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Determination of the Origin of the Sediments Discharged by the Río Grande de Añasco

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Abstract:

The main purpose of this project was to evaluate the potential of remote sensing techniques and selected laboratory analyses to determine the origin and composition of sediments discharged by the Rio Grande de Añasco (RGA). Sediments at the mouth of the river were collected for granulometric and XRD analysis. A Landsat TM image was used to create NDVI and supervised images. Four additional layers of information for the RGA were compared with the generated images, they were the geology, soil, catchment and tributaries,. The sediments at the mouth of the river had a grain size that goes from pebble to silt. The beach sediments had finer grain size, from granule to silt. The river energy at the mouth is low. Small quantities of silt (0.06%, 0.03%) were found in this area because the waves do not let sediments in suspension to settle down on the bottom. Greater amounts of silt (0.27%, 0.15%, 0.09%) were found at the channel because sediments in suspension can settle down at the bottom due to the low energy and to the fact that waves do not affect the area. This correlates with the Kaolinite ($Al_2Si_2O_5(OH)_4$) found in the XRD for the first three samples. Quartz (SiO_2), calcite ($CaCO_3$) and albite ($Al_2Si_2O_5(OH)_4$) were the other minerals detected by the XRD. Concepcion Formation, Rio Culebrinas Formation, Yauco Formation, Maricao Formation, Mal Paso Formation, Lago Garzas Formation, quartz/diorite-granodiorite, beach deposits, Coloso silty clay loam, Dagüey clay and Humatas clay, might be contributing. However, it is difficult to determine which one contributes most to the sediments that carry the river to the Bay. Further studies should be done, where the micro-watersheds of the RGA are analyzed.

Key words: Río Grande de Añasco watershed, Landsat TM, geologic map of western Puerto Rico, and soil map of Western Puerto Rico.

Introduction and Statement of the Problem:

Several investigations have evaluated water quality, nutrient concentrations, turbidity, salinity, phytoplankton, and river discharge in Mayagüez Bay. This research will use data collected from previous works of the Río Grande de Añasco (RGA) and will add new data to make a GIS database for the RGA watershed. This GIS has several layers of information for the geology of the area, land use and land cover, vegetation index and the hydrologic catchments. This effort helps to organize data from the Bay that comes from different scientific sources, making them more accessible and easy to compare. The main purpose of this project was to evaluate the potential of remote sensing techniques and selected laboratory analyses to determine the origin and composition of sediments discharged by the Rio Grande de Añasco (RGA).

The RGA is one of the major rivers discharging into Mayagüez Bay. Two other rivers, the Guanajibo and Yagüez also affect this Bay, but due to time limitations this research was focused in the RGA. The Mayagüez Bay watershed, also known as Río Grande de Añasco, is one of the largest of Puerto Rico with a catchment area of around 52,278 ha (360 km^2), which 48,130 ha belongs to the mountainous area and 4,148 ha are classified as lowland. Seven western towns (Figure 1), Añasco, Mayagüez, Las Marias, Lares, Adjuntas, Maricao and San Sebastián, form the basin. More than 97% of the land area was used in the early 70's to agriculture that included coffee and sugarcane crops. Nowadays this agriculture area is being substituted with urban development increasing the population from 50,000 in 1973 to 150,000 in 1998 (Sotomayor et al., 2004 unpublished information). The Mayagüez area has an annual precipitation range of 200-250 cm. From September through November is the period of the year with more precipitation resulting with the maximum river discharge. From February to April the rivers have the minimum discharge of the year. These differences in discharge produce in the bay changes in salinity, nutrient concentration, and turbidity, among others.

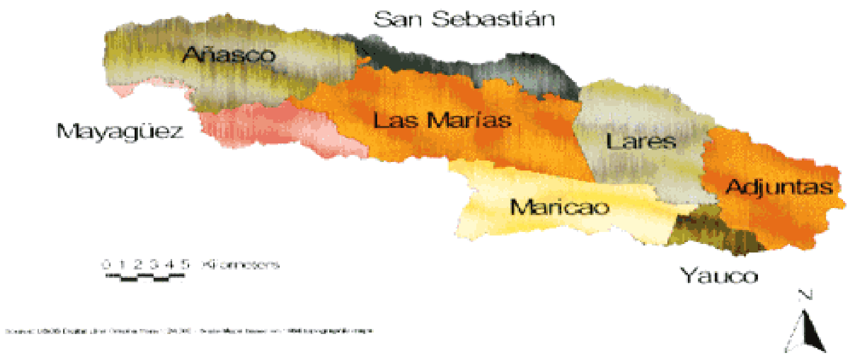

Figure 1: Municipalities within the Añasco Watershed (CIMP, 2004).

The discharge of the Añasco River during the wet season (September-November) ranges from 0.88 to 3960 m^3s^{-1} and during the dry season (February-April) is from 0.13 to 3620 m^3s^{-1} (Gilbes et al., 1996). It is the main supplier of fresh water for the Mayagüez Bay and it has a strong influence in its water quality. This river is born at an elevation of 1,204 m (3,950 ft) near Monte Guilarte and flows westward for 74 km until reaching the Mayagüez Bay. The major tributaries of this river are Río Daguey, Río Humatas, Río Canas, Río Casei, Río Arenas, Río Mayagüecillo, Río Guaba, Río Prieto, and Río Blanco. Possible major sources of pollution include land disposal of wastewater systems, industrial point sources, and agricultural activities (Sotomayor et al., 2004; unpublished information). Human activity, such as urban development, can cause soil erosion that changes the normal sediment loads of the river (Gilbes et al., 1996).

The upland area is characterized by sub-lateritic, red, silty clay acid soils. Lowlands are the result of the erosion of the upland soils with mostly fine to moderately fine sediments. RGA basin is formed mainly by three types of geologic groups, which are Quaternary alluvium deposits, Tertiary, Late Cretaceous volcanic and sedimentary rocks, and Cretaceous sedimentary and volcanic rocks. The first one predominates in the lower flood plains and the river valley. Tertiary and Late Cretaceous volcanic and sedimentary rocks are found in northern part of the watershed. The eastern, central and southern areas are characterized by having Cretaceous sedimentary and volcanic rocks (Sotomayor et al., 2004; unpublished information).

Review:

Gilbes et al. (1996) determined how the variation in river discharge of the western Puerto Rico affects the dynamics of phytoplankton in coastal waters. Nine (9) stations were sampled at three inshore-offshore transects involving the mouths of the Guanajibo, Yagüez and Añasco rivers to oceanic waters (Figure 2). From March 1990 to February 1991 they collected samples monthly to determine the variations in Chlorophyll-*a* *(Chl-a)*, salinity and suspended particles of the Mayagüez Bay. Higher concentrations of Chl-a were in August, September and January. Inshore transects were characterized for having the higher concentration of Chl-*a*. Also, the Añasco and Yagüez rivers had higher concentrations of Chl-*a* than Guanajibo. Maximum concentrations for the Añasco and Yagüez transects were detected in August and for Guanajibo in October and November.

Low salinity in the bay area is caused by high amount of fresh water in the wet season (September-November). During this period there is also an increase in the rivers discharge. The differences in Chl-*a* concentration implies differences in nutrients, suspended sediments and freshwater run-off affecting coastal phytoplankton dynamics. High Chl-*a* was correlated with high-suspended particulate matter that is carried along with nutrients favorable for phytoplankton growth. Along with these results the light penetration was reduced and salinity concentrations were low. The findings by Gilbes et al. (1996) demonstrate the important role of rivers discharge in Mayaguez Bay. Therefore, it is necessary to evaluate the input of sediments from the local rivers.

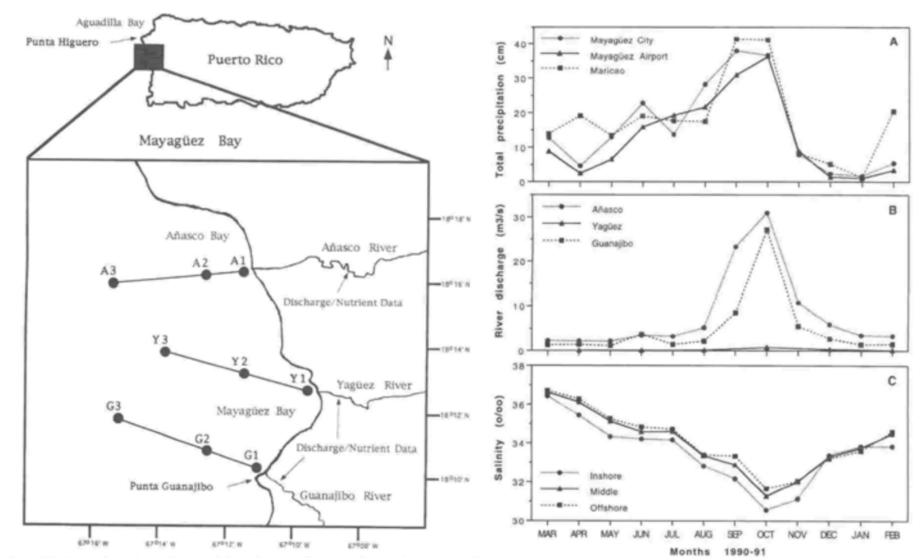

Figure 2: Left: Study area and sampling stations for Gilbes et al. (1996). Right: Monthly variations of total precipitation in the western region of Puerto Rico (A), river discharge of Añasco, Yagüez and Guanajibo rivers (B), and salinity from inshore to offshore stations (C) (Gilbes et al., 1996).

Sotomayor et al. (Unpublished article) selected 5 sub-watershed (Miraflores, Cerro Gordo, Cerrote, Chamorro, and Guaba) of the Río Grande de Añasco watershed to evaluate the water quality such as nutrient concentrations, sediment, biological indicators and hydrologic discharge (Figure 3). The selected sub-watersheds formed only 5.6% of the total watershed and they have farms used for agriculture and pasture for beef-cattle. They developed a GIS of the land use (Table 1), soils and hydrology of the five sub-watersheds. Agriculture, urban-sub urban areas and secondary forest were the classifications with a distribution of 2.9- 20%, 0.6- 11.5% for the first two and the percentage remained belonged to the secondary forest. Analyzing the bacterial transportation, they determined that it was strongly associated with suspended sediments and weakly with hydrologic flow and nutrients in these sub-watersheds. The Enterococcus species indicate that the most probable origin of contamination are humans, animals, herbivores, and poultry. From all the five watersheds, Cerro Gordo had the greatest agricultural land area and higher concentrations of suspended sediments were found that might not be associated with nutrient concentrations nor loads.

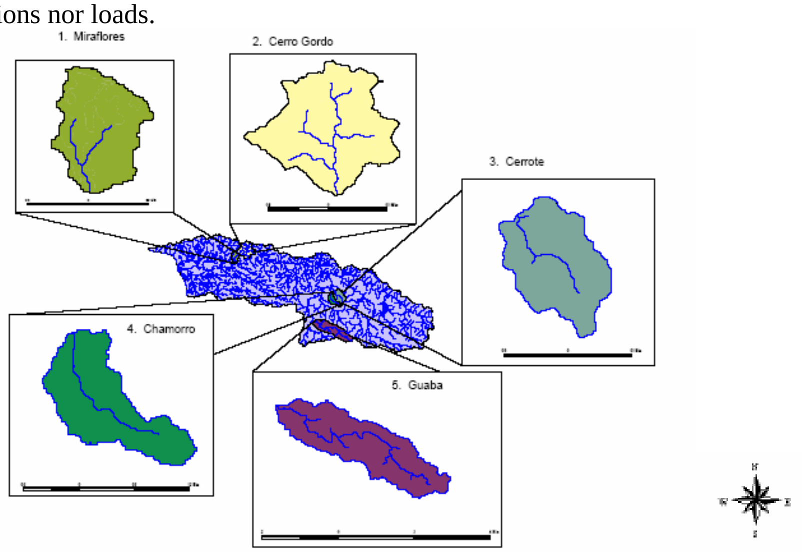

Figure 3: The Río Grande de Añasco (RGA) watershed and sub watersheds studied by Sotomayor el al. (2004; unpublished).

Morelock et al. (1980) indicate that the reefs at the Mayagüez Bay are being changing due to the increase of sediment load from the rivers. Changes in sediment distribution along the Bay could result in loss of the reef environment. Miller et al. (1994) estimated the spatial distribution of suspended particulate matter for Mayagüez Bay using traditional *in situ* measurements and remote sensed data. Otero et al. (1992) used remote sensing to examine the effects of the Añasco, Yagüez and Guanajibo rivers on the phytoplankton production. They determined that *in situ* measurements of sea surface properties combined with airborne imagery were adequate to study the spatial and temporal dynamics of phytoplankton and suspended transport.

Table 1: Sub watershed areas, land use areas and proportion of each land use to total area within the Río Grande de Añasco watershed. (Sotomayor el al., 2004-unpublished)

	Miraflores		**Cerro Gordo**		**Cerrote**		**Chamorro**		**Guaba**	
Land use Type	Area (ha)	(%)	Area (ha)	(%)	Area (ha)	(%)	Area (ha)	(%)	Area (ha)	(%)
Urban	25.8	11.5	8.0	1.1	8.6	2.9	2.4	0.6	17.6	1.3
Agricultural	8.6	3.9	144.6	20.2	25.9	8.8	39.8	10.0	153.6	11.6
Rangeland	51.7	23.1	96.3	13.5	34.5	11.8	23.4	5.9	141.1	10.7
Forest	137.8	61.5	393.5	55.1	224.3	76.5	331.7	83.5	1007.7	76.3
Pasture	0.0	0.0	72.3	10.1	0.0	0.0	0.0	0.0	0.0	0.0
Total	224		714		293		397		1320	
Housing units (units.)	560		776		435		433		975	

Methodology:

Five samples of deposited sediments at the mouth of the Río Grande de Añasco were collected to determine their composition, grain size and distribution (Table ? and Figure ?). The first three samples were collected in the river channel and the other two on the beach area, where the waves break. These last two were taken at one hundred meters north and south from the third sample (Figure ?).

The samples collected were dried for sieving and some were pulverized to know their mineral composition using X-Ray Diffraction. A granulometric analysis was done to determine the sample grain size distribution. Sieves from -4.0 phi to pan were used, except for the sieves –3.5 and 1.5, because they were not found. The amount of sediment left in each sieve was weighted. Carbonate percentages were also determined for all samples. XRD technique is used to know the location of atoms, their sizes, their bonding in crystal structures and chemical composition of unit cell (Klein, 2002). In this case, it was used to determine the mineral (chemical) composition of the samples from different sites of the river mouth. The sieved sediments were grind to form a powder that was mounted on a glass slide. An X-ray beam hit it and X-ray detector rotated picking up the diffracted X-rays signals. A print out called X-ray powder diffractometer tracing have the peaks that represents the minerals and their intensities (Klein, 2002).

A Thematic Mapper image of the western region (Figure ?) from August 2004 and 30 m spatial resolution was used to determine the normalized difference vegetation index (NDVI) and land use in the watershed. This land use was made using a Maximum Likelihood supervised classification. The region of interests (ROI's) selected for the classification were river, lake, urban areas, agriculture, forest and areas without vegetation. They were selected by random visualization of the image. The processing was performed using the software called ENVI (Evironmental of Visualization Images). A subset of the original image was made to contain only the RGA catchment. This allowed to prepare a layer with the catchment that was opened in ENVI as a vector. Other data collected previously in the RGA and provided by PaSCoR were the geologic map, a soil map, catchment and the tributaries. They were used to create additional layers of information in a GIS database that were processed and analyzed using Arc Map 8.3. Finally, 40 points were selected randomly for comparison and to determine their similarity and differences.

Table 1: Simple sites at the Rio Grande de Añasco mouth.

Samples	Latitude	Longitude
1	18° 15’56.1” N	67°11’9.4”W
2	18° 15’54.1” N	67°11’18.6”W
3	18° 15’53.2” N	67°11’19.1”W
4	18° 15’51.8” N	67°11’15.7”W
5	18° 15’56.1” N	67°11’21.1”W

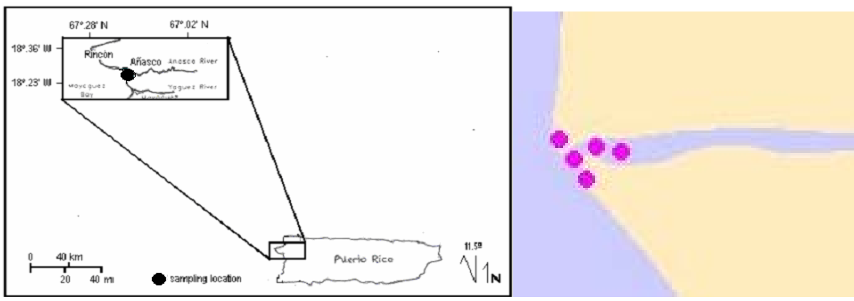

Figure 1: Location of the study area at Añasco River.

Figure 3: Original Landsat 7 Thematic Mapper image of Western Puerto Rico (provided by PaSCoR).

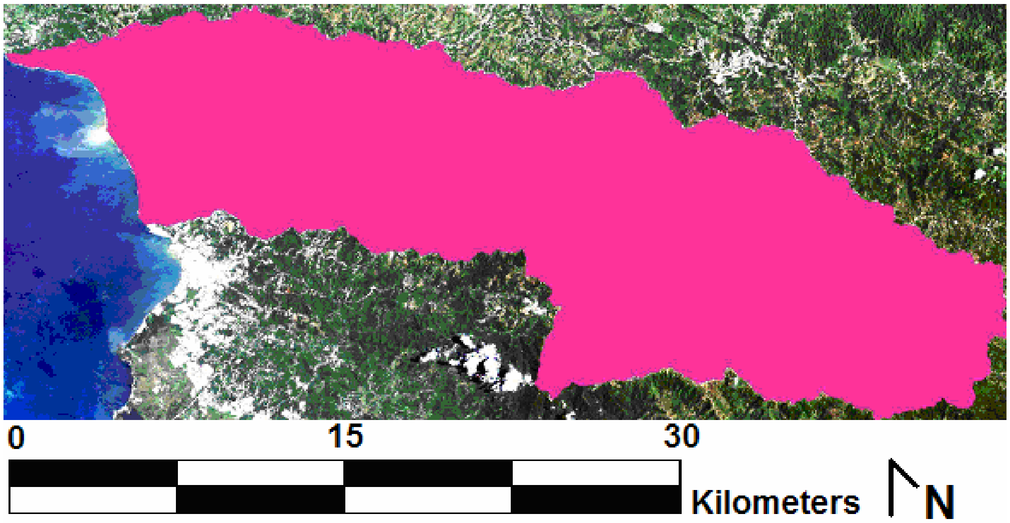

Figure 4: Western Puerto Rico Landsat TM 7 showing Río Grande de Añasco catchment layer.

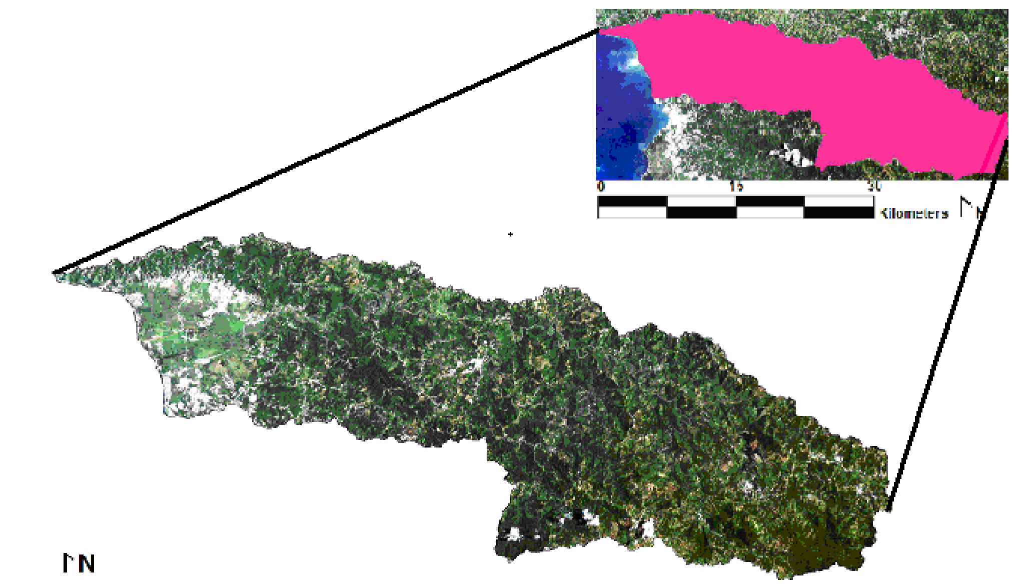

Figure 5: Result of the subset using the catchment ROI for the Rio Grande de Añasco.

Results:

The catchment layer of RGA was used to delimit the original image to have a true color image showing only the area of interest (Figure 6). A NDVI (Figure 7) and maximum likelyhood supervised classification (Figure 8) images were created using the delimitation. In the NDVI image (Figure 7) is easy to identify the areas of urban development, areas without vegetation and the water bodies because they look white. Areas of abundant vegetation are dark green and areas of agriculture are light green. The maximum likelyhood image (Figure 8) shows that forest is the predominant class of the RGA catchment, fallowed by agriculture and urban areas, respectively. From the non-processed image (Figure 6) it is possible to see that there are many areas without vegetation, but it is difficult to see these regions in the supervised image because they tend to be confused with the agriculture and river classification.

Figure 6: Río Grande de Añasco Landsat 7 TM image of the catchment.

Figure 7: NDVI image of Rio Grande de Añasco catchment.

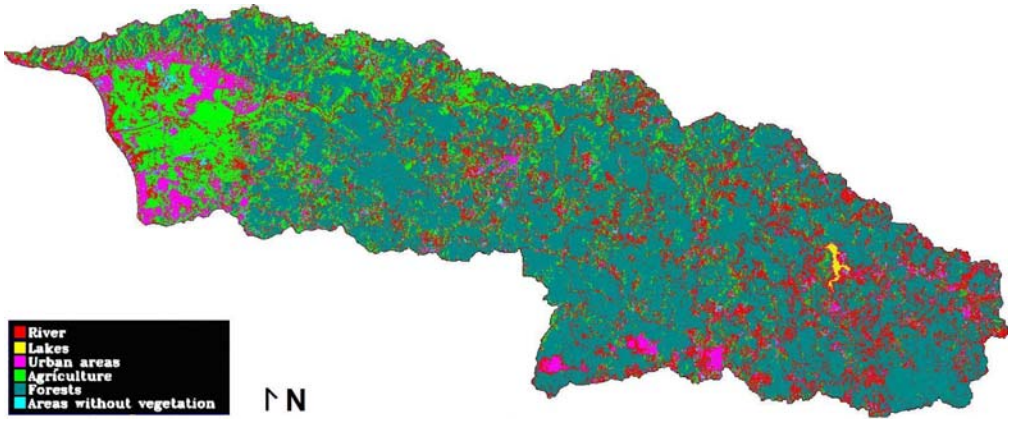

Figure 8: Maximum Likelyhood image of Rio Grande de Añasco catchment.

Figure 9 present the tributaries of the RGA watershed with their respective names. From the geologic map (Figure 10) of the watershed is possible to see that the RGA and its valley are composed by alluvium, consisting on sediments laid down by the river that are from the Quaternary. At the coast, the predominant geological features are beach deposits, swamp deposits, Yauco Formation (Tertiary) and quartz/diorite-granodiorite. This last one has a mineral composition of quartz (SiO_2), biotite ($K(Mg, Fe)_3(Al, Fe)SiO_3O_{10}(OH, F)_2$), hornblende ($(Ca, Na, K)_{2\text{-}3}(Mg, Fe^{2+},Fe^{3+}, Al)_5(SiAl)_8O_{22}(OH)_2$), feldspar, magnetite ($Fe_3O_4$), apatite ($Ca_5(PO_4)_3(F, Cl, OH)$ and plagioclase . Yauco Formation consists of irregularly interbedded calcareous siltstone and claystone, subordinate sandstone and mudstone and minor limestone. It also has clasts of chert and serpentinized peridotite. Alluvium (Quaternary) is characterized for having sandy clay, pebbles and cobbles derived chiefly from volcanic rocks. The beach deposits (Quaternary) include beaches, dunes, and coastal-swamp deposits, composed mainly of fine to medium grained clasts of volcanic rocks, limestone and shell (USGS).

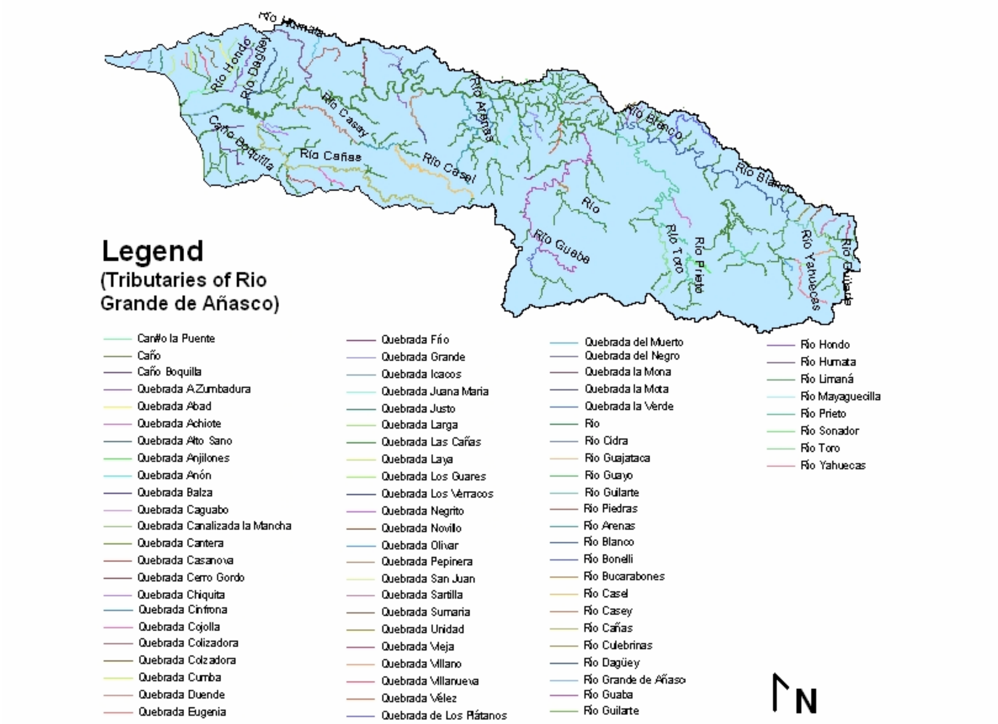

Figure 9: RGA catchment and tributaries (provided by PaSCoR).

The west of the catchment is composed by the Yauco Formation, Maricao Formation, Culebrinas Formation, Lago Garzas Anon Formation Interbed, alluvium, Augite thrachybasalt, beach deposits, swamp deposits and quartz/diorite-granodiorite. Maricao Formation (Upper Cretaceous) is a massive volcaniclastic breccia that has Augite thrachybasalt held in a clay-sandstone. Augite (Ca, Na(Mg, Fe, Al)(Al, Si)$_2$O$_6$) plagioclase (labradorite-andesine), chlorite (Mg, Fe)$_6$(AlSi$_3$)O$_{10}$(OH)$_8$), calcite ($CaCO_3$) and clinopyroxene phenocrysts can be found the formation. The Culebrinas Formation (Tertiary) predominantly has thin-bedded tuffs and fine-to medium grained volcanic sandstone and massive tuff breccias. Quartz, plagioclase, pyroxene and hornblende are the mineral common in the formation. Augite-trachybasalt (Cretaceous) contains abundant deep-green Augite and some plagioclase (labradorite-andesine).

The north of the catchment has the following formations: Lago Garzas-Anon Formation Interbed, Río Culebrinas Formation, Anon Formation and Mal Paso Formation. Anon Formation (Tertiary) is characterized for having massive green, greenish-brown or reddish- brown lapilli tuff with fragments of andesite, dacite, crystals of feldspar, hornblende and pyroxenes, and rare diorite or gabbro. Mal Paso Formation (Tertiary) contains 15 to 20 percent spherical amygdules with calcite and zeoloites, microphenocrysts of plagioclase (labradorite, commonly albitized), clinopyroxene and olivine (Mg, Fe)$_2$SiO$_4$). It could also have alteration of hematite (Fe_2O_3), sphene, epidote ($Ca_2Al_2FeOSiO_4Si_2O_7(OH)$) and chlorite (USGS).

The east of the catchment is composed of the Anon Formation, Yauco Formation, Lago Garzas-Anon Formation Interbed, Augite-trachybasalt and Hornblende Dacite. In the south area of the catchment is possible to see the following: Maricao Formation, Yauco Formation, Lago Garzas and Yauco Formation Interbed, Anon and Yauco Formation Interbed, Maricao and Yauco Formation Interbed and Anon Formation, Augite-trachybasalt, Pyroxene Olivine basalt, diorite and alluvium (USGS).

The center consists of Yauco Formation, Concepción Formation, Lago Garzas Formation, Mal Paso Formation, Río Culebrinas Formation, Anon Formation, Maricao Yauco Formation, Rhyodacite porphyry, alluvium, diorite and quartz/ diorite-granodiorite. Concepción Formation (Tertiary) has dark greenish-gray-to-greenish-gray massive well-indurated pumice lapilli tuff and thin-bedded coarse crystal-vitric tuff with abundant pumice. Hornblende, plagioclase, epidote, chlorite, calcite, quartz and clinopyroxenes can be found. Lago Garzas Formation contains feldspar, pyroxene, amygdules of chlorite, calcite, quartz, chalcedony (SiO_2), epidote and some zeolites (USGS).

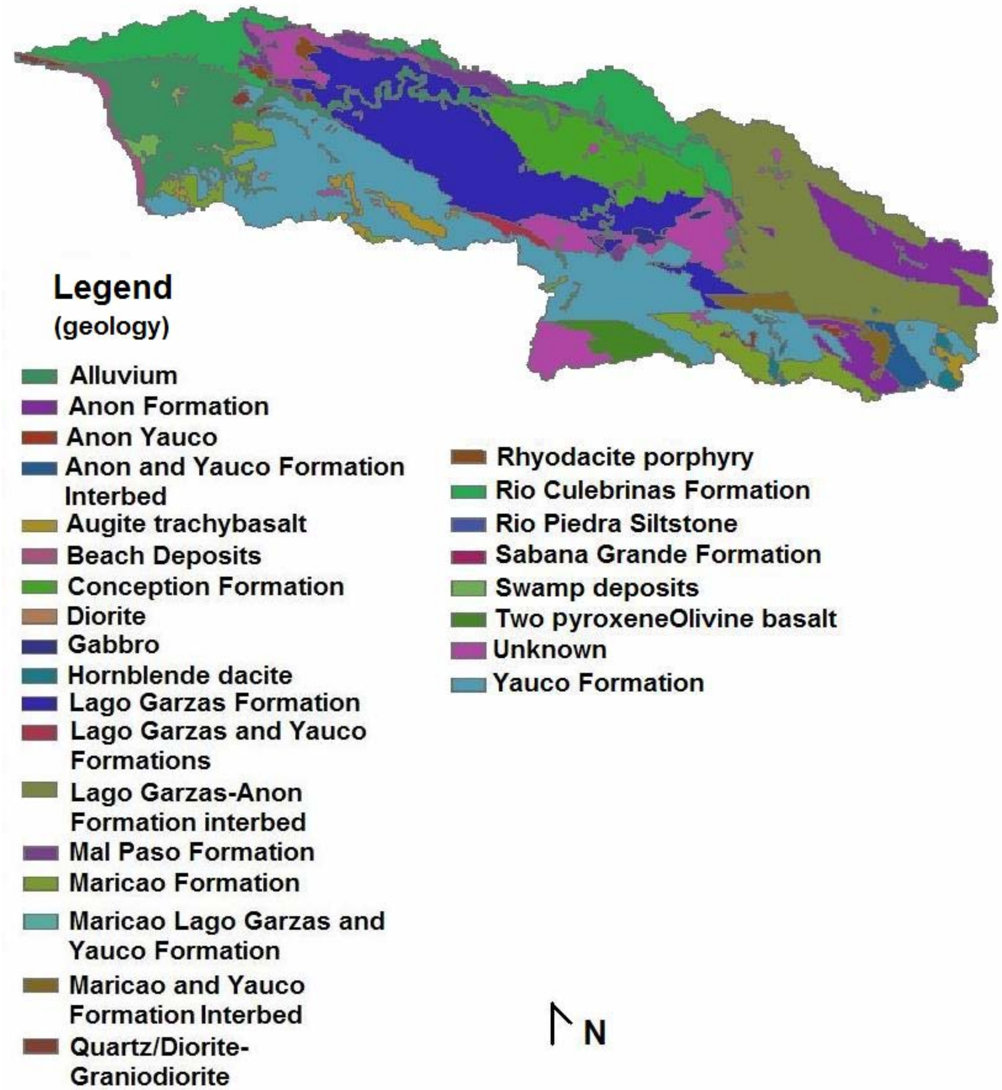

Figure 10: Geologic map of Rio Grande de Añasco catchment (provided by PaSCoR).

The main tributary of RGA catchment is the river with that same name, Río Grande de Añasco. It is surrounded by several clay soils (Figure 11) as Lares clay, Daguey clay, Consumo clay, Humatas clay, Mucara clay, Morado clay loam and Anon clay loam. There are also some silty soils like Dique silty loam, Coloso silty clay loam and Toa silty clay loam. The rest of soil classification is: Cataño sand, Arenales sandy loam, Reilly gravelly loam, Humatas gravelly clay and water. Clay soils have 35 % or more of clay, 20% to 45% of sand and 15 to 40% of silt. Clay loam soils contain 25 % to 40 % of clay, 20 % to 45 % of sand and 15 % to 55 % of silt. Loamy soils have 25% to 52% of sand, 28% to 50% of silt and 5% to 25% of clay. Silty loam soils have 50% or more silt, up to 25 % of clay and up to 50 % of sand. Silty clay soils have up to 20% of sand, 40% of silt and clay. Silty clay loam soils have 25% to 40% of clay, 40% to 75% of silt and less than 20% of sand. Sandy soils contain 85% or more of sand, up to 15% of silt and up to 10% of clay. Sandy loam soils have 45% to 70% of sand, up to 50% of silt and up to 20% of clay. Kaolinite is a common mineral found in the Puerto Rican soils. Aceitunas clay, Coloso silty clay loam, Humatas clay, Los Guineos clay and Daguey clay have kaolinite soils. Cataño has a carbonate soil and Reilly has a sandy skeletal soil (Beinroth, 2003).

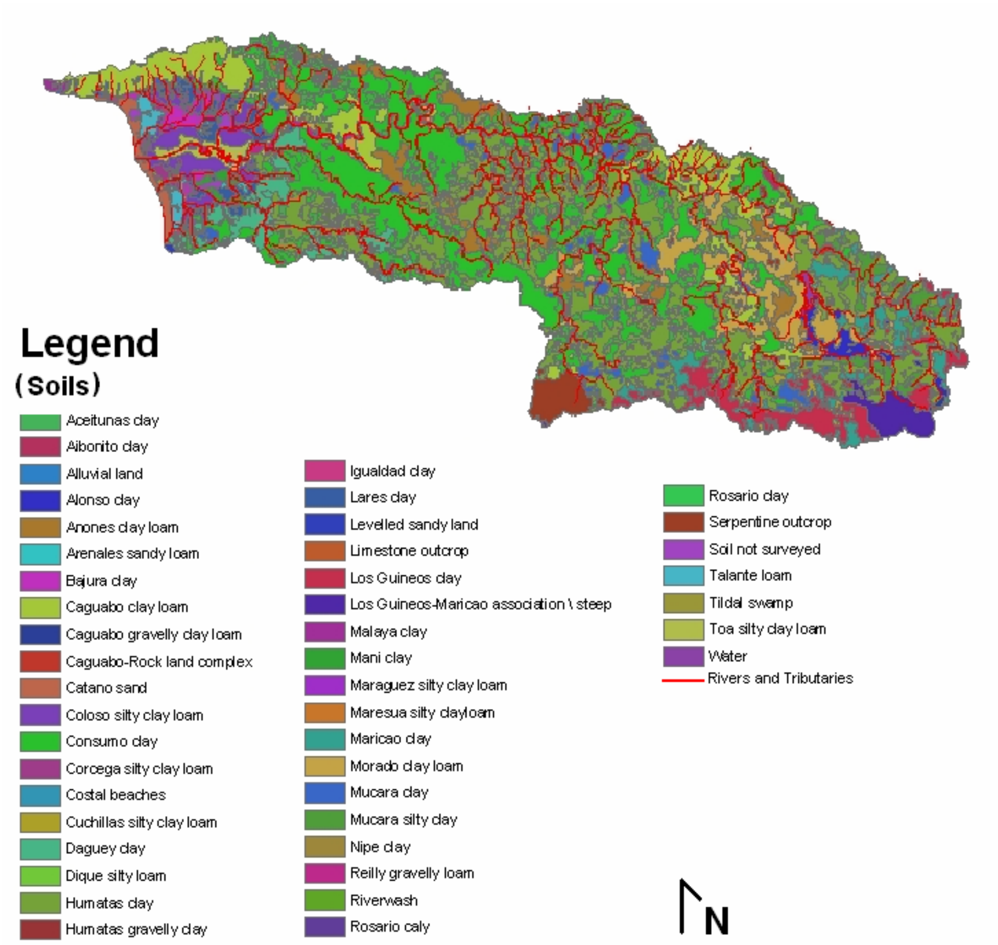

Figure 11: Soil map of Rio Grande de Añasco catchment (provided by PaSCoR).

After doing the granulometric analysis for the samples taken at the mouth of RGA, the histograms were made to show their grain size and their abundance (Figure ?). It was possible to see that all the samples showed high percentages from 0.5 phi to 2.5 phi. This means that they have grain size that goes from coarse sand to fine sand (Udden-Wentworth grain size scale). According to the histograms the sediments collected in samples #1, #4, and #5 are fine and it is representative of a negative skewness, or symmetry. It tells that coarser sediments are less well sorted than fine sediments. The skewness compares the sorting in coarser and finer halves of the histograms. Samples #1 to #3 have the coarser sediments (pebble like) from all of them. Sample #2 and #3 have larger amounts of these pebbles size sediments. The last two samples, taken at the beach, do not have sediments in the negative section (-4.0 phi to –1.5 phi), meaning that the sediments in the zone are sandy like sediments that go from very coarse sand to silt. All the samples have their highest percentages at grain size 2 phi (fine sand). Each samples had a little silt and clay (Table 2). Sample one and two had the highest amount of these sediments. These samples have two significant peaks, one in the area of pebble like sediments and the other in the sandy like section of the histogram. They have a bimodal pattern, showing that they have two types of abundant sediments, sand and pebble. The beach sediments have single modal size pattern in the histograms that is typical of beach sediments.

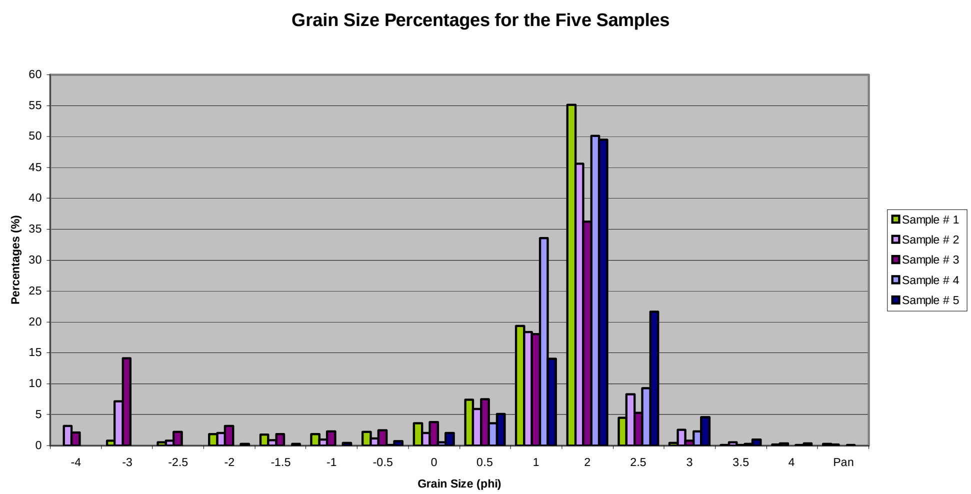

Figure ?: Grain size comparison for the sample of the Rio Grande de Añasco.

Four minerals were found with the XRD analysis: quartz (SiO_2), albite ($NaAlSi_3O_8$), calcite ($CaCO_3$) and kaolinite ($Al_2Si_2O_5(OH)_4$). The sediments corresponding to the river (Figure 2, 3 and 4) had all of them. The beach sediments (Figure 5 and 6) do not have kaolinite. Quartz is a constituent of granite and granodiorite. It is usually associated with albite. It is present in rhyolite and dacite of volcanic rocks. Albite is plagioclase feldspar (alkali feldspar) commonly found in granites, syenites, rhyolites, and trachytes. Calcite is common on sedimentary rocks and can also occur with acmite, apatite, barite, albite and zeoloites, among other. It can occur in volcanic rocks. Kaolinite is always mineral formed by weathering or hydrothermal alteration of aluminum silicates, like feldspar. It is found in soils and transported by water and deposited (Klein, 2002 and Chesterman, 2000).

Forty (40) points were selected randomly in order to compare the RGA watershed (Table ?). The supervised classification, NDVI, geology, geologic time, soil and river were evaluated. The NDVI and classification were compared to know if the index of vegetation had similarities with the land use and land cover. Alluvium from the Quaternary is common in the area, but it is possible to find some beach deposits near the mouth of the river. Toa Silty Loam and Humatas Clay, with a kaolinitic composition, are soils common in the zones selected for comparison. The lake classification (Tertiary-Cretaceous) has a NDVI of 0.0 because water is supposed to reflect a low NDVI since it has little or no vegetation. Urban areas have a low vegetation index typically of those areas. Lago Garzas Formation (Tertiary-Cretaceous), alluvium (Quaternary), Rhyodacite porphyry (Tertiary) and Yauco Formation (TK) are some of the geologic features found in the zones. Cataño sand is the common in these urban areas. Agriculture has between intermediate to high NDVI with the following formations: Anon Formation (TK), Yauco Formation (TK), Lago Garzas Formation (TK) and alluvium (Quaternary). Coloso Silty Clay Loam is the most common soil in the selected point for the agriculture classification. The forest classification has between medium to high NDVI, which is usual in zones of abundant vegetation. Yauco Formation is the most repetitive formation for this classification. Some rivers as Río Blanco, Río Yahueca, Río Culebrinas and Río Bonelli, which they are supposed to have low NDVI are common in the points selected for the forest and have a high NDVI for being water bodies. This might be due to the fact that are small rivers and probably covered by vegetation. Consumo clay and Caguabo clay loam are the predominant soil for the selected points. Areas without vegetation have low NDVI, which is common for this classification. The following formations are common: Concepción Formation (Cretaceous), alluvium (Quaternary) Río Culebrinas Formation (Tertiary), Yauco Formation (Tertiary-Cretaceous) and Lago Garzas Formation (Tertiary-Cretaceous). Consumo clay and Humatas clay soils are common.

Table 4: Comparison between the different layers.

#	Latitude (N)	Longitude (W)	Classification	NDVI	Geology	Geologic Time	Soil	River Name
1	18°16'6.28"	67°11'14.74"	River	0.0	A	Qa	ASL	RGA
2	18°16'4.12"	66°56'28.31"	River	0.18	A	Qa	MC	RGA
3	18°16'24.68"	67°9'20.15"	River	0.06	A	Qa	TSCL	RGA
4	18°16'53.33"	67°1'46.37"	River	0.08	A	Qa	TSCL	RGA
5	18°14'43.47"	66°55'29.02"	River	0.31	A	Qa	HC	RGu
6	18°17'40.21"	67°11'43.38"	River	0.24	BD	Qb	CS	RL
7	18°15'18.08"	67°10'36.43"	River	0.43	BD/SD	Qb/Qs	TS	CB
8	18°14'59.27"	66°52'48.52"	River	0.16	LGAFI	TKla	CCL/ MCL	RBl
9	18°15'59.89"	66°54'28.88	River	0.19	RCF	Trc	HC	QN
10	18°12'10.59"	66°50'3.16"	Lake	0.0	LGAFI	TKla	W	
11	18°16'28.71"	67°11'15.52"	Urban Area	0.16	A	Qa	CS	CLP
12	18°17'32.11"	67°11'12.82"	Urban Area	0.0	A	Qa	CS	
13	18°15'11.40"	66°59'29.67"	Urban Area	0.05	LGF	TKlg	HC	
14	18°17'56.96"	67°2'7.10"	Urban Area	0.0	Rp	Thrp	CC	
15	18°13'49.00"	67°10'7.73"	Urban Area	0.0	YF	TKya	DC	
16	18°16'30.91"	67°8'18.81"	Agriculture	0.43	A	Qa	CSCL	
17	18°16'31.63"	67°7'52.25"	Agriculture	0.40	A	Qa	CSCL	
18	18°11'3.34"	66°45'53.93"	Agriculture	0.40	AF	TKan	HC	
19	18°16'34.64"	67°1'32.29"	Agriculture	0.48	LGF	TKlg	CC	
20	18°15'1.69"	67°7'34.83"	Agriculture	0.27	YF	TKya	DC	

Pegar estas dos tablas con una sola leyenda.

#	Latitude (N)	Longitude (W)	Classification	NDVI	Geology	Geologic Time	Soil	River Name
21	18°11'46.15"	66°45'44.20"	Forest	0.55	AF	Tkan	MSC	
22	18°8'42.46"	66°48'9.40"	Forest	0.51	AYFI	TKay	LGM	
23	18°14'5.68"	66°50'0.71"	Forest	0.45	LGAFI	TKla	CC	
24	18°14'29.53"	66°52'6.00"	Forest	0.58	LGAFI	TKla	CCL	RBl
25	18°18'6.54"	67°13'26.28"	Forest	0.47	Q/d-g	TKqdg	CCL	
26	18°18'57.87"	67°9'19.56"	Forest	0.54	RCF	Trc	CCL	
27	18°13'23.58"	67°6'40.74"	Forest	0.52	YF	TKya	CC	
28	18°12'19.16"	66°58'40.60"	Forest	0.56	YF	TKya	CC	
29	18°14'33.59"	67°3'1.47"	Forest	0.53	YF	TKya	CC	
30	18°10'9.74"	66°47'23.40"	Forest	0.47	YF	TKya	HC	RY
31	18°15'33.31"	67°4'58.24"	Forest	0.49	YF/A	Tkya/Qa	CC	RC
32	18°9'55.83"	66°57'17.54"	Forest	0.46	U	U	SO	RB
33	18°17'51.93"	67°10'2.13"	AWV	0.0	A	Qa	CSCL	
34	18°15'43.59"	66°56'24.47"	AWV	0.13	CF	Kcs	HC	
35	18°11'38.99"	66°50'56.62"	AWV	0.008	LGAFI	TKla	ACL	
36	18°10'14.16"	66°45'19.86"	AWV	0.18	LGAFI	TKla	LGC	
37	18°11'0.65"	66°53'26.11"	AWV	0.0	LGF	TKlg	HC	
38	18°11'0.67"	66°53'28.15"	AWV	0.0	LGF	TKlg	HC	
39	18°19'16.80"	67°6'39.98"	AWV	0.19	RCF	Trc	CC	
40	18°14'3.35"	67°1'26.85"	AWV	0.0	YF	TKya	CC	

Legend:

Classification- AWV (Areas Without Vegetation);

Geology- A (Alluvium), (Anon Formation), AYFI (Anon-Yauco Formation Interbed), BD (Beach Deposit), CF (Concepcion Formation), LGAFI (Lago Garzas-Anon Formation Interbed), LGF (Lago Garzas Formation), Q/d-g (Quartz/diorite-granodiorite), RCF (Rio Culebrinas Formation), Rp (Rhyodacite porphyry), SD (Swamp Deposits), U (Unknown), YF (Yauco Formation)

Geologic Time- Qa (Quaternary A), Qb (Quaternary BD). Qs (Quaternary SD), Kcs (Cretaceous CF), Thrp (Tertiary Rp), Tkan (Tertiary & Cretaceous AF), Tkay (Tertiary & Cretaceous AYFI), TKla (Tertiary & Cretaceous LGAFI), TKlg (Tertiary & Cretaceous LGF),), TKqdg (Tertiary & Cretaceous Q/d-g), Tkya (Tertiary & Cretaceous YF), Trc (Tertiary RCF), U (unknown)

Soil- ACL (Anones Clay Loam), ASL (Arenales Sandy Loam), CC (Consumo Clay), CCL (Caguabo Clay Loam), CS (Catano Sand), CSCL (Coloso Silty Clay Loam), DC (Daguey Clay), HC (Humatas Clay), LGC (Los Guineos Clay), LGM (Los Guineos-Maricao Association), MC (Mucara Clay), MCL (Morado Clay Loam), MSC (Mucara Silt Clay), SO (Serpentine Outcrop), TS (Tidal Swamp), TSCL (Toa Silty Clay Loam), W (Water)

River Name- CB (Caño Boquilla), CLP (Caño La Puente), QN (Quebrada Negrito), RB (Rio Bonelli), RBl (Rio Blanco), RC (Rio Casey), RGA (Rio Grande de Añasco), RGu (Rio Guaba), RL (Río Laya), RY (Rio Yahueca)

Discussion and Interpretation:

The NDVI image has regions with white and green tones. Those areas in white represent a low vegetation index that can be found in the areas of urban development, areas without vegetation and water bodies. This is due to the fact that there are areas with little or none vegetation. Also, it can mean that the green areas are not very healthy or that the leaves are turning yellowish-brownish, typically of autumn season. This is not our case, since the TM image was taken in the summer. On the contrary, areas of abundant vegetation are dark green and areas of agriculture are light green. This is representative of areas with abundant and healthy vegetation. Forest is the predominant class in the RGA watershed as shown by the maximum likelyhood image. Areas without vegetation can be confused with agriculture and river classification. This might be happening because they may have more or less the same spectral response, since the water of the river had suspended sediments that have the same spectral response as the areas without vegetation. The image was taken in the rainy season of Puerto Rico. Probably, if we had chosen an image from the dry season the supervised classification would have turned out different. May be the areas without vegetation could be seen with a defined classification and not part of the agriculture and river classification. Some rivers as Río Blanco, Río Yahueca, and Río Bonelli have high NDVI. This is due to the fact that are small rivers and probably covered by vegetation.

It is necessary to make the NDVI and the supervised classification to determine if areas without vegetation are affecting the suspended sediments influx into the river. Those areas exposed might be near a geological feature, at the same time near a river and when it rains those exposed soils and some rock can come off and end in the river. They travel along the river and if the soil composition and geology of the area are known, sediments sample can be taken and the mineralogy composition can be determined with XRD analysis. By doing so, it could be possible to correlate the sediments with the geology and the soils to know their provenance.

The sediments collected at the mouth of RGA are pebble to silt. This tells that the sediments might be traveling along the RGA watershed reworked for a long distance. The energy at the section of the river, where the samples were taken, is low. It can explain why the sediments are not big enough. The area where samples two and three were taken, have higher energy than sample one, because it is possible to observe in the histogram a bimodal pattern, showing two kinds of abundant sediments, pebbles and sandy like sediments. The sediments collected at the beach tend to have finer sediments because the sediments are reworked by the waves. Silt and clay can be found in these samples, specifically in those taken at the river. They are more copious at the river that at the beach, because the sediments at the river do not have waves that could let the fine sediments, such as silt and clay, in suspension. These sediments have time to settle down at the bottom of the channel.

Correlating the minerals found in the samples and determined using XRD, which are quartz, calcite, albite and kaolinite, with the geology and soils of the RGA watershed is difficult, because they could appear at any geological feature. Knowing the geology and soils of the catchment could help to eliminate those features that do not have the minerals already mentioned. Quartz can be found commonly in the following: Culebrinas Formation, Concepción Formation, Lago Garzas Formation and Quartz/diorite-granodiorite. All of them are along and by the river. They could be contributing to the RGA quartz that ends at the mouth of the river. Calcite can be found in Yauco Formation, Maricao Formation, Mal Paso Formation, Concepción Formation, and Lago Garzas Formation and in beach deposits. As the formations for quartz, the formations that have calcite are along and close to the river. Maricao Formation, Río Culebrinas Formation, Concepción Formation, Mal Paso Formation and quartz/diorite-granodiorite are by RGA and have plagioclases, albite forms part of the plagioclase. The formation descriptions do not tell if albite is part of their mineralogy except for Mal Paso Formation, which apparently has labradorite that is commonly albitized. The albite found at the mouth could come from this formation. Few sodium plagioclase are mentioned in the description like labradorite and andesine $(NaAlSi_3O)_{8.}$ Albite has a diffraction number very close to other sodium feldspar plagioclase and peak of the XRD that supposedly belongs to albite it may belong to other kind of plagioclase, since the difference between the plagioclase feldspar group laid down on the proportions of albite and anorthite. Kaolinite is a mineral typically found in soils because it is weathered. Knowing this and searching which soils have kaolinite it is possible to say that it may come from Coloso silty clay loam, Dagüey clay, Humatas clay and Los Guineos clay. The first three are very close to the river. Maybe these are contributing to the kaolinite that goes into the river.

Conclusion:

It is difficult to determine the provenance of the sediments of the Rio Grande de Añasco by only collecting samples at the mouth of the river. It is necessary to investigate the watershed in longer period of time. The minerals found with XRD analysis are very common in the geology of the area and they can not be attributed to a specific geology source. Quartz might be coming from Concepcion Formation, Rio Culebrinas Formation, and Lago Garzas Formation and/or from quartz/diorite-granodiorite. Calcite might be coming from Yauco Formation, Maricao Formation, Mal Paso Formation, Concepción Formation, and Lago Garzas Formation and in beach deposits. Albite might be coming from Maricao Formation, Río Culebrinas Formation, Concepción Formation, Mal Paso

Formation and quartz/diorite-granodiorite. Mal Paso Formation could be the main source for this mineral because labradorite in this area tends to become albite. The XRD analysis should be done again to prove if indeed the minerals found exist at the mouth of the river, specifically albite that can be confused with others feldspar plagioclase that might be common in the area. Kaolinite might be coming from Coloso silty clay loam, Dagüey clay and Humatas clay. All the minerals might be coming from all these sources, but which one contributes the most to the river can not be established.

Further studies should be done evaluating the exposure or the lack of vegetation in various sections of the RGA watershed that might be adding more sediments than other areas. Also the stability and the slope of the zones should be evaluated because they might affect the sediments that get into the river. More sediment should be collected along the river to analyze their mineralogy. Instead of studying the whole RGA watershed, it might be more appropriate, because of the lack of time, to select micro-watersheds to evaluate the provenance of a particular region of the river. The micro-watershed selected by the investigation of Sotomayor et al. (2004-unpublished) could be the ones, to incorporate more information of the area and compare their results with ones that could be generated. In these micro-watersheds all the analysis done for this investigation could be applied: NDVI, supervised classification, geology and soil maps, sample collection, XRD and granulometric analysis. In the same micro-watershed areas without vegetation versus areas with vegetation could be compared to determine which one contributes the most to the sediments that carry the river. It would be nice to do this with areas that have the same geology and/or soils and could be done twice at the two different seasons (dry versus wet) of Puerto Rico. Soil samples and geology samples of the area should be taken and correlated, by the XRD analysis, with the sediment of the river.

Summary:

Two images were created from TM where the Rio Grande de Añasco watershed is seen, NDVI and maximum likelihood. Low NDVI areas were related with high urban development. In the supervised classification the zones are well defined, except for those without vegetation. This class tends to get confused with the rivers because they have same spectral response. The image was taken during the rainy season of Puerto Rico and rivers are covered with suspended sediments that look like the terrain exposed in the area.

Several samples of the Rio Grande de Añasco were collected from the mouth. The first three were taken from the channel and the last two from the beach. Most of the sediments found are sandy like to clay characteristic of low energy rivers. The beach sediments are fine due to the energy of the waves. The XRD analysis of the samples has quartz, calcite, albite and kaolinite, which are minerals common in the geology of the RGA catchment. These might be coming from Concepcion Formation, Rio Culebrinas Formation, Yauco Formation, Maricao Formation, Mal Paso Formation, Lago Garzas Formation, quartz/diorite-granodiorite, beach deposits, Coloso silty clay loam, Dagüey clay and Humatas clay. It is difficult to know which of them contributes the most to the sediments that carry the river. For this other studies should be done where samples along the river could be taken and analyzed as usual. Instead of analyzing the whole watershed it should be divided into micro-watersheds. Stability and the slope of the zones should be considered. Since several areas are not covered by vegetation, as detected by the vegetation index and the supervised classification, and are near water bodies, these regions may be contributing a lot to the sediments that get into the river. A correlation of these areas with geology can be done and determine which of the geology formation affects most of the catchment. A comparison between areas with and without vegetation could be useful to determine which, if any contributes the most.

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APPENDICES

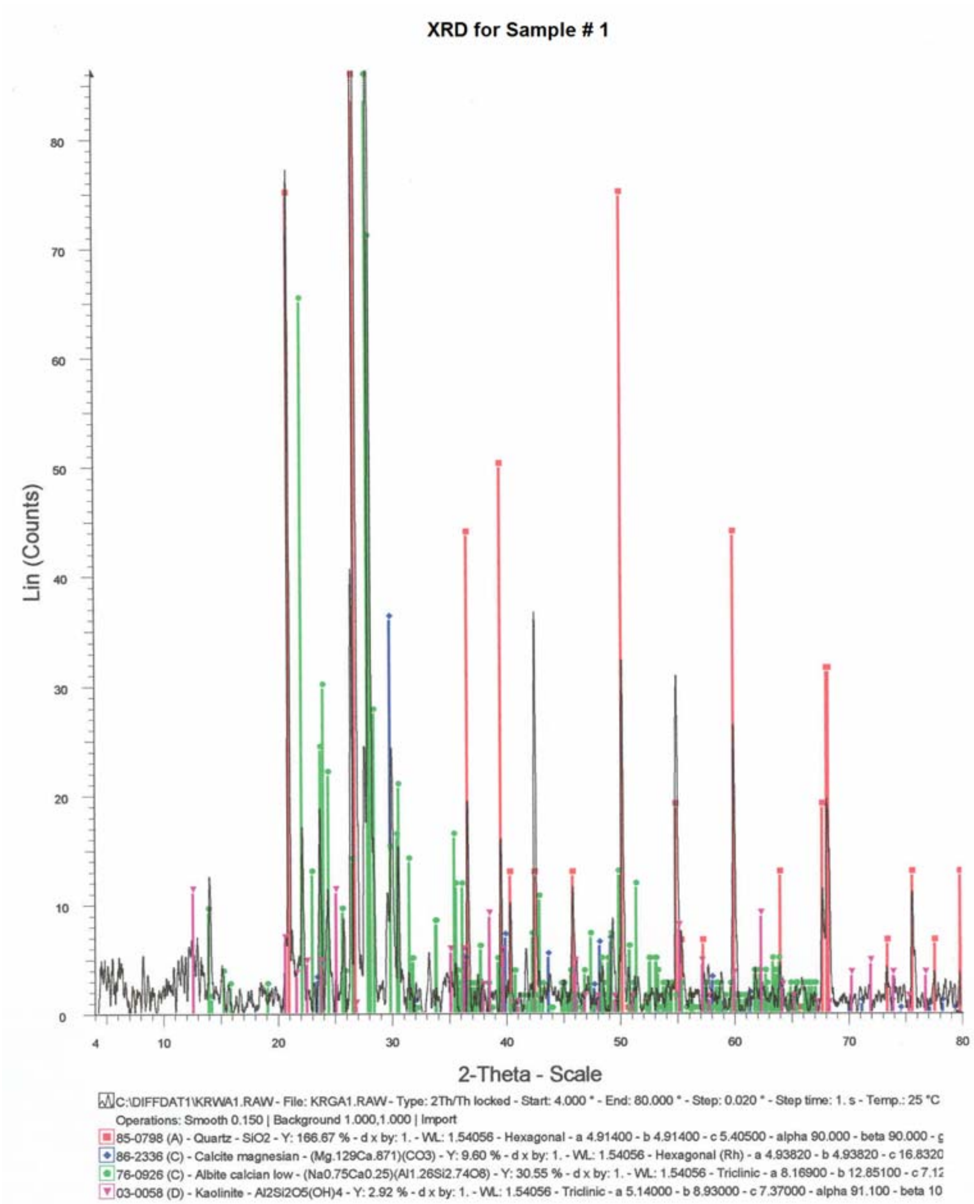

Figure ?: Mineral content for sample # 1.

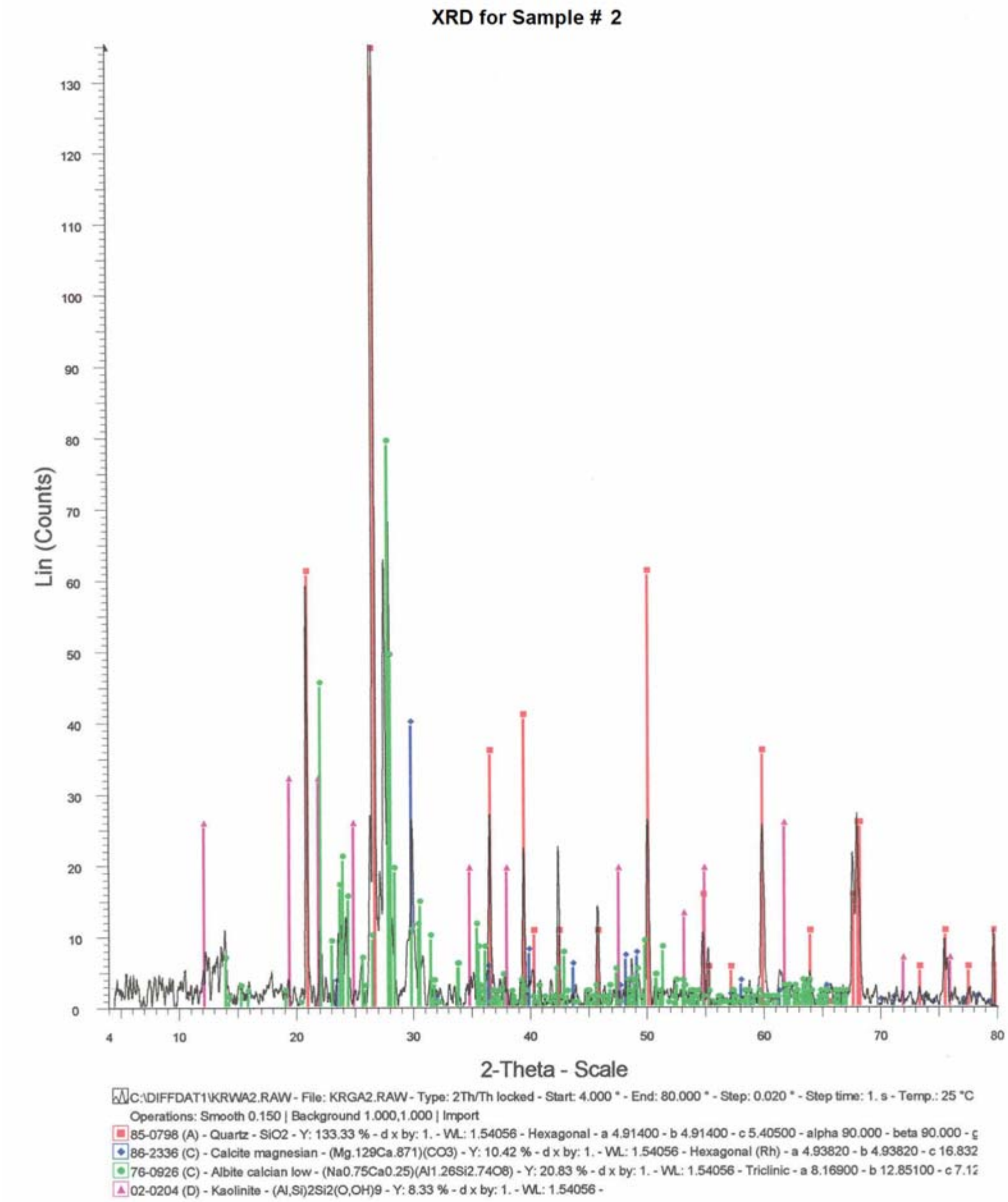

Figure ?: Mineral content for sample # 2.

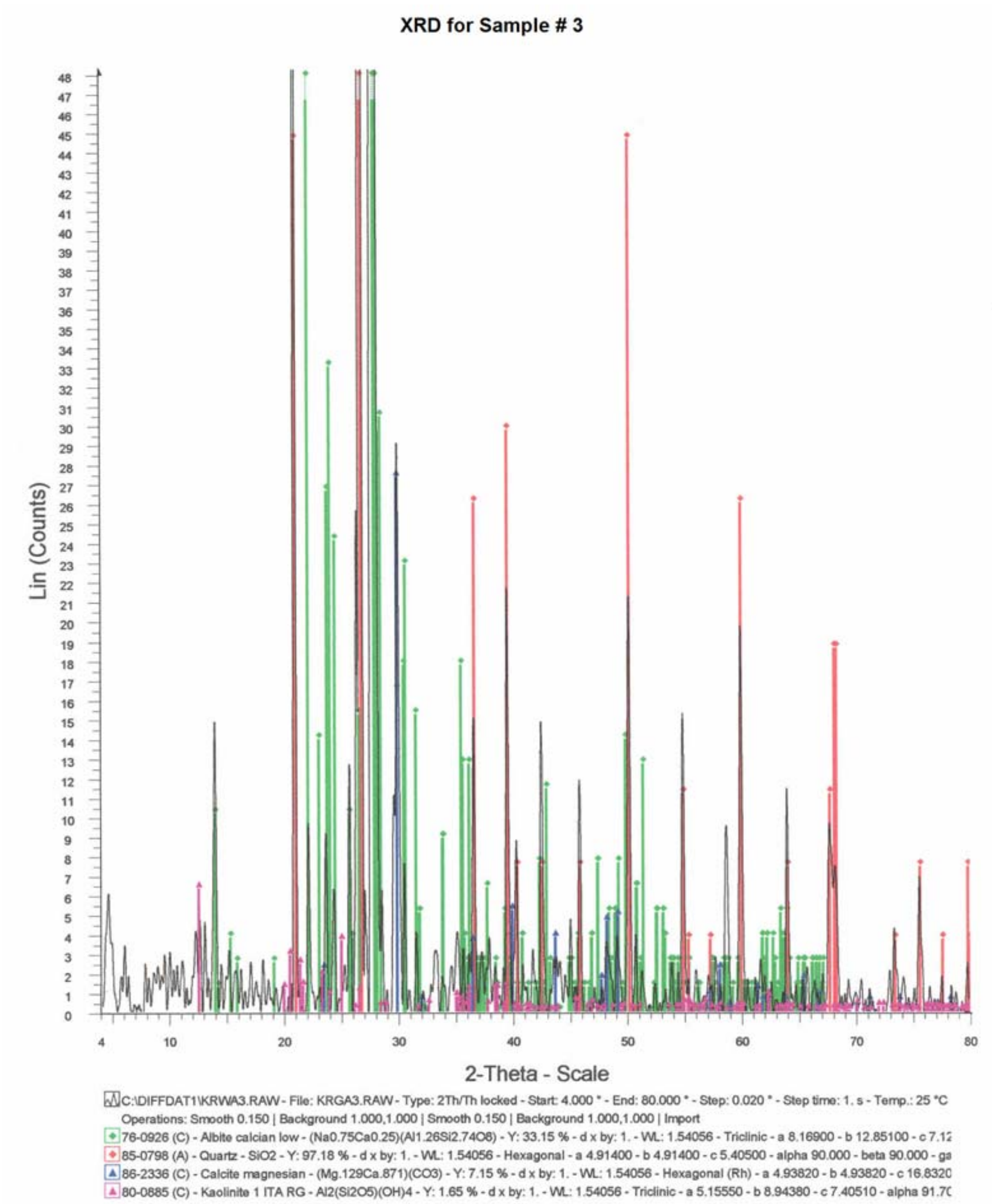

Figure ?: Mineral content for sample # 3.

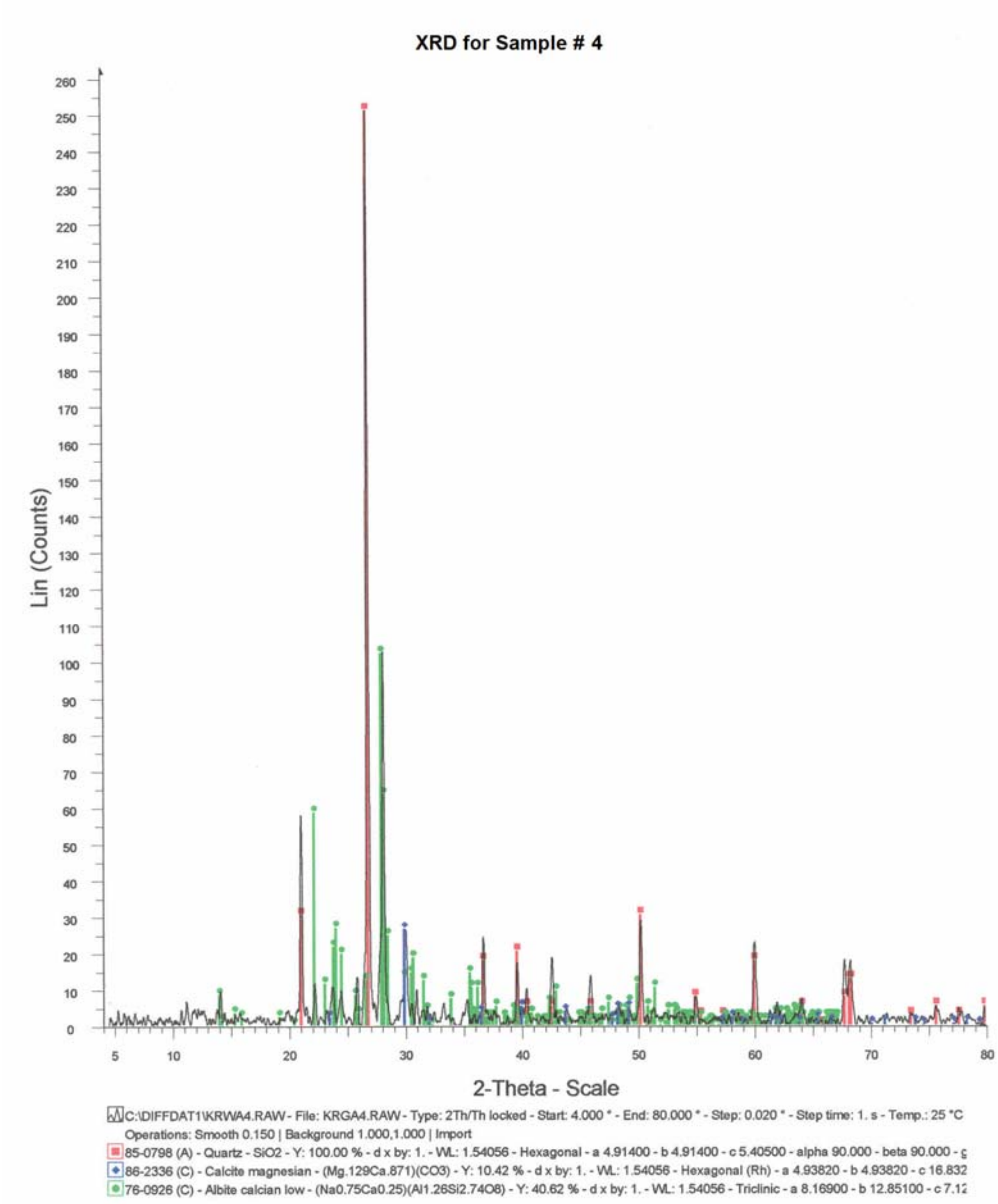

Figure ?: Mineral content for sample # 4.

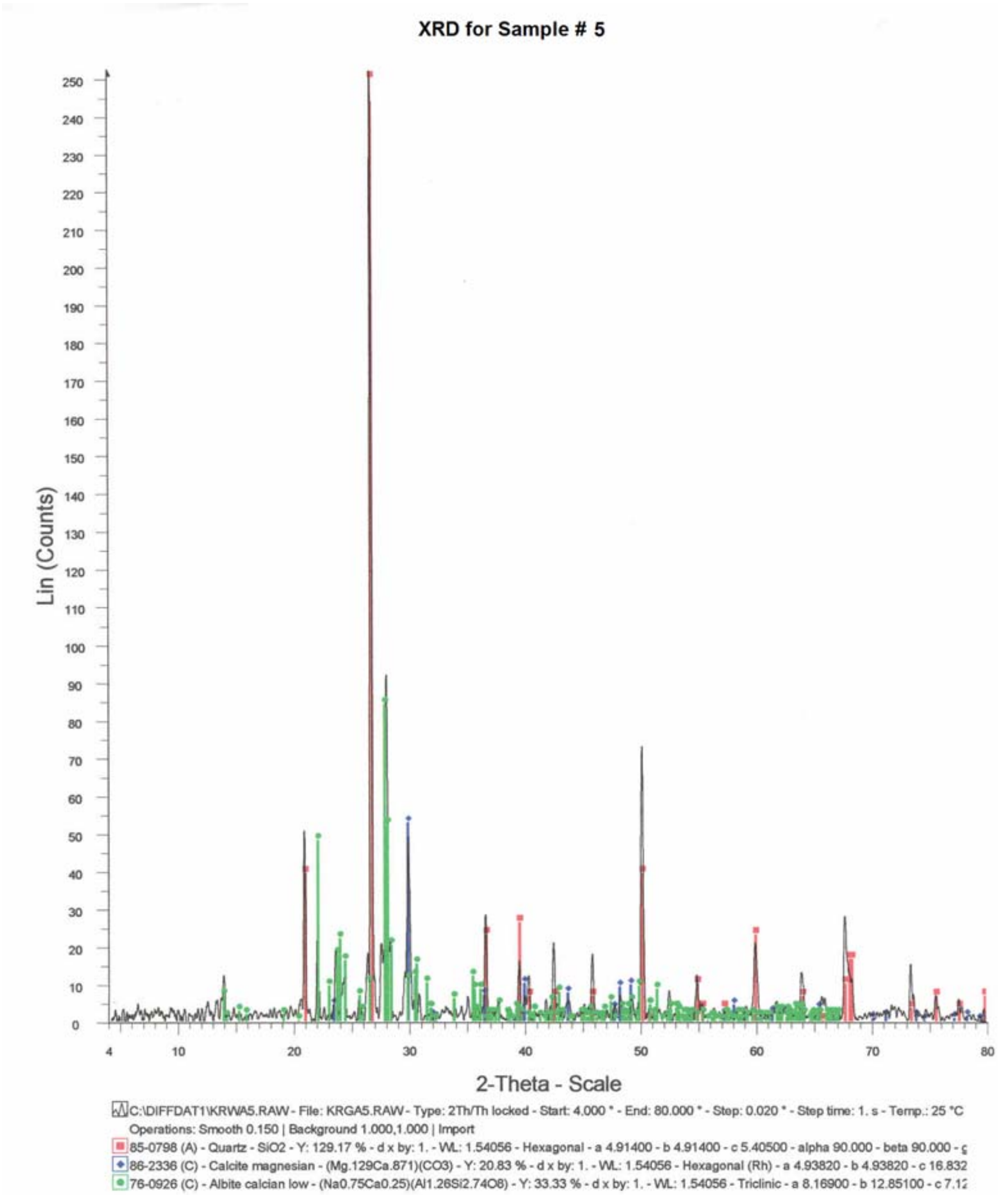

Figure ?: Mineral content for sample # 5.

Table 1: Rio Grande de Añasco granulometric analysis.

Phi	Sample # 1 weight (g)	Sample # 2 weight (g)	Sample # 3 weight (g)	Sample # 4 weight (g)	Sample # 5 weight (g)	Grain Size Classification
-4.0	0	9.58	6.31	0	0	Pebble
-3.0	2.35	21.56	42.22	0	0	Pebble
-2.5	1.68	2.49	6.63	0	0	Pebble
-2.0	5.51	6.01	9.61	0	0.72	Pebble
-1.5	5.20	2.54	5.45	0	0.88	Granule
-1.0	5.51	2.79	6.99	0.12	1.21	Granule
-0.5	6.71	3.42	7.46	0.25	2.20	Very coarse sand
0	10.95	6.21	11.35	1.52	6.00	Very coarse sand
0.5	22.20	17.64	22.43	10.87	15.24	Coarse sand
1.0	57.77	55.17	54.09	100.67	42.00	Coarse sand
2.0	164.86	136.84	108.5	150.42	148.10	Medium sand
2.5	13.37	25.04	15.92	27.92	64.85	Fine sand
3.0	1.39	7.6	2.28	7.01	13.83	Fine sand
3.5	0.23	1.47	0.24	0.85	2.87	Very fine sand
4.0	0.44	1.04	0.08	0.16	1.01	Very fine sand
Pan	0.81	0.45	0.11	0.19	0.10	Silt
Total	298.98	299.85	299.67	299.98	299.01	

Table 2: Rio Grande de Añasco sample weight percentages.

Phi	Sample # 1 weight %	Sample # 2 weight %	Sample # 3 weight %	Sample # 4 weight %	Sample # 5 weight %	Grain Size Classification
-4.0	0	3.20	2.11	0	0	Pebble
-3.0	0.79	7.19	14.10	0	0	Pebble
-2.5	0.56	0.83	2.21	0	0	Pebble
-2.0	1.84	2.00	3.21	0	0.24	Pebble
-1.5	1.74	0.85	1.82	0	0.29	Granule
-1.0	1.84	0.93	2.33	0.04	0.40	Granule
-0.5	2.24	1.14	2.49	0.08	0.74	Very coarse sand
0	3.66	2.07	3.79	0.51	2.01	Very coarse sand
0.5	7.43	5.88	7.48	3.62	5.10	Coarse sand
1.0	19.32	18.40	18.03	33.57	14.05	Coarse sand
2.0	55.14	45.64	36.18	50.14	49.52	Medium sand
2.5	4.47	8.35	5.31	9.31	21.69	Fine sand
3.0	0.47	2.53	0.74	2.34	4.63	Fine sand
3.5	0.08	0.49	0.08	0.28	0.96	Very fine sand
4.0	0.15	0.35	0.03	0.05	0.34	Very fine sand
Pan	0.27	0.15	0.09	0.06	0.03	Silt
Total	100	100	100	100	100	