University of Puerto Rico – Mayagüez
Department of Geology

Puerto Rico's River Plumes during Hurricane Maria vs Hurricane Fiona; An Estimation of Recovery Time

Cherilyn Toro Acosta

Professor: Dr. Fernando Gilbes

GEOL 6225 – Advanced Remote Sensing

May 12, 2023

Abstract

Satellite images from Puerto Rico on the dates of July 2017 to February 2018 and August 2022 to February 2023 were retrieved with the purpose of observing the river plumes around the west and north areas of the island to estimate the amount of time they took to get back into their "stable" state after Hurricane Maria in 2017 and Hurricane Fiona in 2022. The "stable" state of the river plumes was selected by searching for satellite images that showed rivers with no sediment traces in the meander for dates before the hurricanes. For Hurricane Maria the image selected corresponds to July 2017 and for Hurricane Fiona August 2022, since August 2017 images were full of clouds covering the coastline. Consequently, the stable state for river plumes selected for both hurricanes is 2km or less, as river plumes are barely noticeable at a full view of the island and rivers show no sediment trace in the meander at that length of river plume. Once all images were obtained and interpreted, the conclusion obtained is that Hurricane Maria took exactly 5 months to return into a stable state, while for Hurricane Fiona the river plumes can be considered stable at 4 months after the event, but because of clouds presence in the northern area of the island, data was extended to February 2023 to obtain a full view of stable rivers. Finally, this research shows that the effects on the island for a category 4 hurricane were more extreme as vegetation was very affected and noticeable in the images, while a category 1 hurricane showed little to no changes in vegetation.

Introduction

As a tropical island located in the Caribbean, Puerto Rico is subject to experience and prepare for hurricane season every year from June 1st to November 30th (Together Puerto Rico, 2020). Consequently, the atmospheric phenomena that strike the island always leave significant impacts related mainly to floods, high rip currents, and landfalls, also involving the deforestation of some areas (US Department of Commerce, N.O.A.A., 2021). However, one the most recent historical events of this type that caused critical damages to the island occurred on September 20, 2017, and lasted for approximately 3 days (Sept. 19-21), better known as the category 5 Hurricane Maria (US Department of Commerce, N.O.A.A., 2021). This phenomenon caused extreme structural and vegetative damage, coastal flooding, and landslides around the entire island (US Department of Commerce, N.O.A.A., 2021). In addition, Puerto Rico contains approximately 5385 miles based of rivers (Wild & scenic rivers Forest Service National Website), and 270 miles of coastline with approximately 300 beaches (Discover Puerto Rico, 2023), which means a lot of trouble when it comes to maritime advisories and keeping people out from water bodies around the island during atmospheric events and storm surges, especially after the event has passed but the water bodies haven't returned to their stable state (Myers, G.N., 2022). As a result, the purpose of this research is to observe and identify for how long the impacts of the Hurricane Maria lasted in river plumes and vegetation in the west side of the island (recovery/stabilization time) and compare them to recent Hurricane Fiona (September 17-19, 2022) impacts in river plumes and vegetation in the same area. With this, we could observe the impact on the island during a category 5 hurricane and compare it with the category 1 Hurricane Fiona (US Department of Commerce, N.O.A.A., 2022).

The study was developed focusing mainly on western and northern Puerto Rico due to the presence of clouds present on satellite pictures for eastern Puerto Rico. Figure 1 shows an example of how eastern Puerto Rico looks like for most of the satellite images retrieved for September 2022, which is a very low-quality data and not usable at all as resolution is very limited and the coast is not observable at all.

Keywords

River plumes consist of buoyant water that from river mouths that spread into the ocean, depositing sediments, and other materials, influencing the water quality and circulation along the coasts (Warrick, J., et. al., 2017). Their intensity varies as they are affected by local or regional *rainfall events* (Furnas, M.J., 1970). The timing and magnitude of the river plume will depend on the distribution, intensity, and duration of the rain event. River plumes also supply fresh water to the sea, which can cause an isolation of salinity in the upper, creating a layer that divides the two types of water and changing the salinity drastically in that water column. As a result of this barrier, atmospheric events like *hurricanes* can intensify (NASA salinity: Air-Sea Interactions). Consequently, hurricanes cause an alteration to river plumes that can last for months until they come back into their *stable state*. Stable state is considered when river plume is in constant input conditions with no rain event alterations (Community Surface Dynamics Modeling System, 2020).

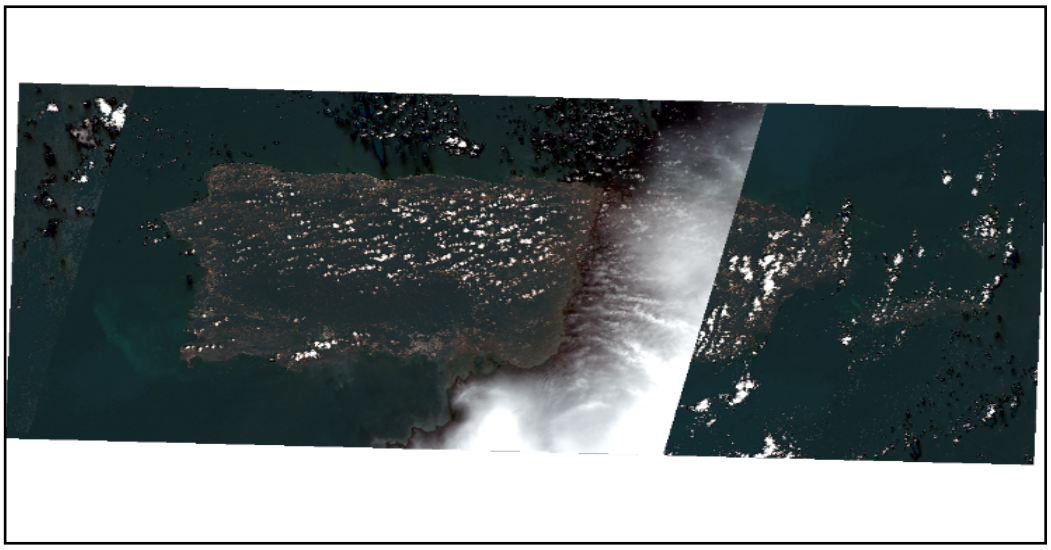


Figure 1: Mosaic satellite image of Puerto Rico made through ENVI using OLI Landsat 8 data for the month of September 2022. Image doesn't have good resolution close to the coastline of the island, river plumes can't be identified, a huge cloud strikes from north to south in the eastern area, presence of scattered clouds can be seen on the northern/central area of the island. Western and northern Puerto Rico looks like the best area of study as presence of clouds is minimum and coastline/river plumes are visible.

Objectives

- Obtain satellite images of the before and after for Hurricanes Maria and Fiona in Puerto Rico.
- Measure river plumes and determine a stable state for river plumes.
- Observe and determine the approximate amount of time that it took for river plumes in Puerto Rico to return to their stable state, based on previous step, after the landfall of both hurricanes on the island.
- Compare results for both atmospheric events and identify the differences and similarities in terms of river plumes stability and vegetation changes.
- Obtain an answer that accepts or denies if the amount of time that takes the island to recover from atmospheric events can be estimated (if the results for both are similar or different).

Methodology

To achieve this, background information has been taken from previous studies of Hurricane Maria using remote sensing instruments to identify the impacts mainly in vegetation and river plumes, stating that the island took approximately 4 months to get back to its normal state (Marlier, M.E., et. al., 2022 | Feng, Y., et. al., 2020 | Miller, P.W., et. al., 2019). Based on that, the data will be acquired using Earth Explorer to search for Landsat 8 – Operational Land Imager (OLI) images to get the complete view of western Puerto Rico river plumes and vegetation for the dates of before and after hurricanes Maria and Fiona up to approximately 4-5 months after (September through January of 2017-2018 and 2022-2023), or until river plumes reach stability, to then compare the results obtained for each one after estimating the amount of recovery time that it took for both. The concept of river plume stability will be based on the river plume appearance on dates before the landfall of the hurricanes, using images from July for Hurricane Maria and August for Hurricane Fiona (1 and 2 months earlier from the hurricane) as a reference, to get an image of the area close to the event but focusing on the status of the river and the length of river plumes (if it is carrying sediment, it would be associated to rain activity and image would not work as reference). August 2017 images contain the presence of clouds along the coastline (Figure 4), not making possible the view of the river plumes, so images from July 2017 were used for river plume stability reference.

Through these images the vegetation will also show changes when affected by the hurricanes, so a comparison of before and after will be made for both hurricanes. In addition, using the mensuring tool from ENVI, the river plumes will be measured starting at the river mouth and following the line of sediment in the water to show the length of them and compare between dates. These measurements will also help with comparing both events and marking a "stability/instability level" for the river plumes.

Coordinates in EarthExplorer

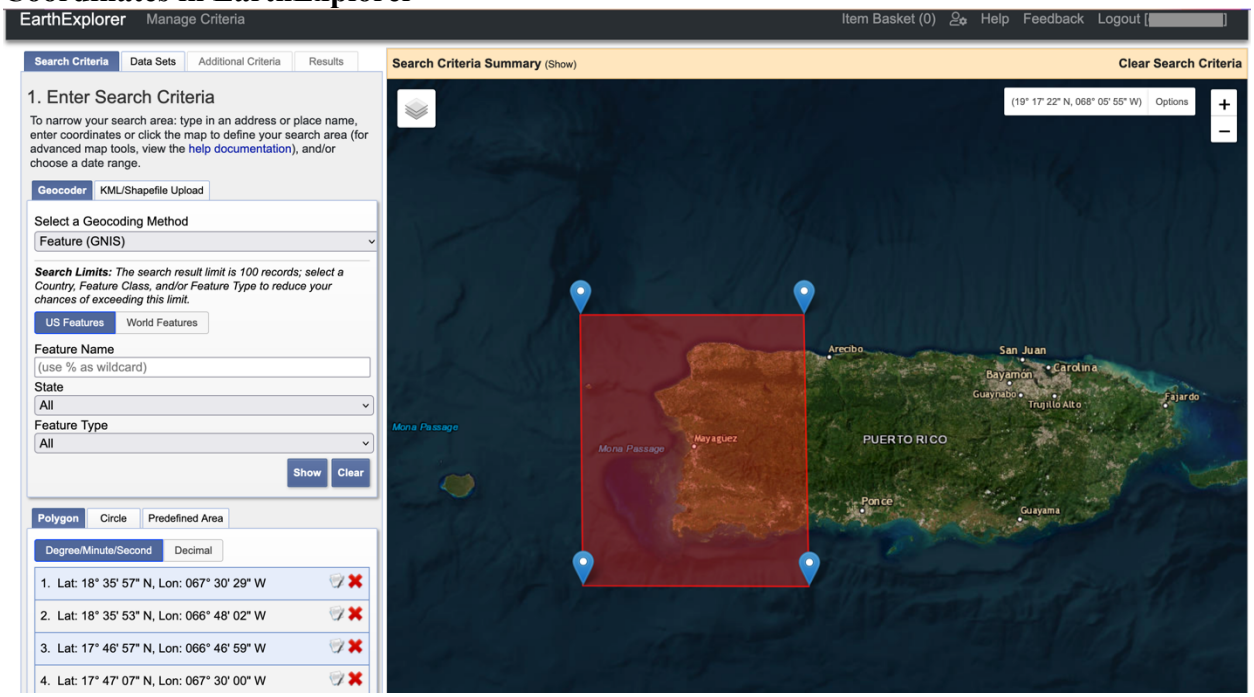


Figure 2: Search criteria entered to Earth Explorer for data retrieval. West and south quadrangles were obtained, only missing eastern Puerto Rico.

Results and Discussion

Hurricane Maria images for Puerto Rico display more variation and changes in the landscape than Hurricane Fiona images. There is a very noticeable change in the island before and after Hurricane Maria, not only in river plumes but in vegetation, and it can be clearly observed through remote sensing data (Figure 10). For the Hurricane Fiona images, it can be confirmed that there was a long period of rain occurring in the island at the time since river plumes were altered since August (Figure 28)(National Weather Service, 2022). In addition, river plumes for both hurricanes show a lot of variation in the lengths between months and in some cases from one week to another, which most probably indicates that rain events could have occurred in between images and altered the river plumes status, extending the time for them to return into stability, and consequently extending the data set for this research up to five months after the hurricanes.

I. Hurricane Maria

Puerto Rico started receiving rain bands and winds from Hurricane Maria since September 19, 2017, but it wasn't until the next day at approximately 6 am that the category 5 hurricane made landfall on the island. Its effects of heavy rain and winds lasted until September 21, 2017, leaving the island with coastal floods, extreme structural and vegetative damages, and landslides (US Department of Commerce, N.O.A.A., 2021). Through the images retrieved from the OLI sensor on the Landsat 8 and 9 for the dates of July through February, we can observe the before and after of the effects of Hurricane Maria in Puerto Rico and approximate that the river plumes took 5 months to return to their stable state based on the measurements made for the images of July and comparing. The measurements from July in Figure 2 show mainly the rivers of western Puerto Rico were the actual river can't be easily distinguished as its not carrying sediment, which indicates there is no presence of rain before the image, and the river plumes for the Añasco and Mayagüez river plumes doesn't exceed 1.8 kilometers, so for the remaining months, any measurement above 2 kilometers would be considered unstable, and the appearance of the river is also taken into consideration. However, it is important to note that some days of data were not processable as the image had very low quality and a high number of clouds (see Figure 5 for example).

a) July

Taken as the “stability month” for Hurricane Maria, river plumes are below 2km length, which is the selected measurement as stable reference. Figures 3 displays a full view of the island with the river plume measurement for the Añasco and Culebrinas rivers.

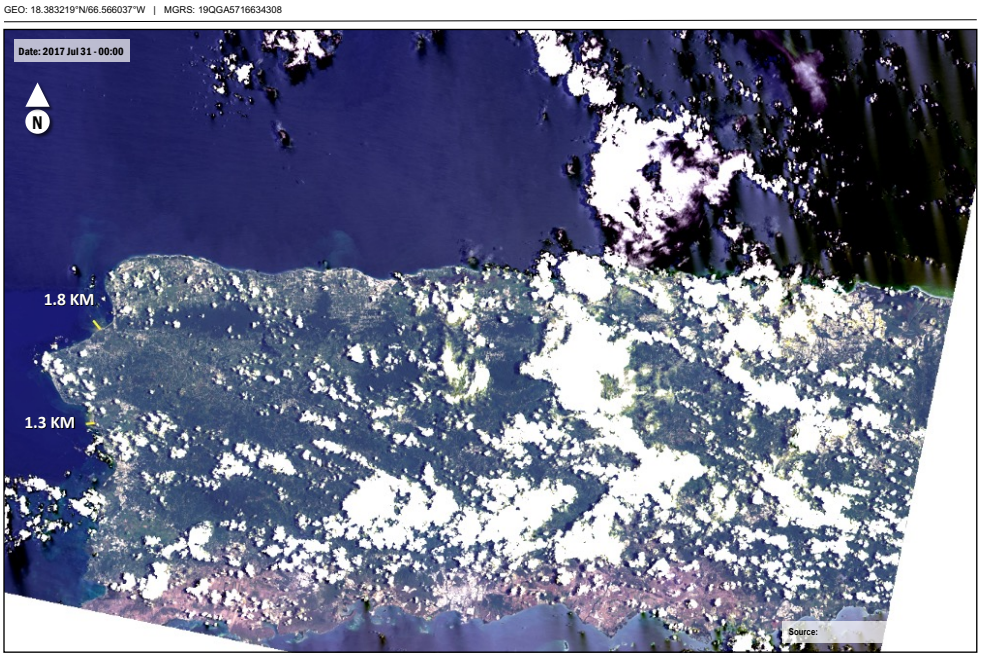


Figure 3: Full view of Puerto Rico with exception of the east. Measurements for river plumes in the Añasco (1.3km) and Culebrinas (1.8km) area can be found.

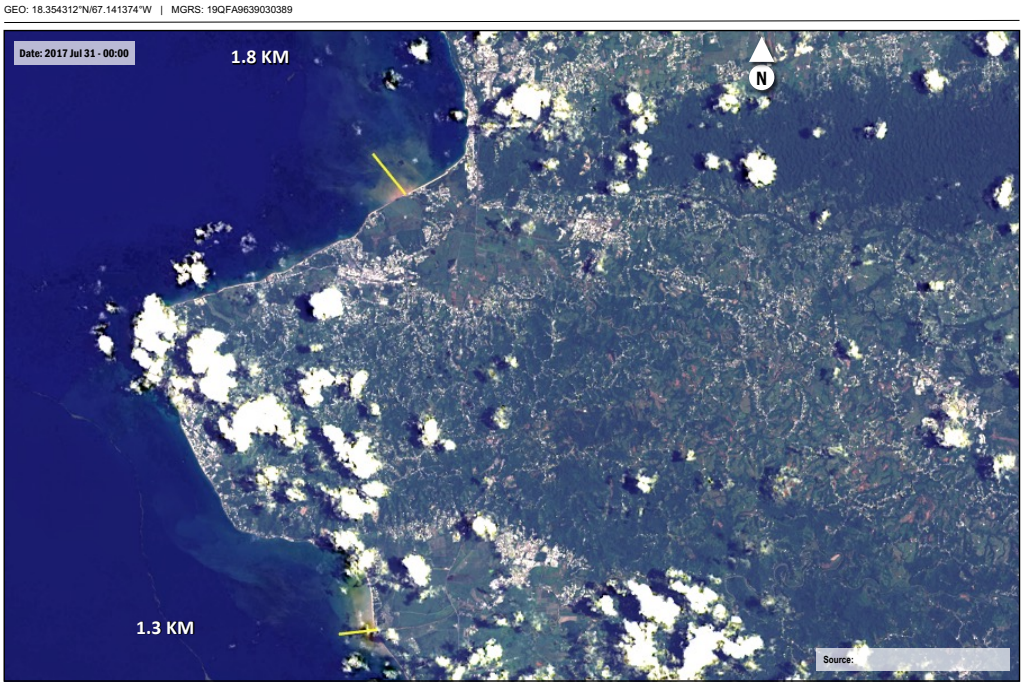


Figure 4: Zoom in for the west area of Puerto Rico to show a close-up view of the river plumes and sediments close to the coast (Río Grande de Añasco and Río Culebrinas).

b) August

The month before the hurricane. Cloud presence avoids river plume observation.

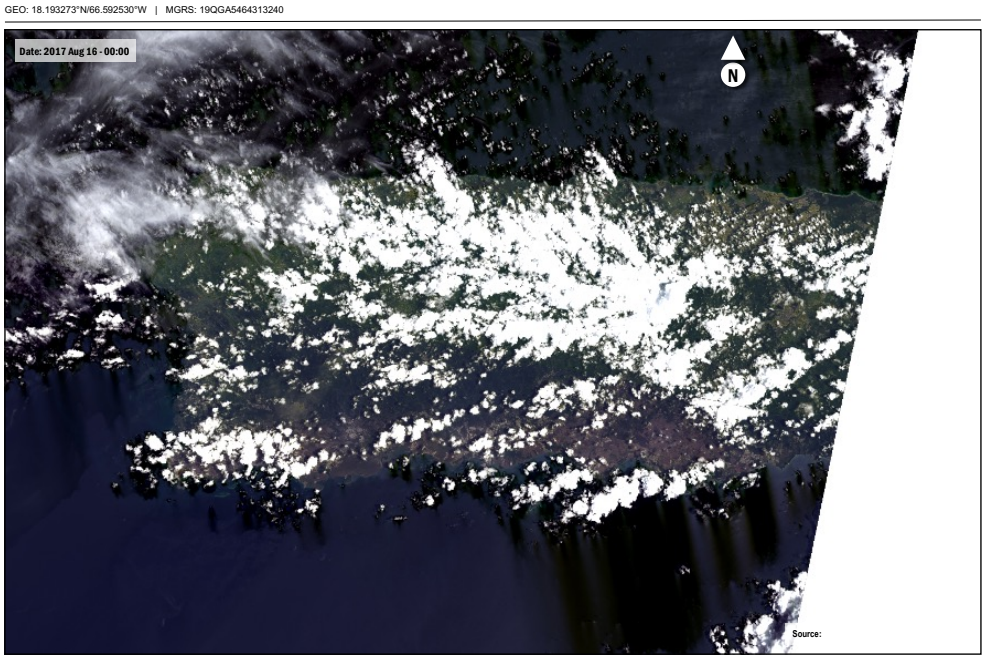


Figure 5: Example of a full view of Puerto Rico with high presence of clouds interrupting the data view and also affecting the quality. Image couldn't be used.

c) September

The month of the hurricane. Presence of clouds is manageable but quality for September 1, 2017, image is very low. River plumes start to increase for September 17, after the landfall of Hurricane Irma in northeastern Puerto Rico on September 7.

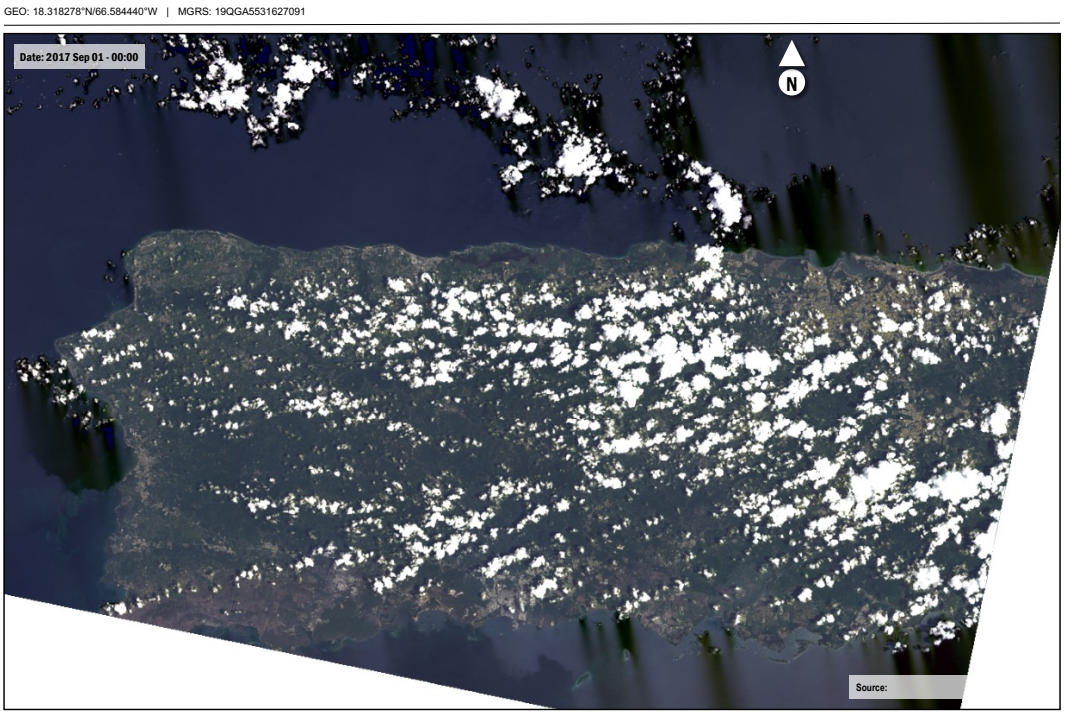


Figure 6: Island view of the rivers and vegetation for September 1, 2017. Figure is missing the eastern and southwestern parts of the island due to low quality of the images taken by OLI on those quadrangles.

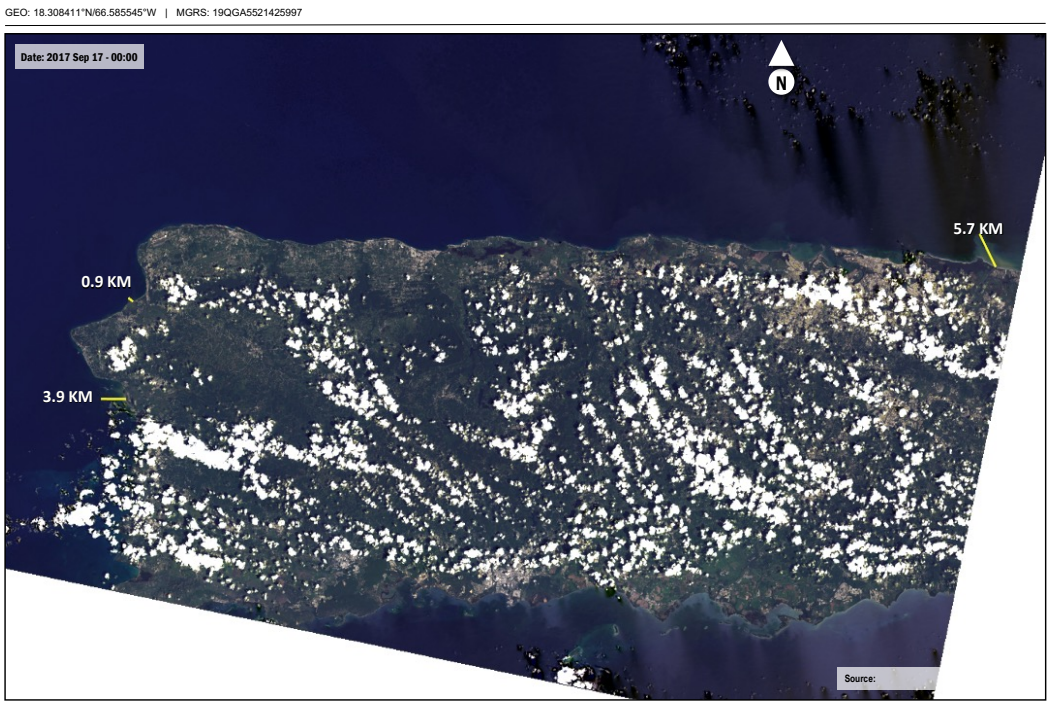


Figure 7: River plume measurements for Río Grande de Añasco (3.9km), Río Culebrinas (0.9km), and Río Grande de Loiza (5.7km) on September 17, 2017, two days prior to Hurricane Maria landfall in Puerto Rico, but 10 days after Hurricane Irma made landfall on the northeastern area of the island, which explains the 5.7km river plume from Río Grande de Loiza.

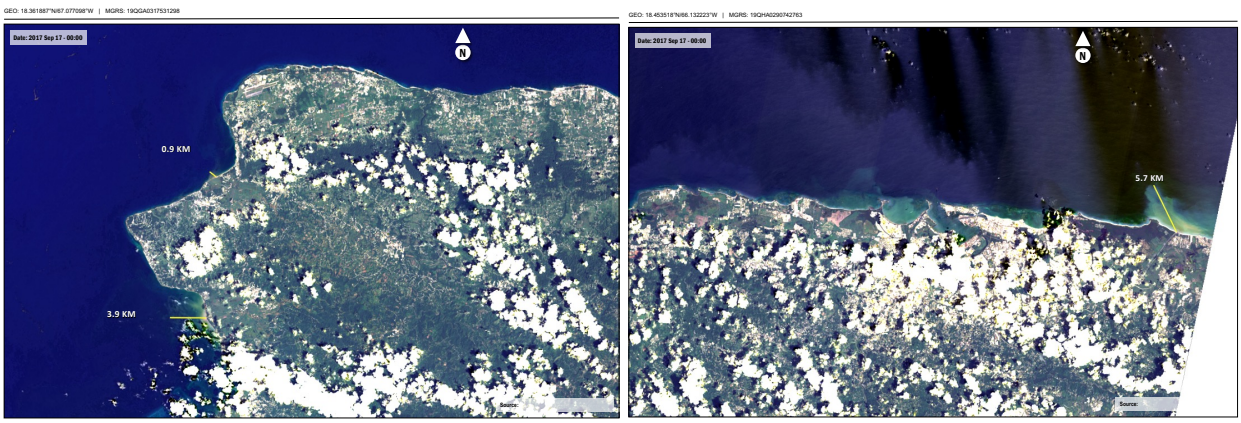


Figure 8 and 9: Left image presents zoomed view of northwestern Puerto Rico for better observation of Río Grande de Añasco (3.9km) and Río Culebrinas (0.9km) river plumes. Right image shows the zoomed in view of Río Grande de Loiza (5.7km).

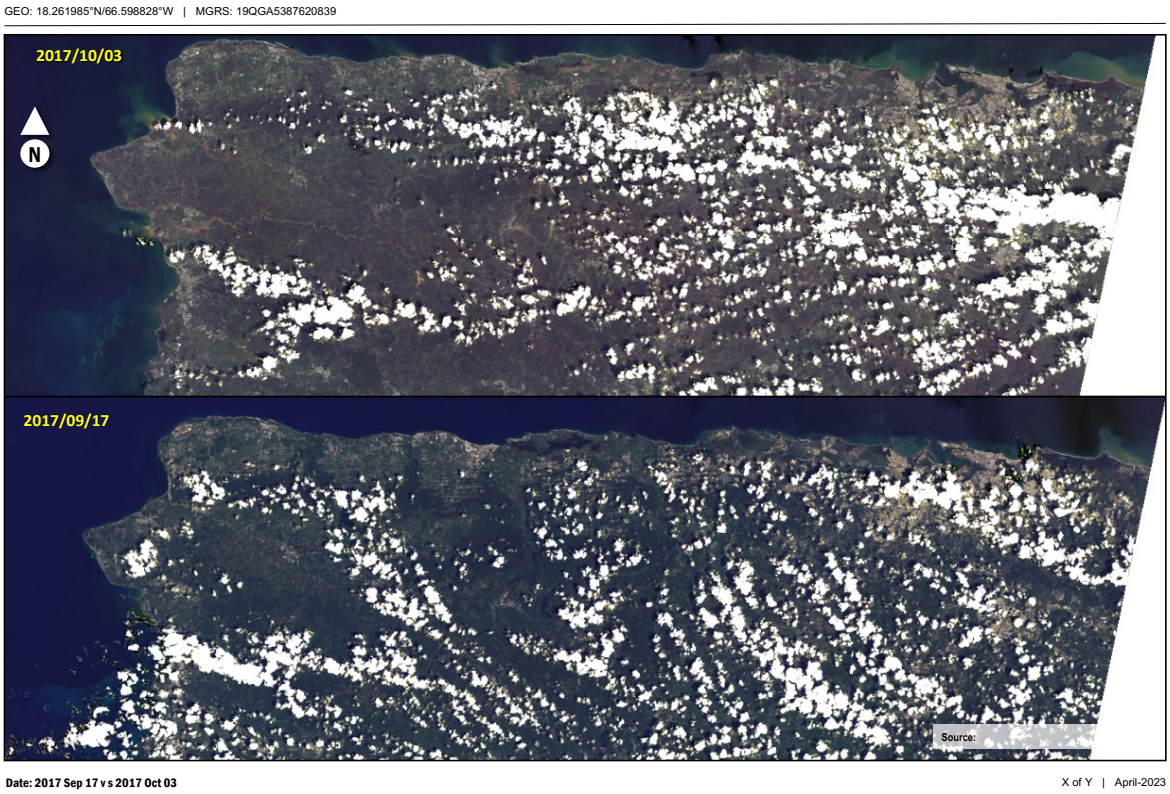


Figure 10: Puerto Rico before (down) and after (up) Hurricane Maria. Images show view of Puerto Rico two weeks after landfall of Hurricane Maria; changes in vegetation are noticeable.

d) October

The month after the hurricane. All of the images retrieved with the exception of just one (Figure 16), are from two exact weeks after the arrival of the first rain bands of the hurricane in the island, October 3, 2017. At first sight the absence of vegetation and abnormality of river plumes can be noticed.

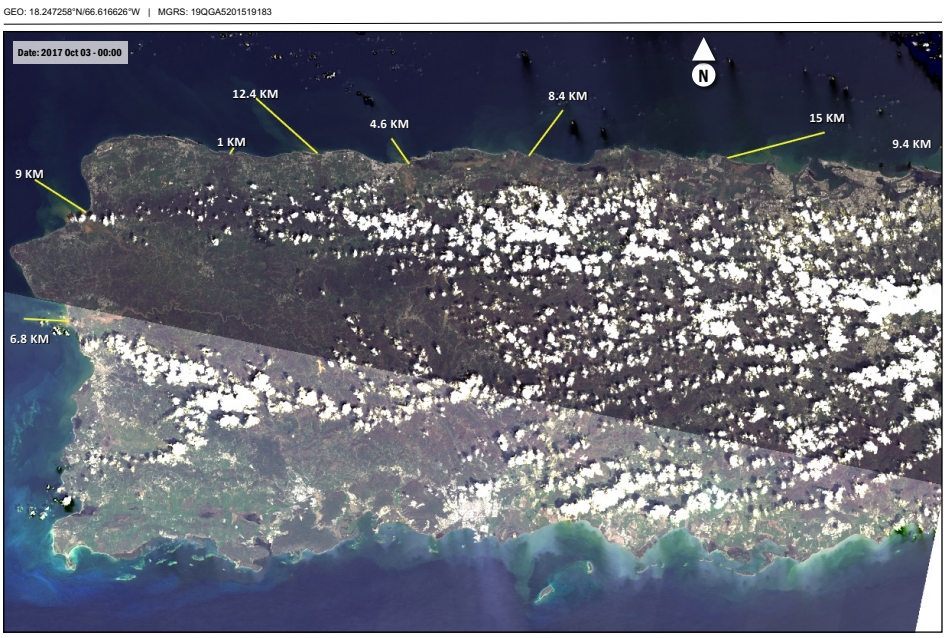


Figure 11: Image shows a full view of the island's river plumes in the north/west for October 3, 2017. All of the observable rivers are out of their stable state, except for Río Guajataca with a river plume of 1 km.

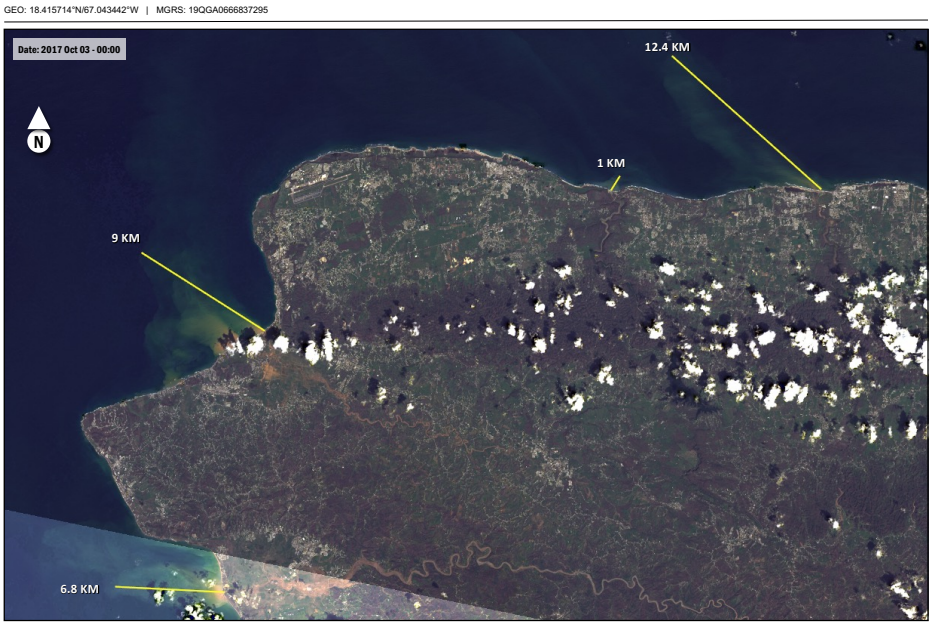


Figure 12: Zoomed view of the northwest of Puerto Rico on October 3, 2017, for better view of the river plumes in the northwest area. Río Grande de Añasco 6.8 km, Río Culebrinas 9 km, Río Guajataca 1 km, Río Camuy 12.4 km.

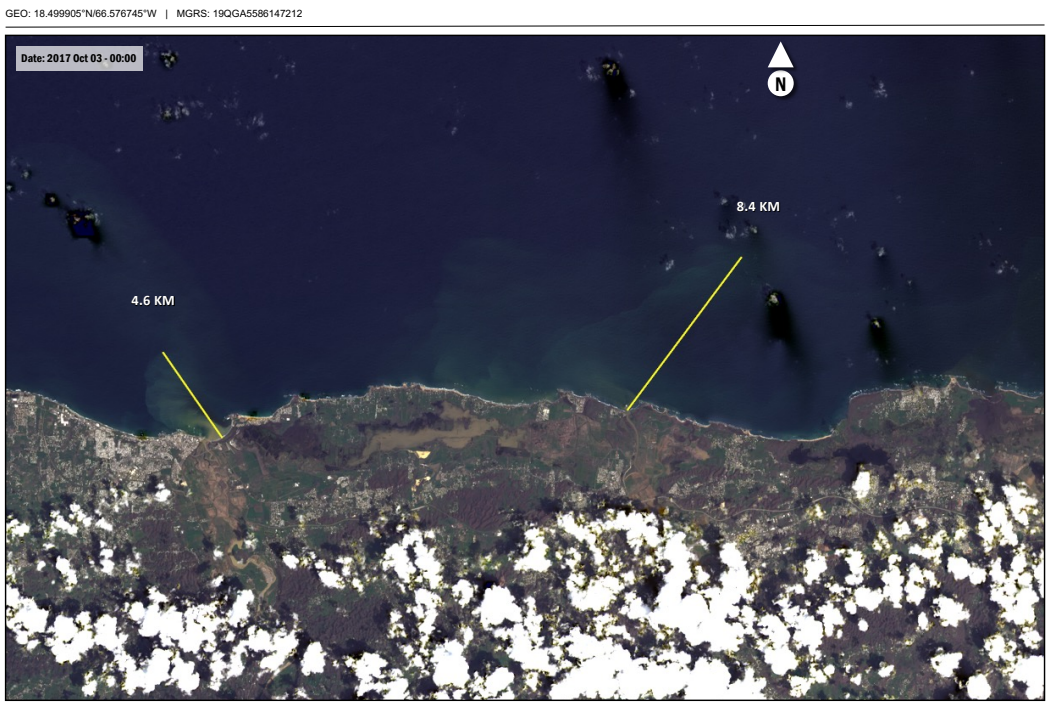


Figure 13: Zoomed view of the north of Puerto Rico on October 3, 2017, for better view of the river plumes of Río Grande de Manatí 8.4 km, Río Grande de Arecibo 4.6 km.

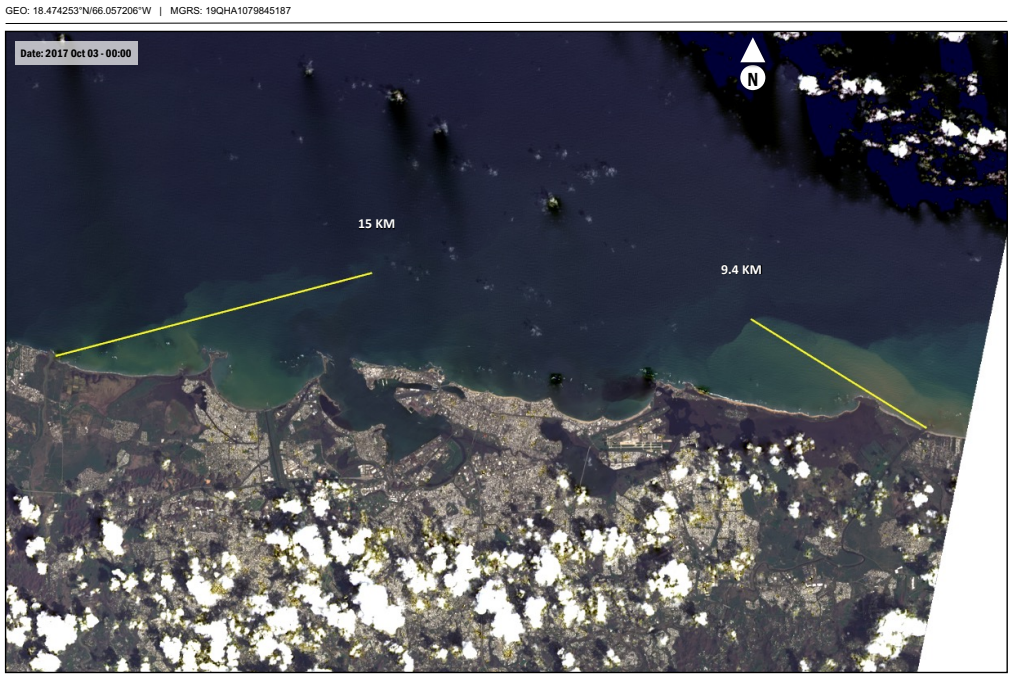


Figure 14: Zoomed view of the northeast of Puerto Rico on October 3, 2017, for better view of the Río de la Plata 15 km and Río Grande de Loiza 9.4 km river plumes.

Figure 15: Full view of Puerto Rico with exception of the east shows the lack of vegetation in most of the center of the island as well as the unstable river plumes around the north and west coastlines on October 3, 2017.

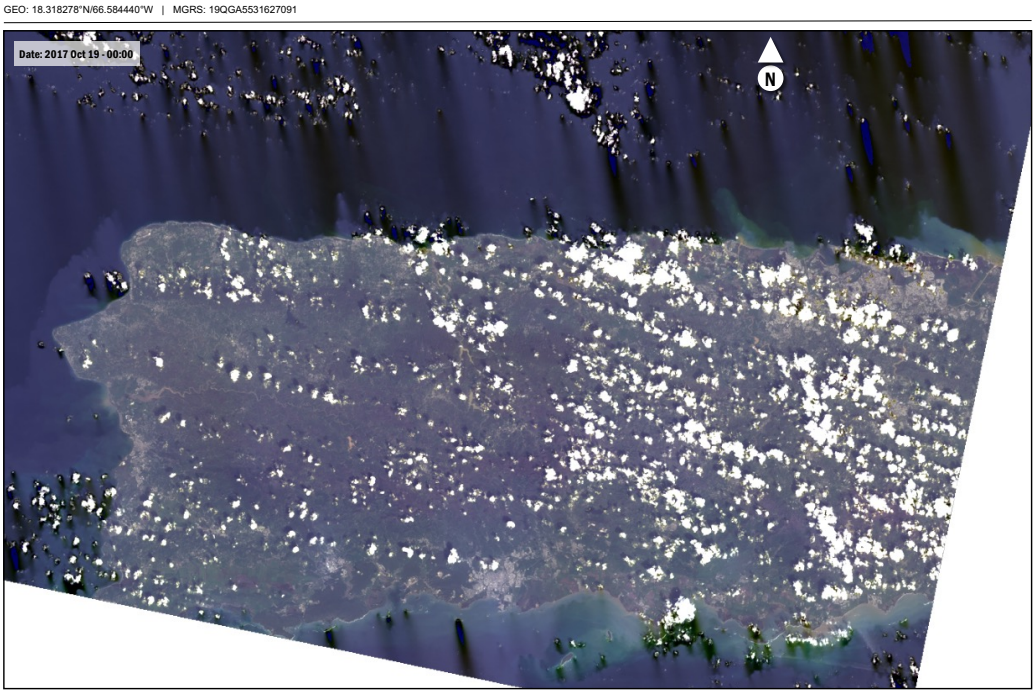


Figure 16: View of Puerto Rico cutting the east side of the island for October 19, 2017, shows low resolution and high number of clouds. However, in the northeast the unstable river plumes can be spotted very easily, as well as the sediment carried and deposited by the Río Grande de Añasco in the west side. The island still shows the affected vegetation caused by the Hurricane Maria landfall 4 weeks ago.

e) November

Six weeks after the hurricane Puerto Rico starts to show vegetation recovery, leaving only a few brown spots around the mountains in the center. Rivers in the northeast of the island still show abnormal measurements above 2 km but the rest of the island is starting to get into stable state as lengths don't surpass 2 km but still show the presence of sediment like the Río Grande de Añasco for example (see Figure 18).

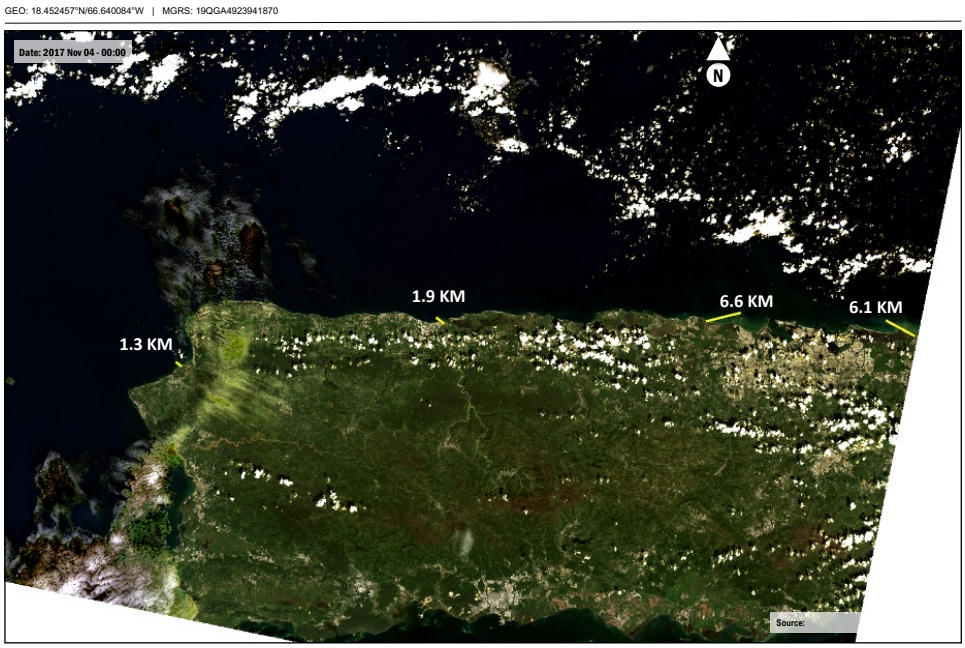


Figure 17: Absence of vegetation can be still noticed on small areas in the center of the island and river plumes at the northeast still show activity that reaches the 6 km. Northwest River plumes doesn't exceed 2 km. Río Grande de Añasco 1.9 km, Río Culebrinas 1.3 km, Río de la Plata 6.6 km, Río Grande de Loiza 6.1 km. This is a significant decrease when comparing to one month ago on October 3 for Río de la Plata and Río Grande de Loiza as they decreased by more than 3 km each.

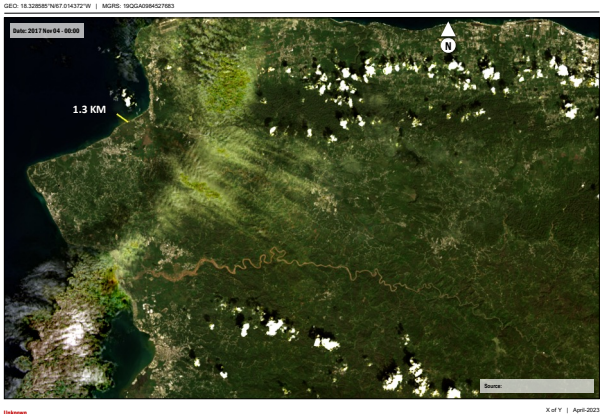


Figure 18: Presence of what seems to be clouds is interrupting the view for Yagüez and Añasco river plumes, and only small presence of sediment can be observed in Río Culebrinas.

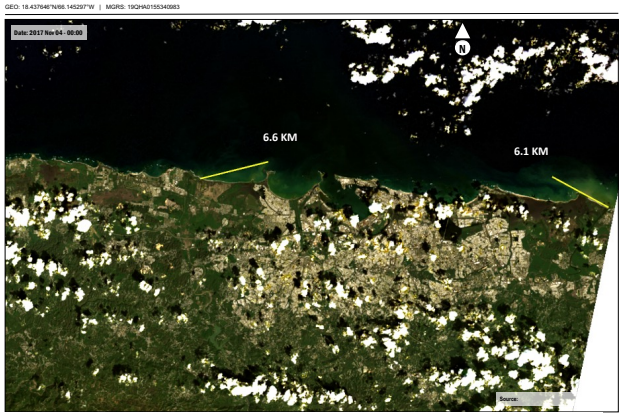


Figure 19: Image shows zoomed in view river plumes for Río Grande de Loiza (6.1 km) and Río de la Plata (6.6 km) for November 4, 2017.

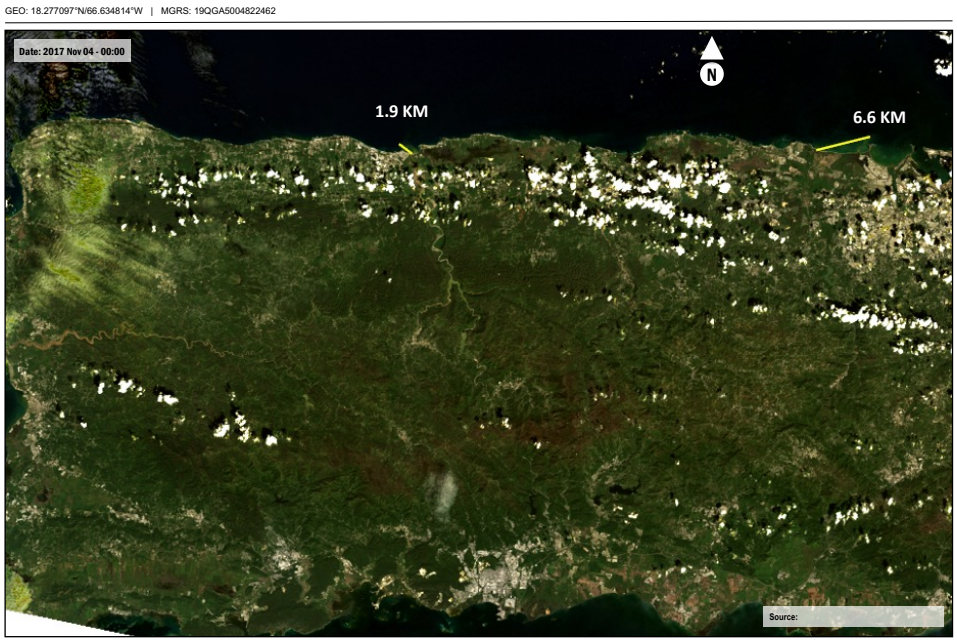


Figure 20: Northern area of Puerto Rico shows Río Grande de Arecibo with a river plume of 1.9 km vs Río de la Plata (6.6 km) indicates that this river plume difference could have been caused by huge rain activity concentrated in the northeast area of the island.

f) December

Three months after the hurricane the island looks entirely green again, but apparently a rain activity could cause river plumes to increase in length again, if assuming that the renovation of runoff is not associated to the hurricane event, which makes the estimation time of river plume stability more difficult to determine.

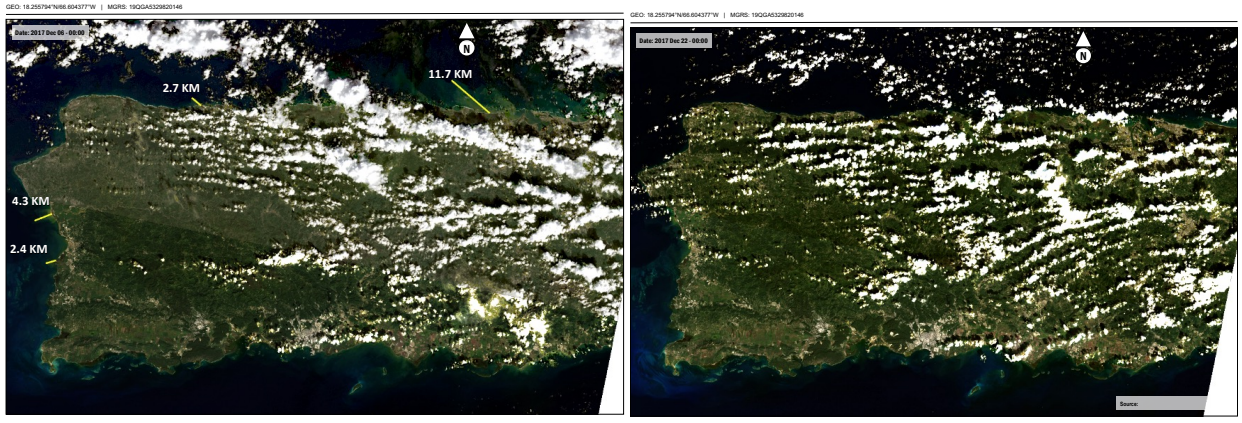


Figure 21 & 22: Images of December 6, 2017, vs December 22, 2017, show a high number of clouds that for the 22nd doesn't allow river plumes to show, while in the 6th a huge river plume can be observed for Río de la Plata, reaching 11.7 km, and also Río Grande de Arecibo (2.7 km), Río Yagüez (2.4 km) and Río Grande de Añasco (4.3 km) are showing instability by surpassing the 2km of river plume. Vegetation looks completely recovered as no brown spots can be easily observed from this full island view.

Figure 23: Image shows a river plume of 4.3 km for Río Grande de Añasco and 2.4 km for Río Guanajibo.

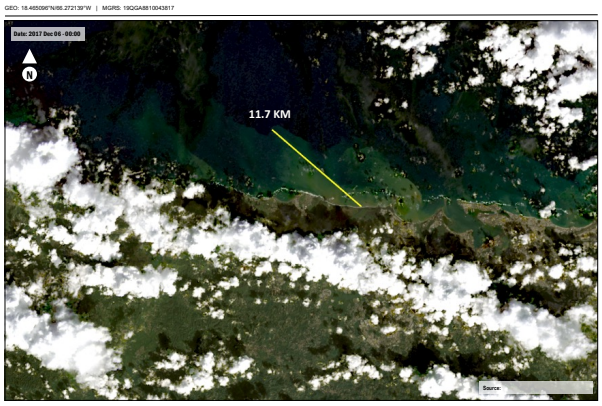


Figure 24: Zoom in for northeast river Río de la Plata with a river plume of 11.7 km.

g) January

Four months after the hurricane river plumes still look unstable but seem to be decreasing into the selected "stable state" of less than 2 km in measurement for the northern area of the island as no river plumes can be observed at first sight without zooming in. However, river plumes on the west still show some significant activity that surpasses the 3 km in length. Images correspond to January 23, 2018.

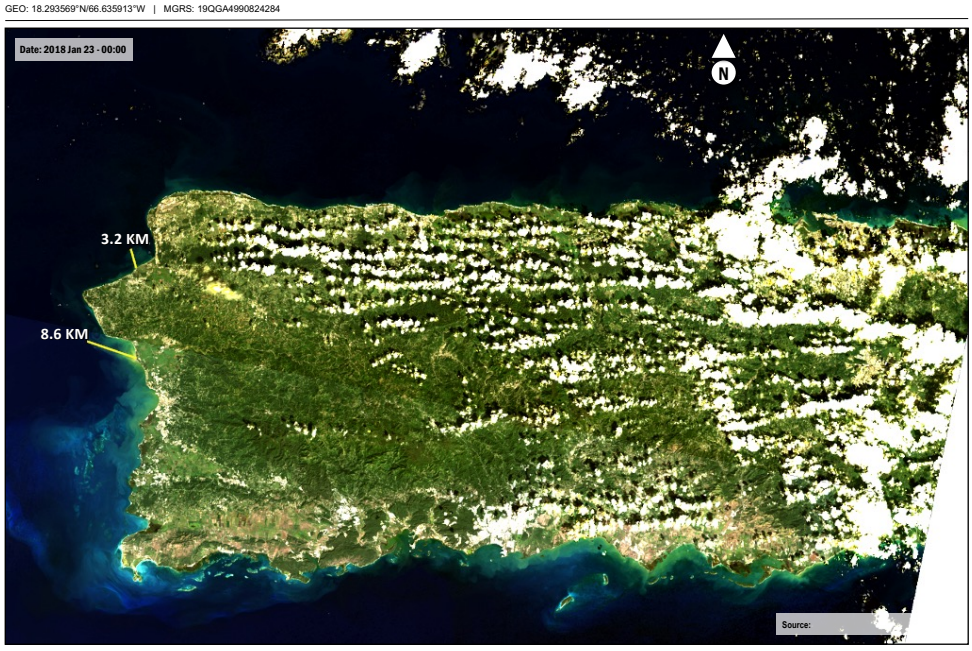


Figure 25: Full view of Puerto Rico with exception of the east shows two unstable river plumes on the west, Río Grande de Añasco with 8.6 km and Río Culebrinas with 3.2 km, while in the northern area river plumes look stable as sediment traces do not exceed 1km and aren't observable in a full island view at first sight like the Añasco and Culebrinas do.

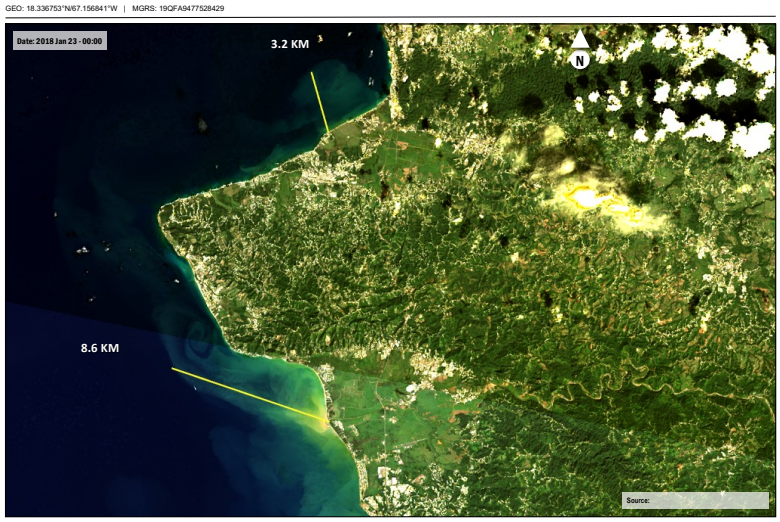


Figure 26: Zoomed in view of the sediment traces for Río Grande de Añasco (8.6 km), and Río Culebrinas (3.2 km).

h) February

Five months after the landfall of Hurricane Maria in Puerto Rico, finally all observed river plumes are found in their stable state (lengths below 2km).

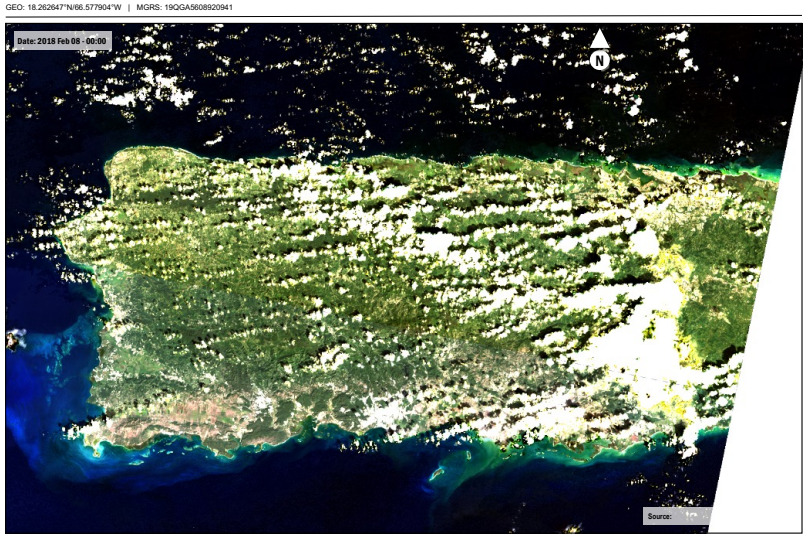


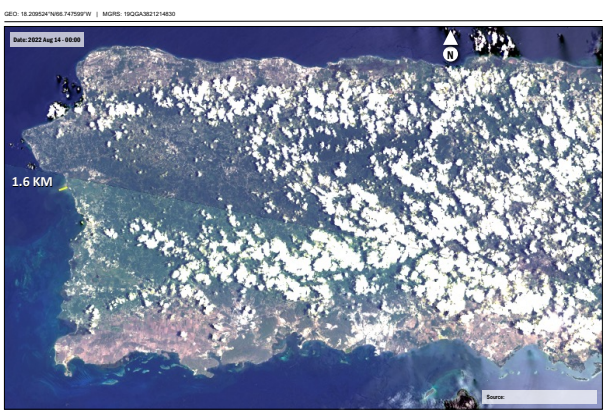
Figure 27: Full view of Puerto Rico with stable river plumes for February 8, 2018, making it five months until river plume stability after Hurricane Maria landfall in September 2017. No extended river plume traces can be observed around the island.

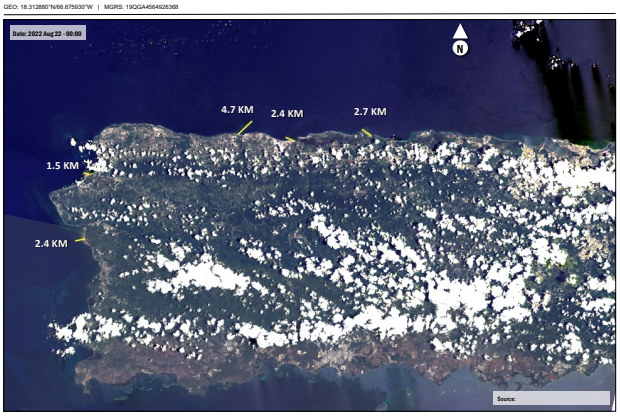
II. Hurricane Fiona

Puerto Rico started receiving rain bands and winds from the storm on September 18, 2022, but it wasn't until the next day (September 19, 2022) that the system became a category 1 hurricane with winds of 70 knots (US Department of Commerce, N.O.A.A., 2022). During the afternoon of the 19th the hurricane made landfall near Punta Tocón in Lajas, leaving the island a couple of hours later and heading to the Dominican Republic (US Department of Commerce, N.O.A.A., 2022). The hurricane left damages in roads and bridges due to the flash flooding and debris, causing over 400 rescues in Salinas due to a flash flooding emergency, island wide utility outages, and landslides/rockfalls (US Department of Commerce, N.O.A.A., 2022). The images retrieved using the Earth Explorer tool for the dates of August to February show the changes in river plumes before and after the hurricane, as well as the low-quality data where the cloud cover affected the view of the coastline and consequently the river plume's view.

a) August

The month before the hurricane shows rivers carrying sediment and "unstable" river plumes based on the <2km reference length for images of August 22, 2022. However, for August 14, 2022, the reference stable length is achieved.





Figures 28 and 29: August 14 vs August 22 of 2022 show a significant change in river plumes as rain activity starts at the end of this month (National Weather Service, 2022). Figure 28 shows a stable view of river plumes while a week later on August 22nd the rain activity started and river plumes became unstable in the west for Río Grande de Añasco (2.4 km), and in the north for Río Camuy (4.7 km), Río Grande de Arecibo (2.4 km), and Río Grande de Manatí (2.7 km).

Figure 30: Zoomed view of north rivers for August 22, 2022. Contains river plumes for Río Camuy (4.7 km), Río Grande de Arecibo (2.4 km), and Río Grande de Manatí (2.7 km).

Figure 31: Zoomed view of the west of Puerto Rico to observe river plumes for Río Grande de Añasco (2.4 km) and Río Culebrinas (1.5 km) on August 22, 2022.

b) September

The month of the hurricane shows very low-quality images with the presence of numerous clouds and very unstable rivers that reach up to 8.4 km in the northeast of the island. All images correspond to September 23, 2022, when Hurricane Fiona had already made landfall in the island and left approximately 4 days earlier.

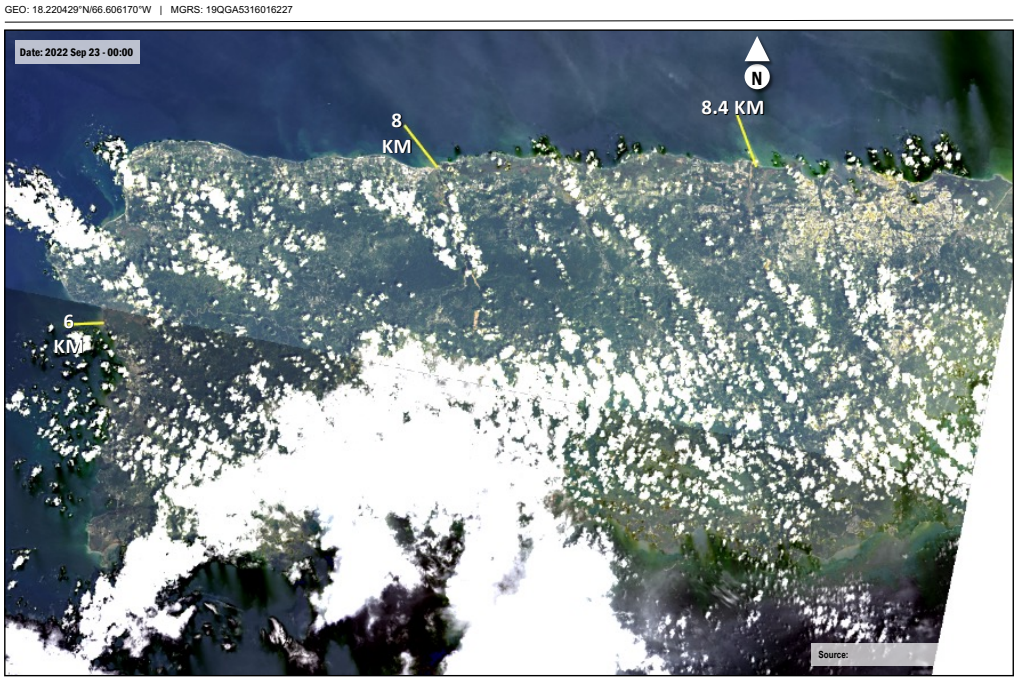


Figure 32: Full view of the island shows Río Grande de Arecibo with a river plume of 8 km, Río de la Plata with 8.4 km, and Río Grande de Añasco plume reached 6 km. There are no noticeable changes in vegetation after the landfall of Hurricane Fiona.

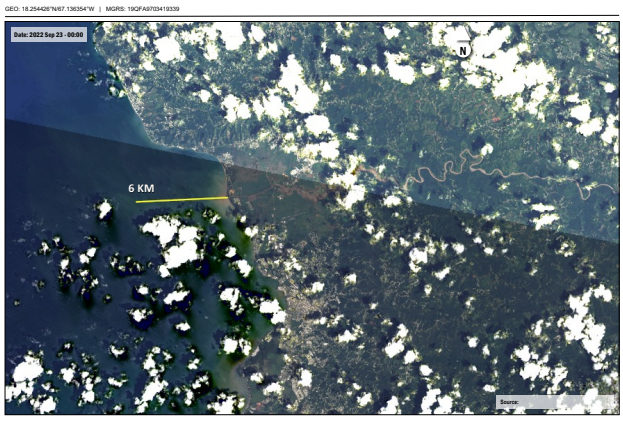


Figure 33: Zoomed view for Río Grande de Añasco to observe the 6km river plume and the brown trace of sediment in the meander.

Figure 34: Zoomed view of northern Puerto Rico to observe the river plumes for Río Grande de Arecibo (8km) and Río de la Plata (8.4km), which also show a sediment trace in the meander.

c) October

One month after the hurricane the images retrieved had the presence of clouds in the northern coastline, which didn't allow the view of the river plumes in that area, but Río Grande de Añasco shows stability with a river plume of approximately1.8 km. However, when looking closer to the meander, there is presence of sediment, which indicates that the river is not stable at all, as it is still carrying sediment after a rain event. Images correspond to October 25, 2022.

Figure 35: Full view of the island shows the presence of clouds in the north/northeast areas, while Río Grande de Añasco shows a river plume of 1.8 km.

Figure 36: Closer view to Río Grande de Añasco shows the sediment trace in the meander and the sediment deposition at river mouth. However, image quality is so low that sediment trace in the water is interrupted by small/blurry clouds at sea, which could explain the short length of the river plume in comparison with the actual status of it.

d) November

Two months after the hurricane landfall, cloud activity allowed the coastline to show, and river plumes are indeed unstable. Río Grande de Añasco shows a river plume of 8.4 km, which confirms that October measurements are affected by the low quality of the image and the presence of clouds. River plumes in the north/northeast show lengths that reach 11.4 km.

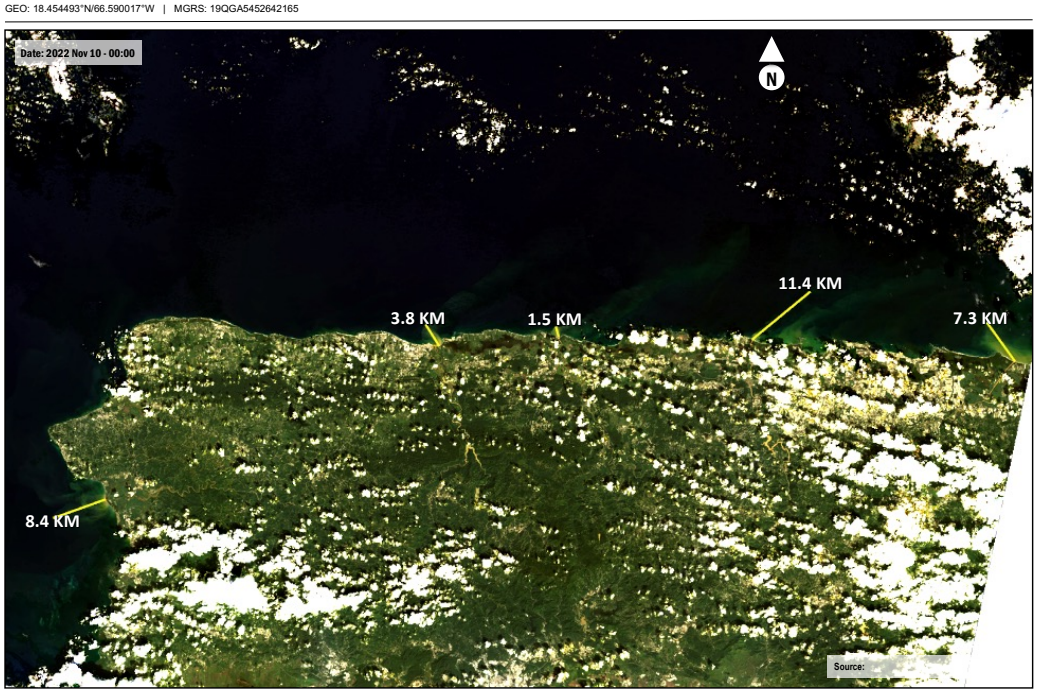


Figure 37: Full view of Puerto Rico for November 10, 2022, shows Río Grande de Añasco with a river plume that reaches 8.4 km, Río Grande de Arecibo in the north reaches 3.8 km, Río Grande de Manatí has a stable level of 1.5 km, Río de la Plata has the longest river plume in the image with 11.4 km and Río Grande de Loiza reaches 7.3 km.

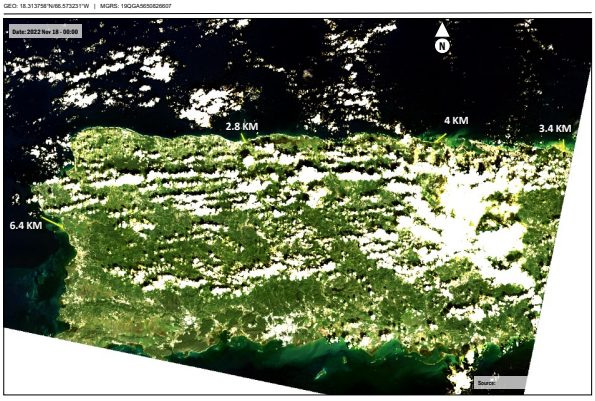


Figure 38: One week after previous image (Fig.37), on November 18, 2022, all the mentioned river plumes show a significant decrease in length. Río Grande de Añasco from 8km to 6.4km, Río Grande de Arecibo from 3.8km to 2.8km, Río de la Plata from 11.4km to 4km, and Río Grande de Loiza from 7.3km to 3.4km.

Figure 39: November 26, 2022, shows no clear river plume traces in northern Puerto Rico, but Río Grande de Añasco hasn't yet returned to the stable state below 2km.

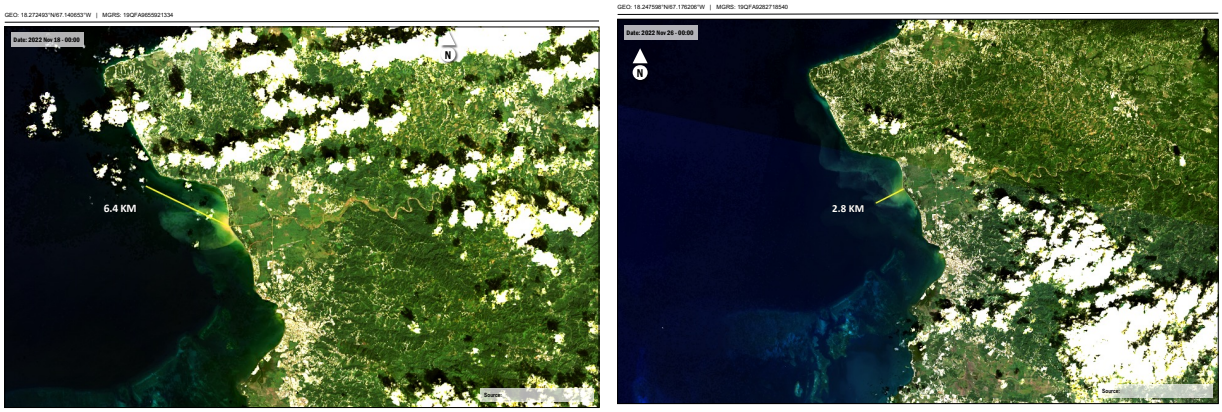


Figure 40 and 41: Closer view to the Río de Añasco river plume for the dates of November 18 (left), and November 26 (right), where in both the sediment trace in the meander can be observed.

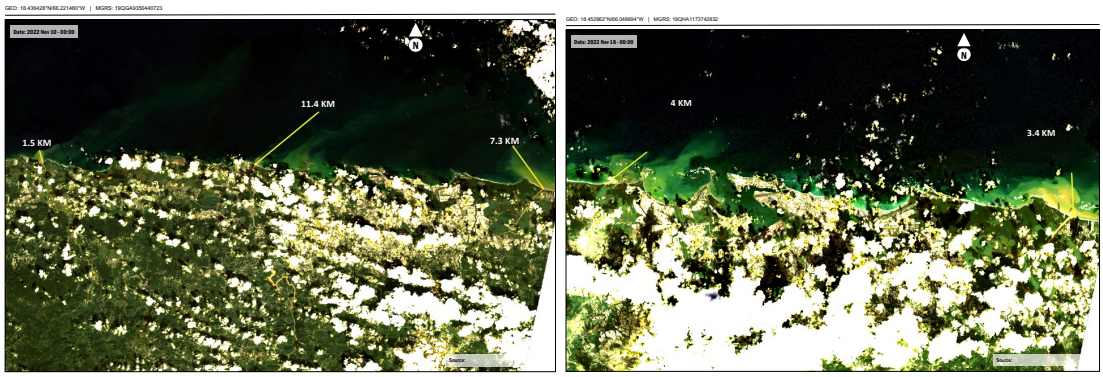


Figure 42 and 43: River plumes for northeast Puerto Rico on November 10 vs November 18 shows significant decrease in the river plumes lengths for Río de la Plata (11.4km vs 4km), and Río Grande de Loiza (7.3km vs 3.4km).

e) December

Three months after Hurricane Fiona river plumes still look unstable around the island but decreasing progressively. The number of clouds in the images are very high and interrupt the observation of river plumes for northeastern Puerto Rico on December 20.

Figure 44: Full view of the island for December 12, 2022, contains unstable river plumes for Río Grande de Añasco (2.1km), Río Grande de Arecibo (2.9km), Río de la Plata (2.8km), and Río Grande de Loiza (3.9km).

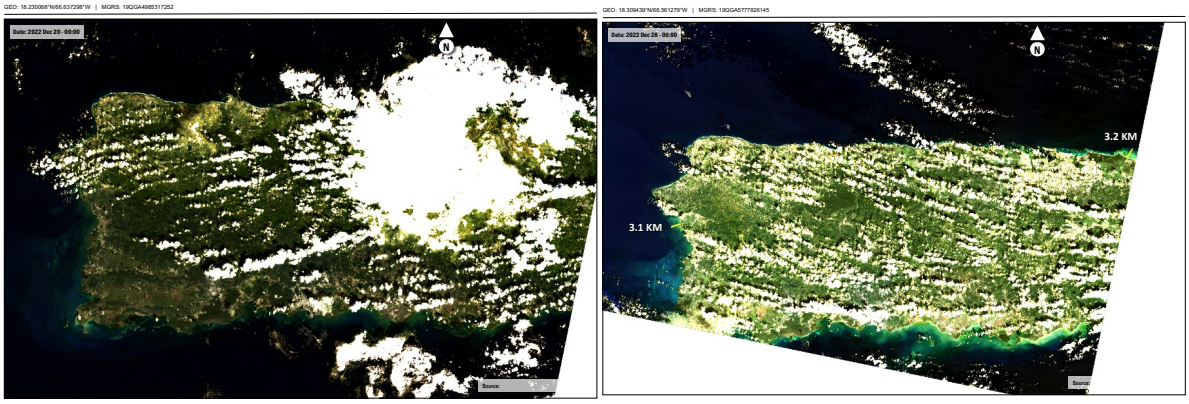


Figure 45 and 46: December 20 vs December 28, 2022, presents the influence of clouds on an image and how the research observations were affected by them. On December 20 no measurements could be made on the northeastern area, while December 28 showed the 3.2km on Río Grande de Loiza.

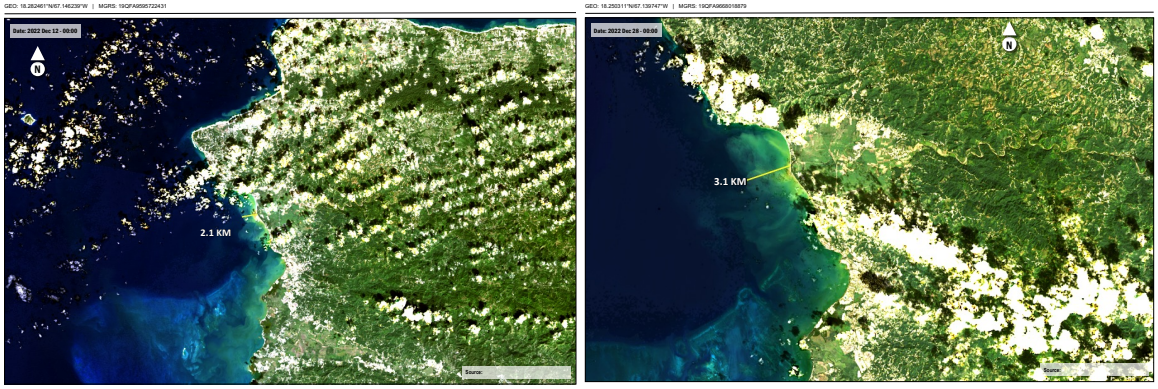


Figure 47 and 48: Left image has the river plume trace of Río Grande de Añasco of 2.1km on December 12, while on the right image the river plume increased to 3.1km on December 28, 2022.

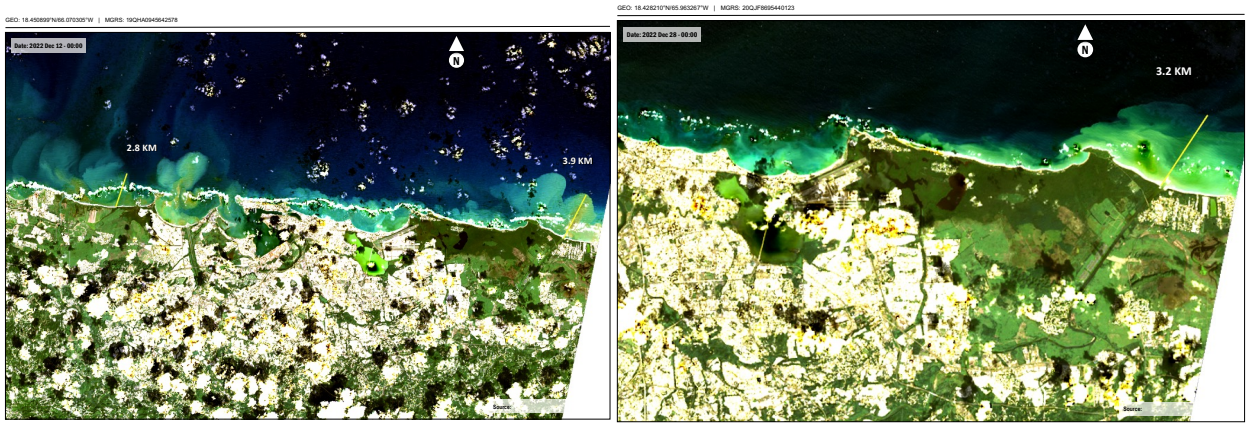


Figure 49 and 50: Images display the decrease in length for Río Grande de Loiza for the dates of December 12 vs December 28.

f) January

Four months after the landfall of Hurricane Fiona on the island river plumes appear to be back into their stable state, but because the cloud presence didn't allow the full view of the island, the data set was then extended to February in the search of a full view of the island with river plumes below 2km in length.

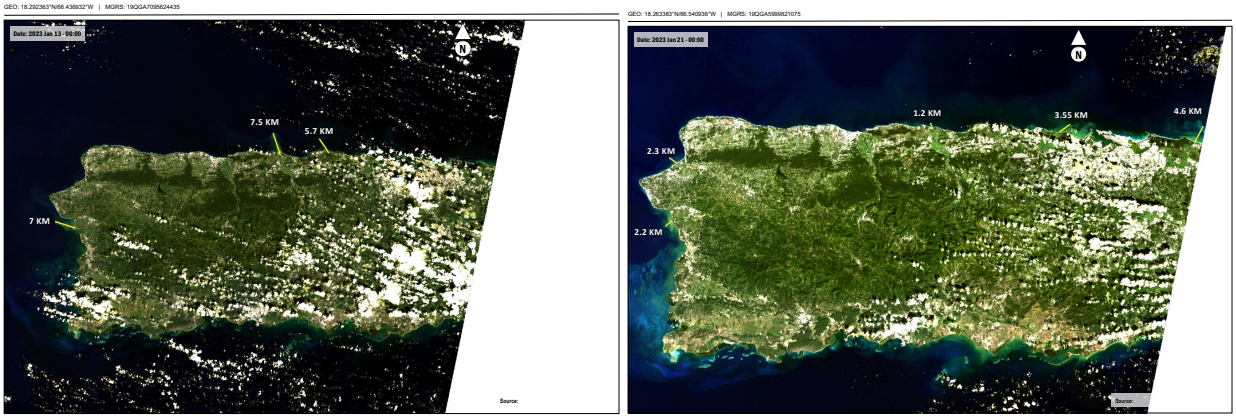


Figure 51 and 52: River plume state for January 13 vs January 21 shows significant decrease in length, but an increase in comparison with last image from December. January 13 doesn't show river plume traces for northeastern Puerto Rico, but January 21 has a 4.6 km trace in Río Grande de Loiza and 3.5km for Río de la Plata.

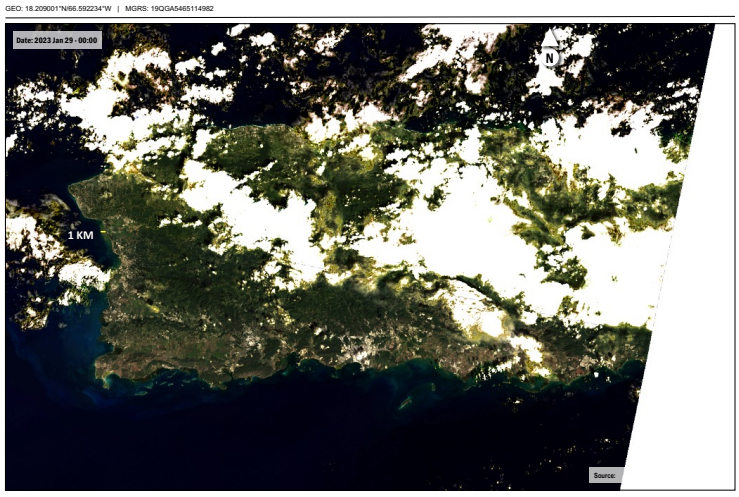


Figure 53: Image displays a huge cloud interference around the north and east areas of Puerto Rico, while on the west Río Grande de Añasco contains a stable river plume of 1km.

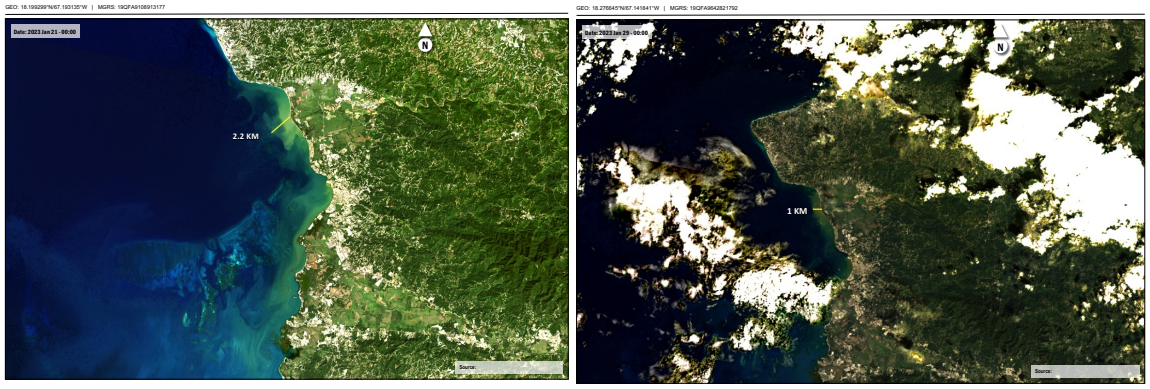


Figure 54 and 55: Left image displays the river plume for the Río Grande de Añasco on January 21 with a length of 2.2km, while January 29 shows the stable state of 1km, which indicates that in a week this river reached its stable state.

g) February

All visible river plumes are finally confirmed as stable, five months after the landfall of the hurricane. There is still interference of clouds in northern Puerto Rico, but the most significative river plumes on the west (Añasco) and the northeast (la Plata and Loiza), are finally stable.

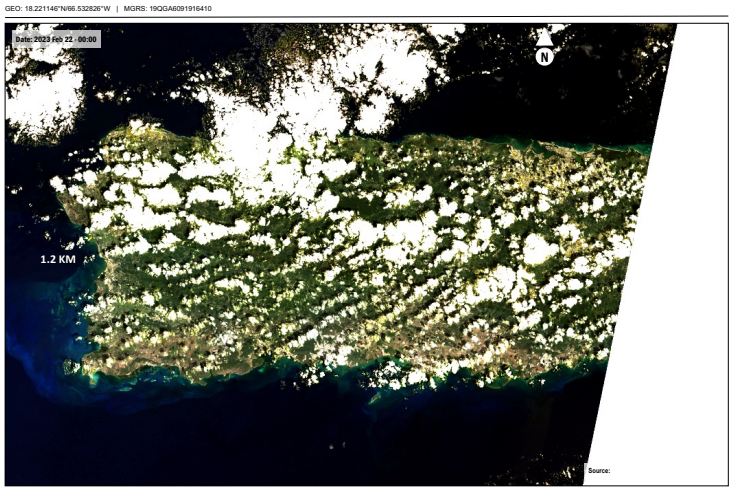


Figure 56: Full view of the island where stable river plumes can be observed in the west and northeastern areas. Northern Puerto Rico is mainly covered by clouds, which affects the view for Arecibo and Camuy rivers.

Summary Tables

	Months & Lengths (km) 2017-2018							
Rivers	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb
Río Grande de Añasco	1.3	1.6	3.9	6.8	-----	4.3	8.6	----
Río Yagüez	-----	-----	-----	-----	-----	2.4	----	----
Río Culebrinas	1.8	-----	0.9	9	1.3	-----	3.2	----
Río Guajataca	-----	-----	-----	1	-----	-----	----	----
Río Camuy	-----	-----	-----	12.4	-----	2.7	----	----
Río Grande de Arecibo	-----	-----	-----	4.6	1.9	-----	----	----
Río de la Plata	-----	-----	-----	15	6.6	11.7	----	----
Río Grande de Loiza	-----	-----	5.7	9.4	6.1	-----	----	----
Río Grande de Manatí	-----	-----	-----	8.4	-----	-----	----	----

Table 1: Summary of the river plume lengths for the Hurricane Maria data set for the dates of July 2017 to February 2018.

	Months & Lengths (km) 2022-2023						
Rivers	Aug14 & 22	Sept	Oct	Nov 10	Dec 12	Jan 13 & 21	Feb
Río Grande de Añasco	1.6-2.4	6	1.8	8.4	2.1	7-2.2	1.2
Río Yagüez	-----	-----	-----	-----	-----	2.3	----
Río Culebrinas	1.5	-----	-----	-----	-----	3.2	----
Río Guajataca	-----	-----	-----	-----	-----	----	----
Río Camuy	4.7	-----	-----	-----	-----	----	----
Río Grande de Arecibo	2.4	8	-----	3.8	2.9	----	----
Río de la Plata	-----	8.4	-----	11.4	2.8	3.5	----
Río Grande de Loiza	-----	-----	-----	7.3	3.9	4.6	----
Río Grande de Manatí	2.7	-----	-----	1.5	-----	7.5-1.2	----
Río Cibuco	-----	-----	-----	-----	-----	5.7	----

Table 2: Summary of the river plume lengths for the Hurricane Fiona data set for the dates of August 2022 to February 2023.

These tables show the critical variation from one month to the other starting in November for both datasets, where instead of decreasing progressively, they increase in December and/or January.

Conclusions

River plume stability can't be standardized as there is so much variation of rain activity on the island throughout the months and with this type of data set it is difficult to determine whether the river plumes from the third month after the hurricane and onward are actually related to the hurricane effects, or if they are related to other rain activities on the island that might have occurred in between image taking from the satellites as the temporal resolution is 16 days (NASA, 2021). Rain activity in between images from months like November and forward, could actually explain the variation in river plume lengths from one month to the other, or even from one week to the other like it is for Figures 47 and 48 that correspond to December in the Río Grande de Añasco, which shows an increase of 1 km for December 28, instead of a decrease. This hypothesis can be slightly confirmed based on the National Weather Service monthly summaries, where for December 18, 2022, a widespread of rain occurred (National Weather Service, 2022), although its accumulations weren't significative, it could be linked to the 3.1km and 3.2 km on Río Grande de Añasco on the west and Río Grande de Loiza on the northeast.

Another observation is the noticeable changes on the island that Hurricane Maria left vs the almost no change at all after Hurricane Fiona in Puerto Rico. This clearly shows the difference of a category 4 hurricane vs a category 1 hurricane on the island. As a result, the longest river plumes measured were taken from Hurricane Maria data set on October 2017, with a river plume of 15 km for Río de la Plata. In addition, for both data sets the river plumes in the northeastern took more time than the river plumes on the west to decrease in length. This could be caused not only by the rain activity on eastern Puerto Rico, but it also could be linked to sediment type and weight, as sediments on the west are known to be more dense and sink faster, while the sediments on the north seem to be less dense and stay floating for longer periods, which makes the river plume appear unstable for longer periods of time although there hasn't necessarily been any significative rain activity on the area supplying the sediment to it. This last hypothesis can be also observed on Figures 57-60, where an estimation of mean annual suspended sediment for Puerto Rico coastal waters was made for the dates of October 1990 to September 2000 (Warne, A.G., et. al., 2005). For the mean annual-sediment yield, the south of Puerto Rico shows the highest discharge, followed by the north, which means in fact that the north of the island produces more suspended sediment than the west, and could explain why the northeastern plumes were unstable for longer periods in comparison to western river plumes.

Region of island	Mean annual suspended-sediment yield, metric tonnes/km^2	Contributing area, km^2	Mean annual suspended- sediment discharge, metric tonnes
North	120 to 1,000	2,317	280,000 to 2,300,000
East	140 to 520	356	51,000 to 180,000
South	1,000 to 4,300	1,300	1,400,000 to 5,600,000
West	1,200	783	960,000
	Mean: 570 to 1,900*	Total: 4,786	Total: 2.7 to 9.0 million

Figure 57: Estimation of mean annual suspended sediment discharge in Puerto Rico coastal waters from October 1990 to September 2000. Table confirms that northern Puerto Rico produces more annual suspended sediment than western Puerto Rico (Warne, A.G., et. al., 2005).

Table 5. Estimates of precipitation and river discharge for the 6-day period from September 20-25, 1998. Hurricane Georges crossed the island on September 21-22, 1998.

[km^2, square kilometer; mm, millimeter; m^3, cubic meter; mm/d, millimeter per day]

Region of island	Area draining to coast, km^2	Fraction of total island area	Precipitation, mm	Precipitation volume, million m^3	Rainfall runoff ratio	Discharge, million m^3	Fraction of total island runoff	Total runoff, mm	Mean runoff, mm/d
North	4,635	0.53	280	1,300	0.45	581	0.57	130	21
East	540	0.06	200	110	0.55	58.9	0.06	110	18
South	1,970	0.23	320	630	0.22	136	0.13	69	12
West	1,566	0.18	360	560	0.45	250	0.24	160	27
Area-weighted average			300		0.40			120	20
Total	8,711	1.00		2,600		1,000	1.00		

Table 6. Summary statistics of suspended-sediment discharge for selected sediment monitoring stations in Puerto Rico, October 1990 to September 2000.

[ID, identification number; km^2, square kilometers; I, Tropical Storm Isabel-October 6, 1985; H, Hurricane Hortense-September 10, 1996; G, Hurricane Georges-September 22, 1998]

Figure 58: Northern Puerto Rico drained an area of 4,635 km^2 on a 6-day period, while western Puerto Rico drained 1,566 km^2 for the same amount of time, although the west received more rain than the north did (360mm in the west vs 280mm in the north)(Warne, A.G., et. al., 2005).

Figure 9. Texture and composition of surficial sediment and their distribution on the insular shelf of Puerto Rico (compiled from Beach and Trumbull, 1981; Trumbull and Trias, 1982; Grove, 1983; Pilkey, 1987; Trias, 1990; Rodríguez and others, 1992, 1998; Scanlon and others, 2001).

Figure 59: Map of Puerto Rico with the selected rivers around the coastline for the Warne, et. al., research, with their corresponding sediment composition, indicating that sediments in the northeast are terrigenous clastic, while sediments in the west are mixed terrigenous and carbonate clastic. (Warne, A.G., et. al., 2005)

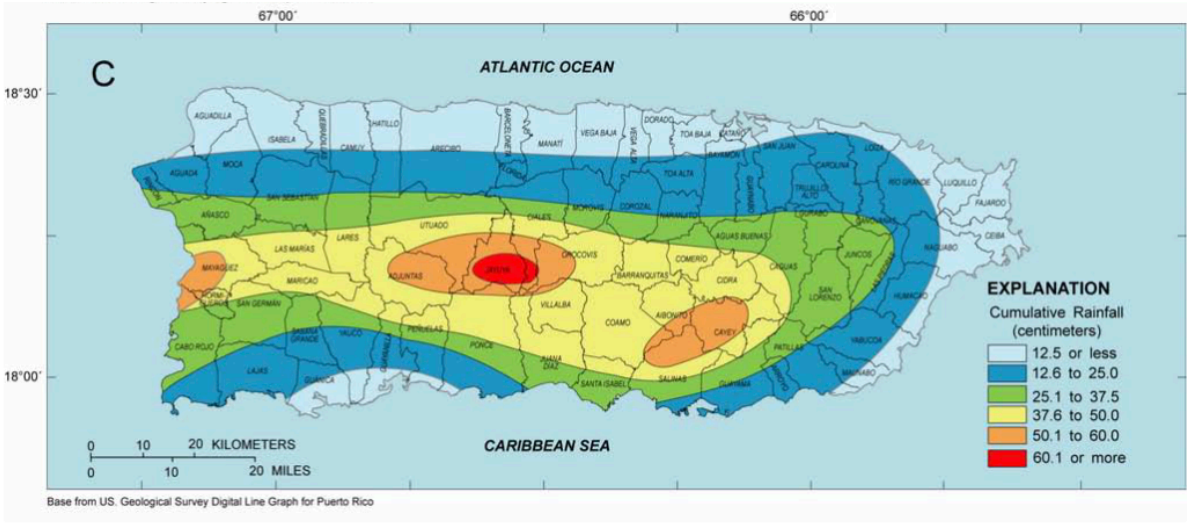


Figure 8. Rainfall-runoff characteristics of Puerto Rico: (A) The four major runoff (climatological) regions of Puerto Rico (simplified from National Oceanic and Atmospheric Administration, 1999). (B) Mean annual rainfall distribution (modified from Calvesbert, 1970) and the major coastal zones of Puerto Rico (after Kaye, 1959); see table 11 for a description of the coastal zones. (C) Cumulative precipitation associated with Hurricane Georges, September 21-22, 1998 (modified from U.S. Geological Survey, 1999).

Figure 60: Map of cumulative rainfall and rainfall-runoff in Puerto Rico. Highest precipitation occurs in the center of the island, but western Puerto Rico receives more rain than northern Puerto Rico (Warne, A.G., et. al., 2005).

Consequently, based on these figures, we can infer that western Puerto Rico receives more rain than northern Puerto Rico, but because of sediment density the river plumes in the north remain for much longer than the river plumes on the west. In addition, northern Puerto Rico have higher discharges than western Puerto Rico. Therefore, this information from Warne, et. al., and the National Weather Service rainfall summary can be used to explain the amount of time that river plumes in Puerto Rico took to get back into a stable state after the hurricanes, by observing the type of sediment deposited by rivers in the west vs rivers in the north, and also taking into consideration other rain events that may have occurred after the hurricane and in between the satellite images retrieval.

References

[1] Community Surface Dynamics Modeling System, 2020, Plume: CSDMS, https://csdms.colorado.edu/wiki/Model:Plume

[2]Discover Puerto Rico, 2023, Best beaches in Puerto Rico, https://www.discoverpuertorico.com/article/best-beaches-puerto-rico.

[3] Feng, Y., Negrón-Juárez, R.I., and Chambers, J.Q., 2020, Remote Sensing and statistical analysis of the effects of hurricane Maria on the forests of Puerto Rico: Remote Sensing of Environment, https://www.sciencedirect.com/science/article/abs/pii/S0034425720303102?fr=RR-2&ref=pdf_download&rr=7985e65c3af867ec

[4]Furnas, M.J., 1970, River plumes and coral reefs: SpringerLink, https://link.springer.com/referenceworkentry/10.1007/978-90-481-2639-2_143 rain events

[5] Marlier , M.E., Resetar, S.A., Lachman, B.E., Anania, K., and Adams, K.A., 2022, Remote Sensing for Natural Disaster Recovery: Lessons learned from Hurricanes Irma and Maria in Puerto Rico: Environmental Science & Policy, https://www.sciencedirect.com/science/article/pii/S1462901122000764

[6] Miller, P.W., Kumar, A., Mote, T.L., Moraes, F.D., and Mishra, D.R., 2019, Persistent hydrological consequences of Hurricane Maria in Puerto Rico: Geophysical Research Letters, v. 46, p. 1413–1422, doi: 10.1029/2018gl081591.

[7] Myers, G.N., 2022, Hurricane Fiona dampened but didn't sink travel to Puerto Rico: Travel Weekly, https://www.travelweekly.com/Caribbean-Travel/Puerto-Rico-tourism-Fiona-aftermath.

[8] NASA, 2023, Landsat 8, https://landsat.gsfc.nasa.gov/satellites/landsat-8/ .

[9] NASA salinity: Air-Sea Interactions: Hurricanes, https://salinity.oceansciences.org/highlights02.htm

[10] National Weather Service, 2022, State climate summaries 2022: Puerto Rico and the U.S. Virgin Islands - State Climate Summaries 2022, https://statesummaries.ncics.org/chapter/pr/

[11]Neal, J.W., Lilyestrom, C.G., and Kwak, T.J., 2009, Factors influencing tropical island freshwater fishes: Species, status, and management implications in Puerto Rico: Fisheries, v. 34, p. 546–554, doi: 10.1577/1548-8446-34.11.546.

[12] Operational Land Imager, 2021, NASA, https://landsat.gsfc.nasa.gov/satellites/landsat-8/spacecraft-instruments/operational-land-imager/

[13]US Department of Commerce, N.O.A.A., 2021, Major hurricane Maria - September 20, 2017: National Weather Service, https://www.weather.gov/sju/maria2017

[14]US Department of Commerce, N.O.A.A., 2022, Hurricane Fiona - September 17-19, 2022: National Weather Service, https://www.weather.gov/sju/fiona2022

[15]Survey, U.-U.S.G. Earthexplorer: EarthExplorer, https://earthexplorer.usgs.gov/

[16] Together Puerto Rico, 2020, http://www.togetherpuertorico.com/preparing-for-a-hurricane/.

[17] Warne, A.G., Webb, R.M.T., and Larsen, M.C., 2005, Water, sediment, and nutrient discharge characteristics of Puerto Rico rivers and their potential influence on coral reefs: Scientific Investigations Report, doi: 10.3133/sir20055206.

[18] Warrick, J., and Farnsworth, K.L., 2017, Coastal River Plumes: Collisions and coalescence: Progress in Oceanography, https://pubs.er.usgs.gov/publication/70186373

[19] Wild & scenic rivers Forest Service National Website, https://www.fs.usda.gov/detail/elyunque/landmanagement/planning/?cid=fseprd713367.