over to the west. You can see some detail with this model.

[12:06] That red feature that's in the upper-right, that's the highest point on the island, an elevation of about 16 meters. That's an anthropogenic landform, so that's the trash landfill. Again, it gives you an idea of the low relief nature of this setting that the highest feature is actually a man-made feature there.

[12:27] We move round to the west, again showing the thin width of the island in some places. Now, we're in the rural area to the west. Again, that red area that's in the central portion there. That's the highest natural feature on the island.

[12:44] Those are some low hills, I guess high hills for this area, but what we could call lower hills of about six meters in height. That's the highest natural feature on the island.

[12:54] Again, a little bit more about the geography of where this falls. There's roughly two parallel island chains in the Marshall Islands.

[13:02] Majuro Atoll is in the eastern part. It's called the "Ratak Chain," which stands for sunrise.

[13:10] Then just some basic stats and facts about RMI. Quite a number of islands, but those are spread out over a fairly large area.

[13:20] When you total up the whole land area though, it's pretty small. It's about 70 square miles. Again, overall the average height is very low, obviously, right next to the ocean. A large portion of the population, the total population for the country resides on Majuro.

[13:38] Most of that population resides on the eastern portion, the east end of the atoll, so a very dense population there.

[13:47] Another atoll in the RMI, you may have heard of it, it's Kwajalein. There's a large US military presence there, and an interesting side light for this one. Perhaps you've read the book or seen the movie "Unbroken," an account of a prisoner of war, a US pilot.

[14:09] He was an Allied prisoner of war held on this island, and that was known by the prisoners there as execution island. It was controlled by the Japanese during the early part of the war until the Allieds were able to take over those lands. Some interesting history in the different portions of the Marshall Islands.

[14:33] Part of that interesting history you've probably at least heard of is the nuclear bomb testing that took place after World War II. That took place primarily on Bikini Atoll, and Enewetak atoll up in the northwest there. That's a huge part of the Marshall Islands history, and resonates even to this day.

[14:56] Here's a picture of a building on Majuro, and if you can see their sign, it says the Bikini Atoll Town Hall. We're some 500 miles away from Bikini, but that was, obviously, evacuated as a result of that nuclear testing.

[15:11] A lot of those Bikini islanders were relocated to Majuro, but yet they still function as a group with their own government, and that's why we have things like the Bikini Atoll Town Hall here on Majuro. Again, a direct result of that nuclear testing history.

[15:29] One of the smaller islands on the north part of the atoll, Ejit, is home to where many of these Bikini islander families are settled.

[15:40] RMI is an independent country, but it's closely aligned with the US under what's called the Compact of Free Association that allows the US to have a military presence there.

[15:54] US provides military protection for the country. Other things, the US dollar is used. Marshall islanders are not US citizens, but they can freely come, and go from the United States. There's, again, a close alignment of the countries.

[16:15] That compact is up for renewal in a few years. As you can imagine, there's a large economic impact to that. There's a large amount of aid that the US provides to the Martial Islands. That's a big part of the geopolitical landscape of the Marshall Islands.

[16:36] Another part of that is the growing Chinese influence in the pacific and RMI is not immune to that. This is just a smattering of recent articles in the press that talk about details of that slip through these really close.

[16:56] It's got some complex components in the geopolitical landscape, and these are overlaid, if you will, with the physical threats, the climate change threats that we're going to talk about today more. Just thought that might be useful as background information for those of you that are really familiar with that setting.

[17:17] Back to the physical setting. Just a simple diagram. Hopefully, this is a review from your physical geography, or Geology 101 class is to how atolls are formed. It's an evolutionary landform from volcanic islands in the ocean, and then there's erosion, and subsidence takes place.

[17:41] These fringing reefs become barrier reefs, and then eventually those limestone reefs are the only thing that are left, and the rest of the volcanic landform is submerged there. That's the case with Majuro, and these other atolls in RMI, and in Pacific.

[17:59] Just a cross-section of that -- and I'll refer back to this later -- but you get this steep drop-off which, again, is the result of that initial volcanic landform. The resulting current atoll, the current exposed landform, is carbonate-based atoll landform.

[18:21] Sea level rise -- obviously, a factor in the Pacific, not just in the Pacific but everywhere. Since we're talking about that as a case study today, just a simple diagram of the components that add to that. I'm sure you've seen many like this. This comes from the IPCC.

[18:43] Thermal expansion, it's not labeled on there, explicitly. But thermal expansion in the ocean is a big factor for sea level rise as well as the inputs that you see from ice sheets and all those sort of things.

[18:48] The oceans absorb that heat from the ever-warming earth system, so that's an important factor. It certainly is the case with what we're seeing in the Pacific.

[18:58] As we look at the historical sea level rise trend, in Majuro, there is a tide gauge at the east end of the atoll on the lagoon. It's been operating for 30 to 40 years, that sort of thing. What we see there is an average of, in this case from this NOAA gauge, 3.6 millimeters per year.

[19:21] That's actually pretty close to the global mean sea level rise average that we're seeing. That trend is at least following there. As we'll see, there's a lot of projected acceleration to that, and that's going to continue to be an issue, not just in RMI but any of these small island states.

[19:41] IPCC, there's a lot of information in their most recent assessment report about this, how the Central Pacific is a hot spot, if you will, projected to be a hot spot of sea level rise -- meaning that the global average there, the sea level rise, the sea level change that's going to happen in that area is going to be generally more than the overall global sea level rise.

[20:08] It's a well-documented projection from a lot of studies. There's plenty of maps in there that show that, so just a couple here so you can see that hot spot in the Central Pacific. On this map, it's over to the right. Again, higher than the global average and likewise on this map, so well documented.

[20:27] Whatever emission scenario you're looking at, or what IPCC calls "the RCPs," there's still an acceleration in the latter half of the century in any of those. Obviously, the magnitude of that change is depending on which emission scenario you're looking at. But that's a factor that's always going to be there.

[20:47] The remote sensing record of the sea level change since the early '90s shows this global average sea level rise of about three millimeters a year. That's again, over the whole globe, but that does vary quite a bit regionally.

[21:03] This is a graph of that which shows that historical record based on remote sensing, global remote sensing. Again, we look at the paleo record, the instrument record since the early '90s, and then the model projections all fall under the same thing.

[21:18] There's going to be a projected significant acceleration in sea level rise. That's always going to affect these oceanic locations like RMI.

[21:29] Specifically to what we're doing there and the techniques that we've applied in addition to exposure assessment for Majuro. One of the big things we look at is uncertainty in sea level rise assessments. That can certainly come in the projections of the contributions of things like the polar ice sheets, Greenland and Antarctica.

[21:54] That needs to be factored in. What we're concentrating on is the uncertainty in the input datasets. Obviously, when you measure water level change that's got to be in reference to a datum. There's uncertainties in those water level datums and how things are measured.

[22:09] Then specifically, also with the elevation data, the input to your spatial data. Those are the things, these last two is where we can really get an idea of how that uncertainty is going to affect our inundation exposure modeling. That's what this example will show.

[22:23] There's been a good amount of research in the last 5 to 10 years about how uncertainty, specifically vertical uncertainty, factors in. Just a snapshot of some of those papers. Some really good results.

[22:38] Despite these results, there's still many sea level rise and coastal flooding assessments that do not account properly for that vertical uncertainty. They choose to ignore it. That's, obviously, something we think is not the way to do it.

[22:54] This example, hopefully, will show you that as well, why that's really important to look at the quality of the elevation data and how to handle an uncertainty in a rigorous and quantitative manner.

[23:06] Again, that vertical uncertainty, it affects a couple of things when we look at a sea level rise, or coastal flooding assessment, the selection of the parameters. What's the increment of sea level rise or water level increase that you can effectively model with high confidence? Then how far can you project that out?

[23:25] Those are directly tied to the vertical uncertainty of the input data, and then how you map that spatially. Every assessment wants to have spatial maps of how that projected inundation is going to work. Both of those are affected by the vertical uncertainty.

[23:42] I'm not going to spend a lot of time on this, a lot of detail. There are some simple ways to calculate a couple of parameters, what I've called here, "minimum sea level rise increment." Again, that could be generalized more to minimum water level increment.

[23:58] Those are based on a contour-line approach, because raising the water level DEM, that's really easy to do, especially in a digital GIS environment. You can take a DEM, you can raise the water level on it and call that an assessment. Very easy to do, but in a lot of ways, very dangerous to do if you don't account for the quality of the data.

[24:18] We want to make sure we're doing that in a way that reflects the quality of the data. Raising that water level, it's inherently a contouring operation. That's why we apply these contour line standards, and we can do that at different confidence levels.

[24:38] A little bit of technical detail here about the way we measure the accuracy of an elevation model. Root-mean-square error, that's the industry standard way of doing that. That's got a confidence level associated with it. That confidence level can be transformed in simple ways.

[24:56] This minimum increment, if you want to model it at a specific level of confidence, that's directly tied to that measure of vertical uncertainty, or the RMSE.

[25:05] Now, you can turn that equation around -- and this is how it's most useful -- if you want to measure a certain amount of sea level rise or coastal inundation, what is the accuracy of the elevation model that you need. This simple relationship can help you determine that, and we'll show that.

[25:26] One foot is commonly used, at least in the US in local and regional assessments. One foot is commonly used as that increment. If you're using the industry standard LIDAR elevation data, which is the best source of high accuracy elevation data, collected in a remote-sensing approach, the accuracies that I'm showing, about 8 to 15 centimeters, industry standard LIDAR can attain those accuracies.

[25:59] If you have LIDAR data, that's great. That's what you want to use. Then, you're not modeling an increment that's too small, given the noise or the error in the elevation data. When you don't have elevation data of high accuracy, like LIDAR-derived -- there's a lot of areas that don't -- global DEMs are often used, but their vertical accuracy is much worse.

[26:22] Not to badmouth these global DEMs, they're actually excellent for a lot of applications, but when you're looking at modeling small increments of water level increase, which is what you would do on a low-relief area like Majuro, or any low-relief coastal area, they're severely limited for that. They should not be used for that. We'll talk more about that in a little bit.

[26:47] These are some of those sources there. There's been some improvements. SRTM, the Shuttle Radar Topography Mission is one that's been widely used. There's been some recent improvements for that by NASA, some reprocessing of that, that helped a lot, but it still isn't at a level where you can model these small increments. By that, I mean sub-meter increments of water level increase.

[27:11] In the US, we have other sources. The USGS National Elevation Dataset, what we call the NED. Better, but still somewhat limited. If we don't have LIDAR, we have to look at sources like UAVs, unmanned aerial vehicles, or what we prefer to call, UAS, or unmanned aerial system, that's commonly referred to as drones.

[27:32] With that, we can produce elevation data that's LIDAR quality. In the same ballpark, the same accuracy level as LIDAR data. That is valuable when we look at places like Majuro. That's what we'll be looking at here.

[27:48] Our UAS-derived DEM that we produced for Majuro, I have some more details about that in just a second, is the only one for Majuro that allows us to model these small or sub-meter increments of inundation with high confidence.

[28:03] You can get lost in the numbers on the slide a little bit, but with these global elevation models, you're looking at water level increases of meters, which would cover the entire island. They are not of any use when you're trying to model inundation in an environment like this.

[28:21] A little bit more about the DEM, how it was made and then how it was applied. This is an example of that aerial image. The same image you saw before, but that's a mosaic of those aerial images that were collected by the UAS or by the drones, and then those were processed into this high-resolution, high-accuracy DEM.

[28:40] Some 20,000 photos were collected, in over a field campaign of about 10 or 12 days, I think it was. Five centimeters, high resolution photos. At the same time, over a hundred thousand RTK GPS points were collected for validation, also for control. Some of those, a very small subset, for control of the aerial photography, and then a large validation dataset collected with RTK GPS there.

[29:12] Structure from Motion might be a term you've heard, maybe you're familiar with it, maybe not, what we call SfM. It's just a fancy name for good old fashioned stereophotogrammetry that's been done for years, but with a twist and much improvement.

[29:28] Stereophotogrammetry would derive elevations from overlapping aerial images or pair two images, while with Structure from Motion, many overlapping images are collected and are used to derive elevation. That allows a much better, a much more accurate depiction of elevation.

[29:51] The motion in this case is the motion of the platform, or the motion of the drone. The drone flies, it moves, it collects these overlapping images. That's where the term comes from, Structure from Motion.

[30:02] The results of this Structure from Motion processing of the photos is a point cloud. That's just like LIDAR, and that's good. Then, that high-accuracy, high-density point cloud, it's an X, Y, and a Z, basically. Each point has an elevation, and obviously, location. Then, those are used to generate a raster DEM of the land surface, and that's what was done for Majuro.

[30:28] Now, I said it's a TBDEM, so it's topographic-bathymetric. The topo side is what was done with the Structure from Motion, from the drone imagery. The bathymetry side was a number of sources, including satellite imagery.

[30:44] We do what we call satellite-derived bathymetry, some sophisticated processing there. There was also some sonar data that was merged in. It's a multi-source elevation model, includes satellite imagery for the bathy, and these other sources.

[30:58] Finally, there's the DEM itself. That covers the land area, all of the bathymetry of the lagoon, and then the deeper offshore bathymetry on the eastern half of the atoll. That's that steep drop-off there. If you remember back to that diagram that showed the classic atoll landform, that steep drop-off, that's what we're seeing on the right.

[31:20] Then, we have what we call spatial metadata. We have this for every CoNED TBDEM. A user can trace back to the origin of every elevation in the elevation model, back to its source data, and then all the metadata associated with each of those source datasets, the quality and how it was processed, all that sort of thing. Very useful spatially explicit metadata there.

[31:46] Lots more details are available, just glossed over. There's some USGS publications here, and then, of course, the dataset itself, the one-meter DEM, is available publicly and freely, as a USGS data release.

[31:58] We've touched upon this a little bit already, but now let's apply this to the Majuro site. Why does elevation accuracy matter?

[32:05] This shows the accuracy or the noise level of a couple different types of DEMs. If you're looking at a nominal one-meter sea level rise or inundation level, you have to be not within the noise level of the DEM. That's what we're going to demonstrate here.

[32:23] Here's a couple of these DEMs, a couple of the global DEMs, in the middle and on the right, and then our DEM from the aerial imagery.

[32:31] This is a view from the lagoon, very low relief area. You can see these huge error bars. It would be worthless to try and model any level of inundation with those huge error bars. We need a much better accuracy. That's what we get with the DEM we produced there.

[32:48] Seven-and-a-half inches is about 19 centimeters. That's our accuracy, expressed as an RMSE. I'm having in inches here because the intended audience in the Marshall Islands uses those English units a lot. That's why I'm going back and forth. We've expressed a lot of this in both metric units and in the English units here. That's why you're seeing both.

[33:16] We can change that confidence level. An RMSE, or our seven-and-a-half inches there, our error, that's about a 68-percent confidence. That can be translated to 95 percent. That gets us at the 15-inch level, about a little bit under 40 centimeters, at 95 percent confidence. That elevation can be plus or minus. The true elevation would be within that plus or minus, so that's why show both.

[33:43] This is how we get the allowable increments, what I call the allowable increments of inundation to be modeled. It's tied directly to the accuracy of that DEM.

[33:51] This is where we get 15 inches of inundation, and then 30 inches of inundation, so where we can be sure that we're not using the increment that's within the noise level or within the accuracy of the DEM. That's our minimum increment of sea level rise.

[34:06] That's tied directly to the accuracy, and it's an expression of how well that contour line, or how well that raised water level, is placed vertically on the landscape or on the DEM.

[34:18] These are the three increments we're using. They're measured above the high tide line, because anything below the high tide or near high water is already subject to periodic inundation. We can measure a 15-inch inundation with a 68-percent confidence, 30-inch at 95 percent, and a 45-inch at 99 percent.

[34:37] The original thought was to look at one-foot increments for mitigation planning in this work. We're close to that, but the DEM through testing doesn't quite support that. That's why we're a little bit off a foot.

[34:52] A lot of the details and how this is derived is published in a paper that I'd be glad to make available, if you want the details. The paper was published a year ago, and I've got some more info on that at the end.

[35:04] That takes care of the proper parameter selection for our study. Now, we have to actually map that inundation onto the landscape using the DEM. There's a couple of different ways to do that. The simplest way that's been done most of the time is what's called deterministic.

[35:21] You just raise the water level on it, and the map, the location and extent of where that inundation happens, it's determined simply by where the elevation falls on that landscape. You have no idea of the quality of that delineation, so it's a very limited approach.

[35:39] A modified version of that is where we at least take what we know about the elevation error, and we basically add that and subtract it from the projected water level, and that gives us a range. That's why it's called modified deterministic. Still a deterministic approach, but at least you can give a range and label that with a quantified confidence level. It's a little better.

[36:03] The best way to do it is a fully-probabilistic approach, and that's what we've done. I'm not going to get into the details, but that's where the error characteristics, or the error statistics, are modeled and then applied in a Monte Carlo simulation.

[36:21] You take those error characteristics, you produce what are called equally probable realizations of the DEM, you do the inundation mapping on those, and then you accumulate that through many simulations, the Monte Carlo approach. Then, you have a full probability distribution of what's going to be subject to a certain level of inundation, and a probability attached to that.

[36:46] Let's look at some results, that's the best way to do it. There are four areas I'm going to zoom in on. A and B are built-up areas in the eastern end of the atoll, the densely-populated areas, C shows some infrastructure in the south-central portion, so you see part of the international airport and then the public water supply reservoirs, and then the west end, that rural end.

[37:09] Interestingly, that water supply runoff from rain is rainwater collection, supplies most of the domestic water supply for the folks on Majuro. They actually collect runoff right from the runway and the airport area, and collect that in these reservoirs. That's an important area.

[37:33] We look at what's called marine inundation, and that's where it has a direct hydrologic connection to the ocean or the lagoon. That's easy to model in a raster sense in a GIS.

[37:44] We also do low-lying areas. Those are areas below the target elevation or the modeled elevation, but they're not hydrologically connected to the ocean. These are sometimes called groundwater inundation areas, but they can also be inundated due to runoff and waves and the like. They're places that will collect water or water will pond up.

[38:03] The results I'm showing here are from the best approach, the probabilistic approach. At that 1.25 feet or 15-inch projected water level, we can say these are the areas with a 68-percent chance, or in IPCC terminology is, likely. That's given what we know about the error of the elevation data.

[38:25] You don't see many areas here, but the dark blue are the marine inundation and light blue are those disconnected, low-lying, more internal areas.

[38:33] Go to our next height, two-and-a-half feet, at the same probability level. We see more areas that are subject. This is the projected inundation, given the vertical uncertainty in the DEM, expressed with a specific probability or chance level.

[38:55] Then, at our highest one, a 68-percent chance, likely. One thing to look at here is how some of these low-lying areas flip back and forth here between the previous one. If you look at some of those light blue areas, when we move to a higher level, then those become marine inundation.

[39:12] Which makes sense, because then at those higher water levels, that hydrologic connection comes into play. The water is high enough to get over some areas that were previously causing that to be disconnected. That's an important thing to consider.

[39:27] One thing we also did was to determine the source of marine inundation. In other words, we looked at whether the inundation was coming from the lagoon side or the ocean-facing side of the atoll.

[39:41] In greater than three-quarters of the cases, so in 75 percent of the cases that we looked at, at different water levels and different mapping approaches, all those sort of things, the percent of marine inundation coming from lagoon was greater than that coming from the ocean side.

[39:58] That makes sense. It's well documented in other studies, that the lagoon shore is generally lower in elevation than the ocean side, and it's also much less armored. It has less sea walls and riprap, and that sort of thing. That's an important consideration, as to where that inundation's coming from.

[40:16] Then, there's some areas that have been identified as being inundated simultaneously from both sides. Those, you could argue, are the most vulnerable areas. Those are those areas where it's a very thin strip of land, and also very low elevation areas, part of the atoll that we see there.

[40:36] Here's a similar map. This is at the highest water level we modeled, 45 inches, but a 95-percent chance. We can change that probability category. Using IPCC's terminology, these are labeled areas to be extremely likely inundated at that water level, given what we know about the elevation error in the model.

[41:02] Some tabulated results. Obviously, you can measure the area, and this case, it was also presented as the percent of the total atoll land area, or the study area.

[41:15] The deterministic results, they will always fall within that range of the modified deterministic approach. You can see some of them highlighted there.

[41:23] The probabilistic result, that percent of that land area, it usually falls toward the lower end of that range. That's an interesting observation.

[41:35] Then, the probabilistic is always less than the deterministic. That was the case with all the results. Not only does deterministic not have any expression of the confidence, but it also seems to be over-predicting the amount of area that would be inundated. It's an approach that has a lot of shortcomings, and really shouldn't be used. Same case there, just with the higher confidence level.

[42:06] Using the uncertainty provides better estimates and selectable risk levels. It's a continuous field, this inundation probability, the results from the probabilistic approach, so you can select.

[42:18] Now, I showed you that 68-percent chance and 95 percent, but that could be selected at anything. 80, 85, whatever. That's a real advantage, to have that selectable risk level. The way we've applied this high-accuracy DEM allows us to do that.

[42:38] A quick one here, to demonstrate that event-based inundation, like we showed at the very beginning with the high wave event from last week.

[42:45] There's a system, PacIOOS, which is the Pacific Island Ocean Observing System. They generate wave forecasts, wave run-up forecasts. A case here, where there was a high wave event from a few years ago. What this allows us to do now, with this high-res, high-accuracy model, is to have a spatial representation of where that inundation might happen again, with an attached probability to it.

[43:16] As with all these exercises, there's certainly limitations of this. These are some ones that are apparent. I want to make sure we touch upon these. It's a good DEM, but still has some uncertainty, especially in forested areas, the structure from ocean approach.

[43:33] When the drone takes pictures, it takes them off the top of trees in dense forested areas, tops of buildings. That information has to be filtered out or removed, and then the ground level has to be interpolated. There's, obviously, some error there, and we see that in the DEM.

[43:55] We've captured a lot of the sea walls and a lot of the flood protection barriers, but we know, not all of them are completely accurate, some of them that might even be below the resolution of the DEM. There's some issues there.

[44:08] Then, the big one is the inundation modeling we did. It's been called passive flooding or hydrostatic, a couple of different names, and truly the simplest approach. It's a good start, but it doesn't account for wave run-up and coastal erosion, and all these dynamic processes.

[44:24] There's a couple of papers highlighted there on the lower-right corner, published in the last year or so, that demonstrate very clearly that when you add in the dynamic processes, especially wave run-up and that sort of thing, that that increases the vulnerable areas and the severity of it.

[44:43] That's something that does need to be added in addition to this initial hydrostatic approach there. That's a big one to keep under consideration.

[44:55] A few other examples here of the inundation, some ground shots. It's not just sea level rise that's going to increase, but the high tide events, or what are called king tides. Those come much sooner than even the highest rates of sea level rise. That's important to keep in mind. There's a record of a lot of these events that happen on Majuro and the rest of the Marshall Islands.

[45:21] Low relief area, this was a national telecommunications facility, right along the lagoon shore. There is a sea wall there in front of it, but highly vulnerable.

[45:32] The country itself is looking at some pretty drastic measures about how you can have an engineering solution to some of these, actually raising portions of the island and different facilities, some press covers of that.

[45:49] The local mitigation approaches that are already being used, you've got to do best you can and protect things in the best way possible.

[46:01] This is an example of that. This is one of the drone images. Direct your attention to the north-center part of that. This is a bunch of rough use material that's piled up along the shore there to provide a bund, to provide some level of flood protection.

[46:21] It's obviously a critical issue, and will continue to be. These kind of datasets and approaches are going to be helpful with this kind of planning.

[46:31] A lot of studies on the general vulnerability of atoll landforms. There's not complete scientific consensus about the rates of that and how that happens. There's some competing studies about how these islands can be adaptive to that. There's some good science that's being done, but yet more work needs to be done.

[46:54] In either case, the datasets that go into the modeling and the mitigation planning and that sort of thing can certainly be improved. That's what we believe we've done here, with the work that we've done in Majuro.

[47:08] Those datasets are all available publicly, as a USGS data release, the many different scenarios and mapping approaches. Those are all available as a USGS dataset out there, for public consumption.

[47:23] A lot of details are wrapped up in a paper. This paper is in revision now. It's likely to be accepted pretty soon here and published shortly, hopefully within the next month or two. If you're interested in details, those are available.

[47:37] Then, for further information, a lot of the background information about this consideration of vertical uncertainty that we applied in this case, be glad to supply these, point you to them if you have an interest, and they're a lot more detailed.

[47:51] Then, for CoNED itself, back to that general or larger topic, it's a good website, data access through that website, and then a couple of good journal papers from a few years ago about the details, about how these 3D DEMs are put together, so direct you to a lot of that for further information.

[48:08] Finally, one on ongoing efforts. This is a current project also sponsored by PI-CASC. This is some work that's being done at the National Park Service site. I won't even try to pronounce the full name. I'll use the National Park Service abbreviation of PUHO.

[48:29] We're doing a similar type of inundation assessment here, but with some additions that cover maybe some of the shortcomings, if you will, of the Majuro work. We have highly detailed 3D data from a couple of different sources, terrestrial LIDAR, to get at these very accurate measurements of elevations of structures that will affect the flow.

[48:52] This is a highly significant cultural site on the west coast of Hawaii. We've got LIDAR collected from UAVs, we've got imagery, for structure from ocean, and then terrestrial LIDAR, working with our friends in Phil Thompson's group at UH. The result for this will be that type of inundation assessment modeling.

[49:14] The important addition here as well is, there's wave sensors out in the ocean, so we'll have a good knowledge of the wave climate and the water level record of, if you will, seasonal changes and that sort of thing, to apply to the inundation analysis projection and planning for this National Park site.

[49:36] That's some good work going on that's related and directly driven off of our previous work.

[49:42] Some takeaways, hopefully, you've gotten, but I'll list these quickly. These high-resolution, high-accuracy models are critical for doing these type of detailed coastal assessments. Global elevation models, not so much. They shouldn't be used for that.

[50:01] Also critical is accounting for that vertical uncertainty. We believe we've struck upon ways where that can be done in a rigorous manner and a very precise manner, so we've demonstrated that.

[50:12] Then, this approach of using UAVs, it works well in these remote locations, where the traditional, standard approaches where you fly airborne LIDAR on an airplane, those can have significant challenges, logistically and cost-wise. UAVs is a technology that has worked, and it can be adopted and used by the local stakeholders and local entities. That's an important development as well.

[50:43] Of course, thanks to many people, I had the privilege of presenting this today. This is particularly the Majuro effort. Many names there, I'm sure I've left off a few. A huge number of participants and supporters and collaborators. Certainly couldn't have done this work without all of those, so I certainly want to mention that here.

[51:03] Then, with that, I'll close off and be glad to take any questions or comments. Thank you very much.

Katie: [51:11] Katie says, "Thank you for the summary at the beginning, of the status of coastal studies and publications in the US states. Within the Pacific, beyond Hawaii, does USGS anticipate moving beyond Majuro to other atoll or coastal analyses in Palau or the FSM?

Dean: [51:31] Yes, good question. We actually have done some work in FSM, the island of Pohnpei. It's a little bit different flavor from this. Really, there it's about the resiliency of the mangrove forest, the fringing mangrove forest in Pohnpei.

[51:47] One of the big needs there is for a high accuracy elevation model. We don't have that in Pohnpei, so we've done some field collection of some very site-specific elevation data. The goal there is to have, eventually, that type of high accuracy, high resolution data in Pohnpei.

[52:05] As far as other atoll locations within the Pacific, as you can imagine, there's been a good amount of interest in these results. We've had discussions about other areas specifically. In our minds, none of those have come to fruition yet, but we continue to have those and there's a lot of interest in that.

[52:26] Again, our sponsors at PI-CASC and other folks within USGS, specifically Dr. Dave Helweg, who's a liaison to the insular areas affiliated with the US, continues to seek opportunities for that and to seek efforts to do that. We hope to do more of that.

Katie: [52:50] Heather says, "Are you able to talk about user of the data, specifically the Majuro government?

Dean: [52:56] Yeah. I did want to mention that. Thanks for the prompt, Heather. One thing we know is that we presented a lot of this work initially...It's an ongoing project for members. We presented this to representatives from the Majuro government and some of their consultants about a year ago.

[53:15] At that time, they were looking at funds for seawall construction. I know they were interested in this information for that use. We know it's also being looked at to do an initial screening of these low-lying areas where water can collect.

[53:36] Whether that's connected to the ocean or not, but on a certain water level conditions or even precipitation events where those areas can be located. The data are being used for initial screening for that. Just a couple examples of how the data are being used for those types of planning.

Katie: [54:00] Katie says, "Yup, FSM is very interested in coastal analysis of upland since [inaudible] patches along the coast are important, coastal plains between mangroves and uplands."

[54:17] Benedict says, "Thank you, sir, for sharing the presentation. I was wondering if you're planning to include Majuro Airport in your future UAV fieldwork."

Dean: [54:27] Good question. Actually, the Majuro Airport, I know when I was showing the DEM, there was a missing piece there. When we look at the DEM we have for the area, it actually does include the airport area. It was not collected with UAV imagery though.

[54:44] The difficulty of flying over that sort of area with incoming and outgoing flights, that sort of thing. There were portions of time where we were able to map the airport property with RTK GPS. We have very dense survey points over that area. The portion of the DEM that covers the airport was collected with GPS data.

[55:09] Again, that's going to be much more accurate on a point-by-point basis than anything derived from the UAV imagery. But that's how that portion of the DEM was covered, with RTK GPS points.

Katie: [55:24] Martin asks, "The Marshall Islands Conservation Society is undertaking similar work on five outer atolls, specifically focused on flood risk assessment. Would you and your office be available to discuss or assist us?"

Dean: [55:41] By all means, yes. At the end there, I didn't add there. Logo's up for just a short period of time, but the Marshall Islands Conservation Society was listed there. They were a partner already in this work. We'll be more than interested in that.

[55:57] I'm guessing some of the folks we work with are already aware of that, but by all means. Facilitate a contact and my contact information or any of our team, and we'll be glad to visit about that. Thank you.

Katie: [56:13] A big thank you to our presenter, Dean, today. Thank you, Heather, for the introduction. Thank you all for tuning in.

Dean: [56:20] Thank you.

Katie: [56:21] Thank you.

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