Reduction and control of sediment-laden runoff near critical coral reef and other coastal ecosystems through the implementation of BMPs in Culebra, Puerto Rico FY-2016

FINAL REPORT

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1 PARTNERS AND COLLABORATORS FOR THIS PROJECT

Culebra Municipality

Punta del Viento Estates Homeowner Association (PVEHA)

2 SUMMARY

The purpose of this project was to reduce the impact of unpaved roads on coral resources on Culebra, a CRCP priority area and the Caribbean Habitat Focus Area in Puerto Rico. This project furthers implementation of priority restoration objectives of the 2014 Culebra Watershed Management Plan. Specifically, this project seeks to refine and prioritize feasible unpaved road restoration sites on the island, stabilize 1 mile of road, decommission the use of approximately half a mile of secondary unpaved roads and allow it to restore to naturally occurring vegetative cover, monitor performance, and produce an unpaved road guidance manual. These projects have utilized green infrastructure practices to intercept stormwater runoff and utilize plants, soils, and natural processes to filter and reduce runoff pollution.

Efforts to support and implement the ***Culebra Community Watershed Action Plan for Coral Reefs and Water Quality*** has led to unprecedented collaborations between the Municipality of Culebra, the Department of Natural and Environmental Resources (DNER), National Oceanic and Atmospheric Administration (NOAA), the US Fish and Wildlife Service (FWS) through the Partners for Fish and Wildlife Program, local organizations, and the community in general. As part of the funding cycle from NOAA's Coral Reef Conservation Program (CRCP) for Fiscal Year (FY) 2016, and in collaboration with the Horsley Witten Group (HWG) and the USFWS and the DNER, Protectores de Cuencas (PDC) implemented high priority projects in Culebra to stabilize unpaved roads and to restore and protect coastal ecosystems.

Work was performed on 1 mile of the Punta del Viento Estates dirt road network, San Isidro Ward, located in the Puerto del Manglar, Almodóvar and Manzanillo subwatersheds

(Figure 1). This project consisted of stabilizing 1 mile of the southeast lower drainage area of the Punta del Viento Estates dirt road network. This project was done in collaboration with the Punta del Viento Estates Homeowner Association (PVEHA) (Figure 1). Specifically, PVEHA funded the paving of a steep portion of the road and agreed to decommission the use of a secondary road to allow it to naturally restore back to native vegetation. The completed project represents major sediment and stormwater runoff control practices on unpaved road systems impacting Culebra's coastal and marine resources. The selected sites drain directly to important unique habitat that is vital for coastal wildlife, seagrass beds and coral reefs. The goals of these projects were to address runoff from the adjacent roads and bare soil areas prior to being discharged to the marine environment. These efforts had the endorsements of the Municipality of Culebra, the Conservation and Development Authority of Culebra (ACDEC) and the support of the DNER, as well as from the local community. Furthermore, the Homeowner Association agreed to provide long term maintenance of the stabilized roads by contracting PDC on a yearly basis.

It is important to point out that much of the labor for these efforts has been contracted locally from Culebra. These projects received technical assistance from the DNER, the USFWS and NOAA. DNER provided logistical support and accommodation for the work team at their facilities in Culebra. Project sites were selected in coordination with agencies, Horsley Witten Group, NOAA, the Municipality of Culebra and homeowners from the area.

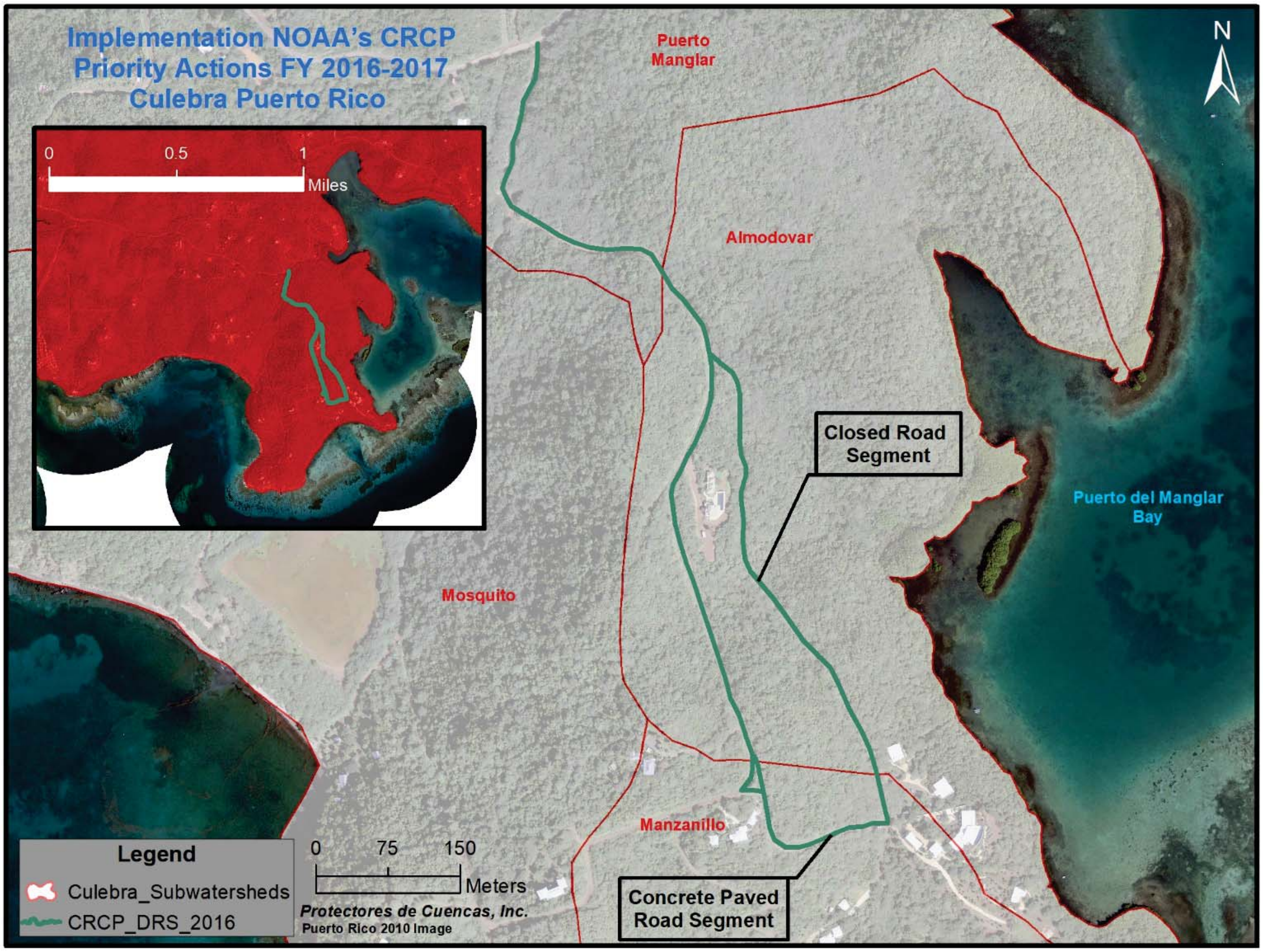

Figure 1. Culebra map with site locations where the green segments refer to the dirt road system project stabilized.

3 INTRODUCTION

Increased levels of land-based sediment loads associated with coastal development is one of the most important factors affecting coastal marine ecosystems in Puerto Rico. Puerto Rico coral reefs are among the most threatened marine ecosystems in the Caribbean. The degradation of coastal water quality in Puerto Rico has caused a decline in the population and health of coral reefs. The ability of reefs to survive is gradually being reduced as fine sediment and nutrient discharges from the land to the coastal waters increase. From the stand point of marine ecosystems conservation, degradation of water quality due to dispersed land-based sources of pollution has caused negative and sometimes irreversible damage to the integrity of the coral reef communities, sea grasses, mangroves, and other highly valued coastal ecosystems.

High rates of sedimentation, excess nutrients, urbanization, and sanitary sewage overflow are the main causes of the degradation of marine ecosystems. This phenomenon is mainly due to the lack of sustainable management from the perspective of integrated watershed management. Erosion and habitat degradation are other serious problems that our wetlands, estuaries, and coastal waters face. The removal of vegetation and land clearing activities for construction without proper erosion and sedimentation control practices impact marine and coastal ecosystems and diminish the attractiveness of coastal areas for recreation and tourism. High sediment loads discharging to marine environments as a result of poorly maintained dirt roads without the installation of proper management practices is a very common problem in Culebra.

As mentioned by Ramos-Scharrón and Amador-Gutierrez (2011), experts agree that much improvement on coral reef conditions in Culebra can be achieved by decreasing sediment load rates into its coastal waters. It has been determined that unpaved roads are likely to generate sediment at a rate of up to four orders of magnitude greater than undisturbed lands. Increased loads caused by the continuously growing unpaved network in Culebra have increased the rate of sediment and nutrient delivery to the marine environment, threatening the island's fragile coral reef systems (Hernández-Delgado et al., 2006).

Geospatial Information System models suggest that sediment delivery rates in four general areas of Culebra including Punta Soldado, Bahía Mosquito, Puerto Manglar, and Zoní range between 20 and 120 tons km^{-2} yr^{-1} (tons of sediment divided by km^2 of land area per year) (Ramos-Scharrón, 2009), and this ranges from about half to up to 10 times higher than those estimated for three comparable watersheds on St. John, USVI. In the case of Puerto del Manglar watershed, a total of 9.4 km of unpaved roads are calculated with a total delivery 112 tons of sediment every year into the receiving coastal waters, representing 86% of the entire watershed surface area sediment yield. The data presented by the studies show that sediment pollution from particular road segments outweigh their counterparts in their relative contribution to watershed-scale sediment yields.

4 Site Description

As part of the restoration projects completed, we continued to address issues of concern through the implementation of multiple BMPs in 1 mile of the Punta del Viento Estates dirt road network. The Punta del Viento site is composed of a community dirt road system. This dirt road is very steep and is one of the major sources of sediment runoff to Mosquito and Manzanillo Bays. The homeowner association for this area provided matching contribution to pay for part of the costs of these projects. Approximately 1 mile of dirt road was stabilized to reduce sediment transport to the marine environment. The lack of proper planning, management, and the absence of erosion and sediment control practices has led to an increase in sediment pulses that affects the adjacent bay and its resources.

5 PROJECT GOAL AND RESULTS

The primary goal of these projects was to stabilize bare soils in in high priority areas of Culebra by implementing sediment and erosion control measures to reduce sediment loads into the marine ecosystems. This will protect coral reef ecosystems in Culebra and make them more resilient to future threats.

Prior to stabilization, in most parts of the dirt road networks, runoff was flowing down the center of the road causing erosive forces to transport sediments into the nearshore environment. After completing the installation of temporary sediment and erosion control measures, PDC stabilized approximately 1 mile of dirt roads in three priority sites. Installed BMPs included sediment traps, check dams, swales, regrading, rip-raps, hydroseeding, Vetiver grass plantation and paving with granulate fill material and compacting. These projects will improve water quality and contribute to the health of adjacent coral reefs, and ultimately, support the Culebra local economy.

6 IMPLEMENTATION

The main problem of this dirt road system was that it was constructed in the flow patterns of two natural dry channels. Most of the runoff that drained naturally through the dry channels during storm conditions had been intercepted by the road, resulting in runoff flowing on the top of the road before discharging directly to the marine environment without any treatment (Figures 2). Several swales, Vetiver grass check dams, and a series of rip-rap and sediment traps were constructed to stabilize the road. The use of crossing underground drainage pipes was also constructed to ensure proper conveyance of runoff to forested areas after passing through a series of treatments. Due to the coordination with the PVEHA, we were able to stabilize one of the steepest segments of the dirt road system by paving it with the use of concrete and also one of the most sediment runoff contribution segments were closed and stabilized.

This project received the financial support from NOAA and the PVEHA and the support of the Municipality of Culebra, the DNER and the USFWS. Other contributions from land owners include space for storing heavy equipment, water for irrigation, and maintenance of green areas restored.

Figures 2. Sediment runoff and accumulation along dirt road at Punta del Viento during a small rain event prior to stabilization.

Before starting any restoration work in the area, we installed a series of temporary sediment and erosion control practices at the current road and near the coastal zone and where work was going to take place. Sediment control practices included installing silt fences and soil berms to redirect filtered runoff to forested areas.

All the dirt road stabilized was regraded to the desired hydrological patterns and compacted (Figure 3). Runoff was conveyed into continuous swales with 4-12" stones and Vetiver grass check dams at intervals of approximately 25-50 ft., depending on the slope (Figure 4). The regrading process was conducted using a Crawler dozer, and soil was compacted with a 15-ton compacting roller.

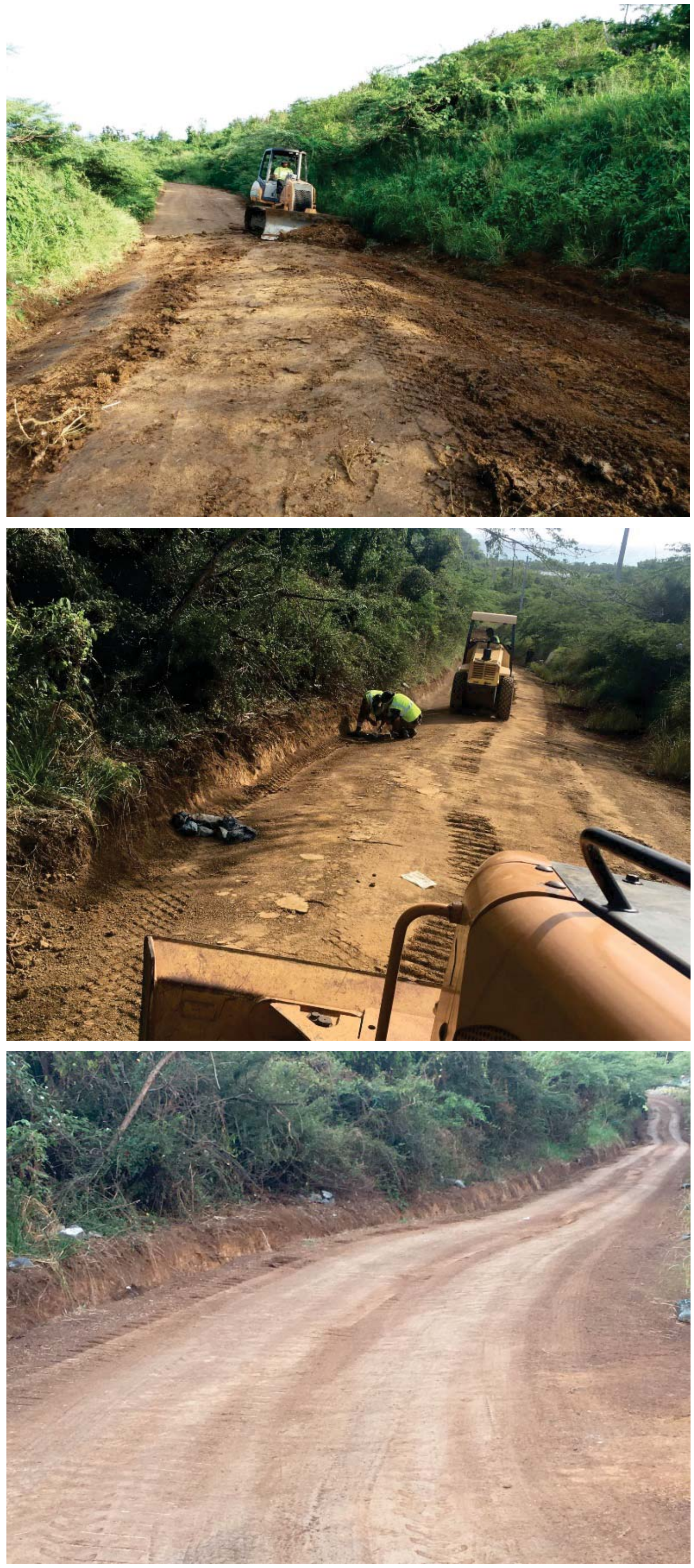

Figure 3. Regrading and compaction process during dirt road stabilization.

Figure 1. Construction process of installing check dams.

A series of crossing corrugated pipes were installed to cross runoff from one side of the road to another into forested areas (Figure 5). After the pipes where installed the soil was regraded and recompacted (Figure 6). A total of 13 crossings were installed on all sloped segments of the stabilized areas. Concrete catchments where constructed with overflow spillways on the inflow side of the crossing pipes (Figure 7). On the outfall side, cascade type rip-rap where installed in combination with Vegetative buffers (Figure 8). A series of rip-rap terraces were built on the areas that less pipes were installed because of the proximity of houses (Figure 9).

Figure 5. Process of installation of crossing pipes.

Figure 6. Regrading and compaction of road after installation of crossing pipes.

Figure 7. Construction process of installing concrete catchments for the crossing pipes.

Figure 8. Installation of rip-rap and Vetiver on the outfalls of crossing pipes.

Figure 9. Installation of rip-rap terraces.

A total of three sediment traps were constructed to help filter stormwater that was causing erosion problems and discharging sediments (Figure 10). The traps were formed by excavating an area across a low portion of drainage swale, and berms were constructed and compacted with the small compacting roller. After compacting, the sediment traps were covered with 4-12" stones as rip-rap to prevent erosion from the berms, the bottom was punched through with the backhoe to promote infiltration, and Vetiver grass half-moons were planted to help trap sediment and promote infiltration and evapotranspiration. A rip-rap overflow was constructed with bigger 1-2 ft. stones to reduce energy of the water (Figure 11). Sediment traps are excavated as a first step because they serve as a temporary sediment control measurement if unexpected rain events happen during work implementation (Figure 12).

Figure 10. Example of one of the sediment traps constructed.

Figure 11. Process of constitution of the sediment traps.

Figure 12. Example of a rain event captured by the sediment traps during project implementation.

A segment of the dirt road that was very steep and had very limited areas for BMPs establishment was stabilized by using concrete pavement. The total area of concrete is calculated to be of approximately 150 meters long by 4.5 meters wide and 6 inches in depth (Figure 13). The paved segment was regraded and compacted prior to concrete installation (Figure 14-15). The homeowner association paid for the concrete segment as a matching contribution. A total of 110 cubic yard of concrete was used. Rebar #3 was used to reinforce the concrete slab and every 100 ft a deeper trench was established of 1ft x 1ft to ensure concrete strength on the slope if heavy vehicles are used (Figure 16).

Figure 13. Aerial image of the project site area showing the concrete pavement and part of the closed dirt road segment.

Figure 14. Regrading and compaction process prior to concrete paving.

Figure 15. Molding preparation for concrete paving.

Figure 16. Rebar installation and concrete pouring.

Thanks to the concrete pavement the homeowners agreed to close a segment of the dirt road network. This road was used as an alternative to the steep road that was paved, mainly because it was not passable after rain events because of its steepness and it was very dangerous to drive on it. The closed segment of the road was approximately 500 meters in length and was one of the major contributions of sediments to the nearshore as it intersects one of the dry waterways of the subwatershed. The road was stabilized and closed to vehicular access. The expected outcome is that this segment grows back to forest cover (Figure 17).

Figure 17. Some of the practices implemented on the closed segment of the road.

7 MONITORING COMPONENT

The overall goal of this project component is to estimate reductions in sediment delivery resulting from the implementation of an erosion control strategy. Logistical challenges prevent us from directly measuring changes in sediment delivery, as there are no well-defined locations to measure pre- vs post-implementation changes and due to the lack of adequate time to establish pre-treatment delivery rates. Therefore, effectiveness measures are to be estimated based on indirect measurements through empirical experiments, hydrologic and sediment modeling, and field monitoring.

The monitoring protocol has the following four objectives: (1) *Quantify runoff and sediment production for both unpaved roads and undisturbed hillslopes at the plot-scale (~3.5 m^2)*; (2) *Develop runoff and sediment production models for both unpaved roads and undisturbed hillslopes based on the empirical data*; (3) *For some of the erosion mitigation strategies that have been implemented (i.e., check dams within road ditches and detention ponds) quantify the rate of sediment accumulation/retention; and (4) Rely on the results from objectives 1-3 to provide watershed-scale assessments of the sediment delivery potential both prior and following the implementation of erosion control practices.* These four objectives are addressed through a combination of empirical experiments, data analyses and modeling, in addition to a monitoring protocol. The two general approaches (experiments-analyses-modeling and monitoring) are relied upon here as an organizational framework to describe the progress achieved to date on this project.

This portion of the project is generating information based on two different types of field experiments: rainfall simulations and soil permeability using the Guelph permeameter.

The particular goals of these experiments are to: (a) characterize the hydraulic properties controlling infiltration capacities of soils at the sub-plot scale; (b) characterize the runoff response of soils at the plot (~ 3 m^2) scale; (c) characterize surface erosion rates of soils at the plot scale. A key objective of this portion of the project is to determine differences in the character of runoff production and erosion for undisturbed soils (i.e., undisturbed) in comparison with two types of unpaved road surfaces. Road surfaces are classified into those that were recently graded (< 2 weeks to few months; graded roads) versus those that had not been graded for more than a year (i.e., ungraded) as these have shown to have distinct erosion rates in similar settings (Ramos-Scharrón and MacDonald, 2005; Ramos-Scharrón, 2018).

The main purpose of these measurements is to develop a runoff and sediment production model for all three surfaces similar to those previously developed for the U.S. Virgin Islands (Ramos-Scharrón and MacDonald, 2007; Ramos-Scharrón and LaFevor, 2016). The undisturbed model will provide estimates of background runoff and sediment yields that can be used as a baseline to compare both pre- and post-implementation rates. The road runoff and erosion model will help establish an algorithm that can be used to estimate per storm runoff/sediment production. This model will then be incorporated into a GIS system to map runoff/sediment delivery spots (i.e., runoff and sediment total at specific road drains) and to evaluate how these have been managed by the erosion mitigation plan. Runoff and sediment production rates for each road drain will be compared to sediment accumulated in check dams and sediment detention structures as part of the monitoring protocol described below to evaluate how effective these structures are in retaining sediment. Runoff generation from drains leading to detention ponds will be compared to water accumulation observations at specific ponds being collected as part of the monitoring component of this study. These observations will help in determining if the sizing of those ponds is adequate in handling the runoff and sediment being delivered to them based on theoretical expectations based on runoff influx relative to pond size (Dendy, 1974).

Rainfall Simulations

Plot-scale rainfall simulations were used to quantify Horton Overland Flow (HOF) and erosion rates. Thirty-one simulations were run in July-August of 2017. The key factors expected to control runoff production and erosion rates in Culebra are: (a) surface type (undisturbed hillslopes, graded and ungraded roads); and (b) slope (three categories ranging between 3% and 40%; Figure 18). Plots were bounded on all sides by steel plates hammered into the ground. The plots have an approximate area of 3.2 m^2, with a rectangular shape (~3.2 m long by ~1 m wide) similar to those previously used elsewhere in Puerto Rico (Ramos-Scharron and Thomaz, 2016; Ramos-Scharron and Figueroa-Sanchez, 2017). At the front of the plot, the smaller steel plates converge to connect with the collector, which contains a small opening located downslope where runoff samples are collected. Runoff is measured in cubic meters per minute every minute during the 1 to 3.5-hr long rainfall experiment using a pre-calibrated bottle and a stopwatch; suspended sediment samples are collected every 5 minutes.

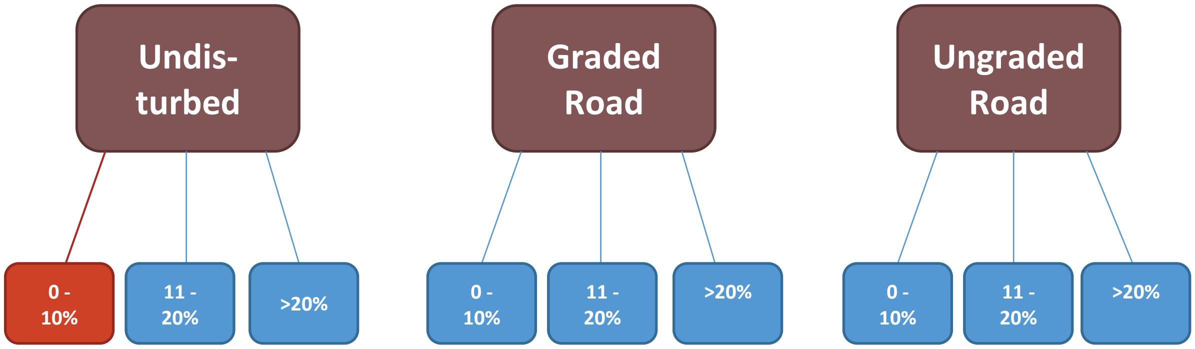

Figure 18. *Study design framework for rainfall simulation experiments. Surface type (i.e., undisturbed hillslopes, roads graded less than 2 weeks prior to the experiment, and roads not graded for months or roughly a year), as well as slope were considered as the two main factors controlling runoff response and erosion rates from the three zones of interest in Culebra*

In order to establish differences in runoff and erosion rates between graded and ungraded roads, our study design prescribes conducting 15 simulations on each road type with five replicates on each of the three slope categories (Figure 18). The three slope categories are: (a) gentle ($\leq$10% slope); (b) moderate (11% to 20%); and (c) steep (> 20%). Similarly, three replicate simulations in each of the three slope categories have been conducted in undisturbed areas where there have been no recent human disturbances, for a total of nine simulations. Designing the study in this manner will allow us to determine how significant slope gradient is in producing runoff and erosion at the plot scale, while also distinguishing runoff and sediment production among the three surface types. Data will allow the calculation of runoff coefficients, rainfall threshold for runoff development, infiltration capacity curves, suspended sediment concentration, sediment loss rates, and rainfall and area normalized erosion rates.

Guelph Permeameter

An instrument known as the Guelph Permeameter was used to establish hydraulic parameters required to estimate an infiltration capacity curve for unpaved roads and undisturbed hillslopes (Figure 19). The method consists in digging to dig a borehole of about 30 cm in depth and conducting a test that measures the transmission of water from the instrument into the soil while maintaining a constant pressure head. A total of 88 Guelph Permeameter tests have been completed at 22 different sites (two boreholes per location and two tests per borehole using different pressure heads). All Guelph permeameter tests have been completed but analyses is pending. Soils samples have been collected at each of the 22 sites for pre- & post-moisture content analyses as well as texture analyses.

Figure 19. *Guelph Permeameter test on an undisturbed hillslope (left) and on an unpaved road (right).*

Preliminary Results

Data collected from fieldwork that occurred in July of 2017 has been only partially analyzed at this time (Table 1). Basic information on runoff response has been evaluated for 31 of the 39 rainfall simulations. Average runoff coefficients for graded and ungraded roads were very similar at around 66%, which contrasts with the 3% average for undisturbed sites. The runoff coefficient represents the ratio of the total runoff generated to the amount of rainfall added to each plot over the entire simulation.

Table 1: *Averaged preliminary results for rainfall simulation data*

	Runoff Coefficient (%)	Bulk Density (g/cm^3)	Time to Runoff (min)	Peak Runoff (cm/hr^1)	Time to Peak Runoff (min)	Average Precipitation (cm)
Graded Road	67	1.32	5.68	5.80	18.60	5.77
Ungraded Road	66	1.61	5.08	4.84	17.83	5.12
Undisturbed Area	3	0.97	135	1.46	23.13	16.11

In terms of bulk densities (i.e., soil compaction), there is a noticeable difference among the three surface types. Ungraded roads had the highest bulk density at 1.61 g/cm^3. Graded roads had an intermediate density of 1.32 g/cm^3, and undisturbed surfaces had the lowest average density (0.97 g/cm^3). The difference between ungraded roads and graded roads does not appear to affect the runoff coefficient.

Time to runoff (i.e., the time elapsed between the beginning of rainfall and the onset of runoff) for recently graded roads was about 40 seconds later than that for ungraded roads, but it tended to occur at around the 5- and 6-minute mark for both road types. For undisturbed surface plots, time to runoff took 2 hours and 25 minutes on average. This is in agreement with the expected marked differences in the slow infiltration capacities for roads, in comparison to the high values for undisturbed soils.

On average, discharge rates were greater for recently graded roads than for ungraded roads by about 1 cm. However, this discharge difference is likely due in part to the average total precipitation rate being higher for graded roads by about 0.65 cm in comparison to ungraded roads. Peak runoff rates also reflect this slight difference in total precipitation between the two road types. Graded roads had a mean peak runoff rate of 5.8 cm hr^{-1}, while ungraded roads were about 1 cm hr^{-1} less at 4.84 cm hr^{-1}. Peak runoff for undisturbed plots was about 1.5 cm hr^{-1}. Unsurprisingly, average time to peak (i.e., time from the beginning of runoff to peak or a stable runoff rate) for graded roads occurred 50 seconds later than ungraded roads at around 18 minutes and 36 seconds. Average time to peak discharge for undisturbed plots took 23 minutes and 8 seconds. All of these preliminary values represent a notable difference in infiltration and runoff rates between unpaved roads and undisturbed hillslopes, but there seems to be little difference between graded and ungraded roads.

Pending Fieldwork and Analysis

We returned to Culebra during the summer of 2018 to complete the following fieldwork: (a) additional rainfall simulations, particularly on graded road surfaces; (b) detailed mapping of roads, road drainage patterns, and drainage structures. As in 2017, moisture content analyses of soils and road surface material as well as suspended sediment concentration of runoff samples were conducted at the UPR lab (Table 2). The remaining analyses will take place at UT-Austin.

Once the runoff/erosion regression model is generated, it will be integrated into a new GIS procedure that will extrapolate the data to the watershed scale. Infiltration capacity will be used to estimate runoff by precipitation excess, while runoff rates in combination with suspended sediment concentrations will be used to estimate sediment production rates. This analysis will be used on a storm by storm basis. These models will be compatible with ArcMap 10.4.1, and will allow the following analyses: (a) identifying areas within our observed watersheds generating the largest amounts of runoff and sediment; and (b) identifying the outlets through which these areas have the potential of draining into coastal waters. These analyses will be done for both the pre- and post-mitigation conditions to visualize the impact of the mitigation strategy in altering the pattern of runoff/sediment delivery to coastal waters.

Table 2: *Completed and remaining rainfall simulations and Guelph permeameter tests with the respective collection locations.*

	Punta Aloe	**Fulladosa**	**Punta Del Viento**	**Total**	**Remaining**
Rainfall Simulations	Graded - 0 Ungraded - 11 Undist. - 9	Graded-0 Ungraded – 7 Undist. - 0	Graded-5 Ungraded-0 Undist.-0	Graded-5 Ungraded-18 Undist.-9 All-32	Graded-10 Ungraded-5 Undist.-0
Guelph Permeameter Tests	Graded-0 Ungraded-8 Undist.-8	Graded-0 Ungraded-36 Undist.-36	Graded-0 Ungraded-0 Undist.-0	Graded-0 Ungraded-44 Undist.-44 All-88	Graded-0 Ungraded-0 Undist.-0

As stated, the ultimate goal of the resulting models and analyses is to assess the effectiveness of the implemented erosion control strategies in reducing sediment delivery to the bay. One basic metric that we intend to establish to assess effectiveness is to estimate the reductions in direct delivery of sediment into the coastal waters of Culebra. A graphical description of how we intend to conduct and present our analyses is shown as Figure 20. Here we display the spatial distribution and total amount of sediment being delivered from the road to the coastline and to specific erosion control practices. In the hypothetical case shown in Figure 20, direct sediment delivery to the bay from that unpaved road segment was estimated to have been reduced from 100 Mg per year to 20 Mg per year. The remaining 80 Mg per year are being treated by several practices before being delivered to the coastline.

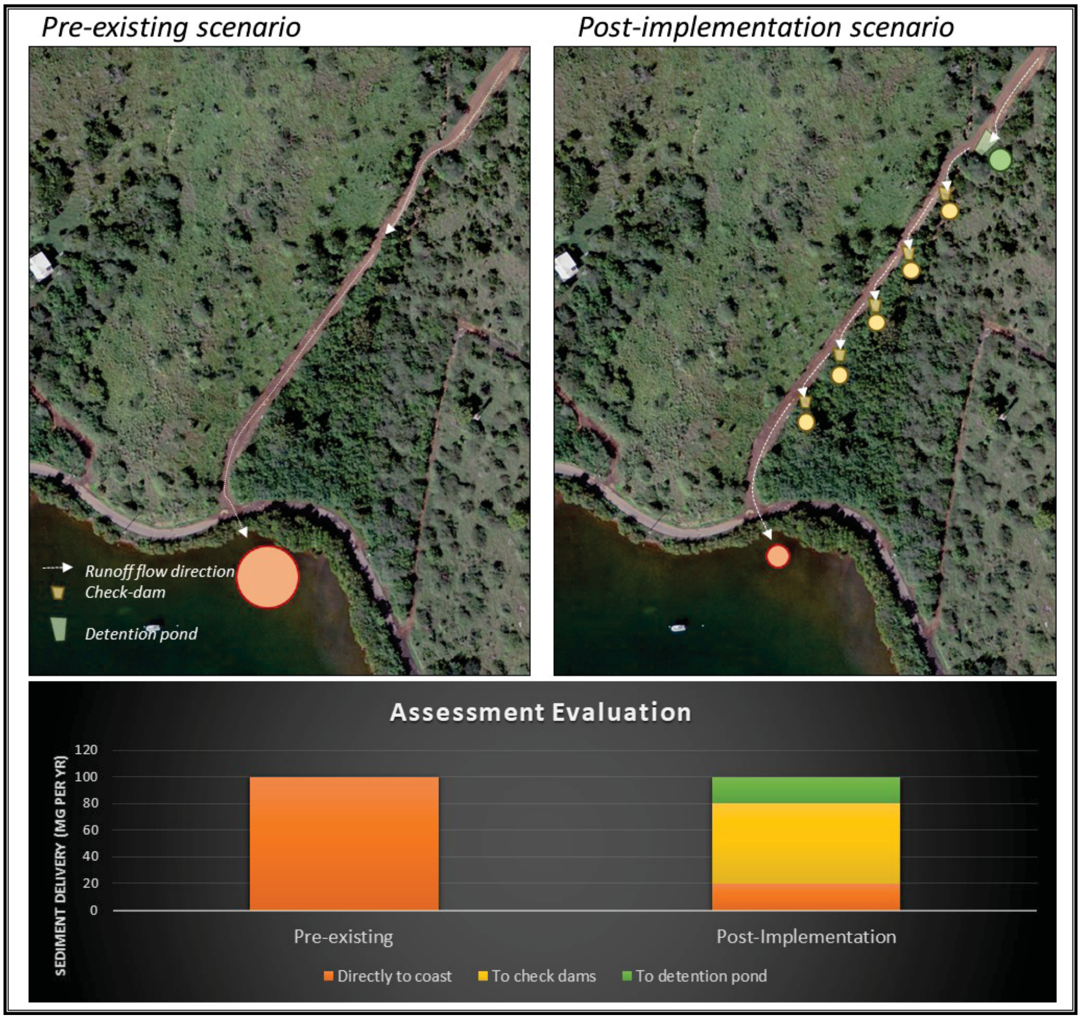

***Figure 20**. Hypothetical representation of the potential use of the erosion and GIS model to assess the effectiveness of erosion control measures at the road segment scale. The size of the circles refers to the amount of sediment being delivered at each road drain location.*

Monitoring efforts began in the summer of 2017 for the implementation of Punta Aloe, Fulladosa, and Punta Del Viento. In addition to the experimental efforts described above, silt fence aprons, peak crest gauges, Hobo-brand water level recorders, single-stage suspended sediment samplers, and recording rain gauges were installed throughout the three focus areas. Sites were visited roughly once a month between August of 2017 and March 2018. The rationale behind the various methods being employed as part of the monitoring component is quite diverse:

- *Rain gauges*: These serve as the basis to document the types of rainfall conditions matching all of the monitoring observations being collected.
- *Silt-fence aprons*: These have been installed at locations where road runoff is being disrupted by a check-dam or by a road drain diverting water off the road in the Punta Aloe area. Aprons, and not typical silt fences, were chosen because the objective of these is to measure how much sediment is being trapped by the existing rock-based check dams and the drains. Any sediment trapped is sediment that presumably is no longer available to be delivered to the bay and is therefore a direct measure of effectiveness. The difference between the modeled sediment production (based on rainfall simulation data) for a particular road segment draining towards the silt-fence apron and the measured amount will be taken as an estimate of the amount not being trapped by the check-dams, and thus an indirect metric of trapping efficiency (i.e., ratio of amount trapped to amount delivered to it).

- *Peak-crest gauges*: Several peak crest gauges have been located upstream and downstream of road drains to evaluate which storm events induce runoff generation on these ephemeral channels. Upstream sites typically represent undisturbed conditions, while downstream sites represent stream segments receiving road runoff. The objective of these crest gauges is to establish when runoff is occurring in Culebra's ephemeral stream network and to evaluate if road drainage is increasing the potential for runoff generation and delivery from these streams into coastal waters.
- *Single-stage suspended sediment samplers*: Water samplers typically accompany peak crest gauges and are meant to document the concentration of suspended sediments being carried by the runoff generated along different portions of Culebra's streams. Sets of samplers have been set at three ephemeral streams and these include an upstream and a downstream location relative to road drains. At most locations, upstream sites are meant to document undisturbed suspended sediment concentrations. The comparison of upstream vs downstream samples is meant to represent a simple measure of the localized impact of road drains in suspended sediment concentration as it has been described elsewhere (Thomas and others, 2014).
- *Water level recorders*: These have been placed within detention ponds as a way to document the filling of these with runoff during individual storm events. These will aid in evaluating if the design of these structures (in terms of placement and size) is adequate. Evaluation of these data will likely be completed after some of the Culebra projects have been completed. However, we will also rely on a combination of road runoff predictions (based on both the runoff simulations and the Guelph results) and

trap efficiency metrics developed elsewhere to determine the expected percentage of sediment reaching the traps that is expected to be retained. Trap efficiency (the percentage of delivered sediment that is actually retained by the trap) has been found to be a function of the ratio of pond volumetric capacity to incoming runoff (Brune, 1953; Verstraeten and Poesen, 2000). Once runoff generation models have been developed, we will use observed rainfall data from Culebra to make estimates on the rate and total amount of runoff reaching each of the built ponds on a storm by storm basis. These estimates will be compared to the volumetric capacity of each pond (established from detailed topographical surveys) to determine the expected trapping efficiency of all ponds for rainstorms in Culebra.

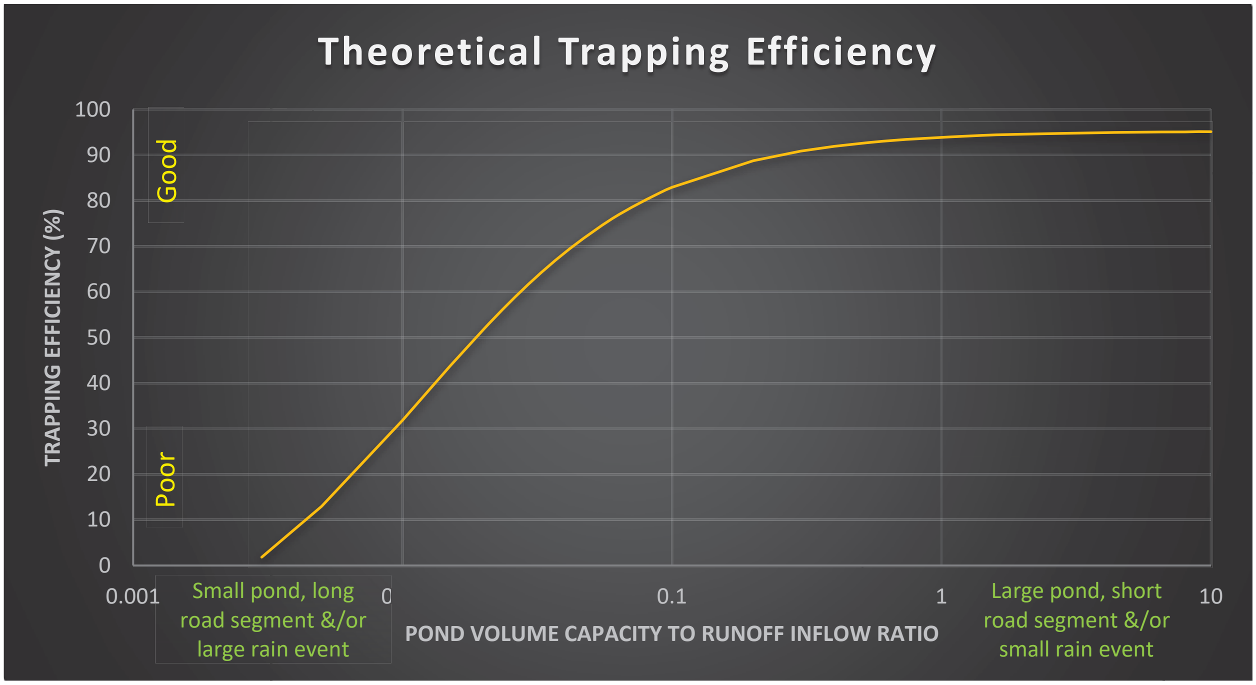

Figure 21. *Theoretical relationship between the ratio of detention pond size and incoming runoff against the trapping efficiency of the pond (percent of incoming sediment retained). The figure suggests that the trapping efficiency increases when the size of the pond is high in relation to the incoming runoff. Graph taken from Ref. 11.*

Rainfall Data

Figure 22*: Tipping bucket rain gauge at Fulladosa*

Three tipping bucket rain gauges were installed in Culebra at Punta Aloe, Fulladosa, and Punta Del Viento (Figure 22). The Punta Aloe and Fulladosa the rain gauges have been recording data since July 2017, while at Punta Del Viento the rainfall data has been recorded since November 2017. Figure 23 presents the monthly rainfall in inches for the three locations from August 2017 to February 2018. September and October 2017 report the highest rainfall amounts with 13” and 10” respectively, while the lowest rainfall amount was reported in December with 1.2”. In September Hurricane Irma and María produced 3.5” and 5” at Punta Aloe and 4.7” and 4” at Fulladosa, respectively.

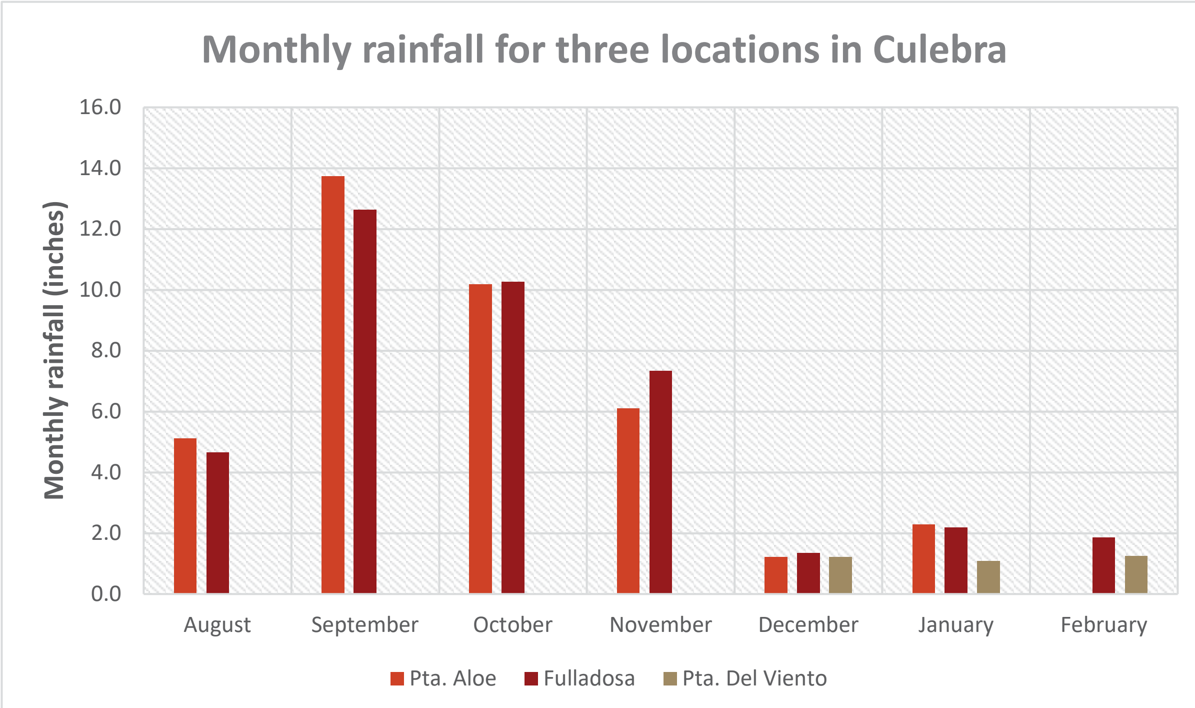

Figure 23. *Measured monthly rainfall from August-2017 through February-2018 for three locations in Culebra*

<u>*Stream Monitoring*</u>

Three streams draining to Fulladosa Bay are being monitored for water level and sediment concentration using water level recorders, peak crest gauges and single stage samplers (Figures 24-26). The three streams are *Punta Aloe North* and *Punta Aloe South* (which drain the unpaved road that was treated by PDC in 2016), and *Fulladosa* which drains an unpaved road that PDC started to treat during March 2018. As the majority of the streams in Culebra, these three streams are ephemeral and remain dry during most of the year. During our field visits, streamflow has been observed only twice.

One important event producing streamflow occurred on 15 October 2017, and this was from a storm totaling 3.5” of rain. Peak stages recorded by the crest gauges reached 1 ft. and 2 ft. at the northern and southern stream of Punta Aloe (respectively), and at 2 ft. at Fulladosa stream. During the 15 October 2017 storm, several grab water samples were collected from Punta Aloe's north stream and from the road runoff entering the detention ponds and outflowing to the bay.

Figure 24: *A peak crest gauge and single stage samplers in Punta Aloe North Stream*

Figure 25: *Grab sample collection in Punta Aloe North Stream during 15 October 2017 storm*

Figure 26: *Single Stage Samplers in Punta Aloe North Stream during 15 October 2017 storm*

The single stage samplers and peak crest gauges were visited and serviced a total of seven times in Punta Aloe North, six times in Punta Aloe South, and six times in Fulladosa between October 2017 and March 2018. Table 3 shows some preliminary data from the field visits. The maximum water level the streams have reached is approximately 2 feet and is associated to the rainfall produced by Hurricanes Irma and María. A larger number of samples has been collected in Punta Aloe North because more samplers are installed in this stream and because luckily two runoff-triggering events (i.e. 15 October 2017, 16 November 2017) have occurred during field visits and this has permitted collecting grab samples. The two hurricanes caused the loss of the monitoring equipment in Punta Aloe South, thus a relatively low amount of samples has been collected at this location. Suspended sediment concentration analyses of these samples are ongoing.

Table 3. *Preliminary results of water level and water samples collection for three streams*

Stream Monitoring Preliminary Data			
	Punta Aloe North	Punta Aloe South	Fulladosa
Max Water Level (inches)	22.8	22.6	23
Total Samples Collected	17	4	8

Sediment detention ponds

Two detention ponds in Punta Aloe and one in Punta Del Viento are being monitored with a Hobo water level recorder (Figures 27-29). This data has not been examined at this point.

Figure 27: *Water level recorder installed at the detention pond in Punta Aloe*

Figure 28: *Detention Pond at Punta Aloe*

Figure 29: *Detention Pond at Punta del Viento*

Silt-fence aprons

Silt-fence aprons were installed at the 23 energy dissipating structures (i.e., check dams along ditches or road drains) that were constructed by PDC in Punta Aloe during an earlier erosion control project. The purpose of these is to quantify the mass of sediment retained by these structures. The sediment traps consist of silt fence fabric nailed to the ground within the area occupied by the energy dissipating structures (Figure 30). These have been measured six times between August and March. The collected soil samples are being processed in the laboratory, but results are still not yet available. As of September 2018, a similar monitoring approach is now being followed at all of the 171 check dams built in Punta del Viento.

Figure 30: *Sediment apron at a check dam in Punta Aloe*

Our current appreciation is that the performance of the energy dissipating structures (check dams) in trapping sediment along Punta Aloe varies significantly among the 23 monitored sites in Punta Aloe. Traps 1 and 2 serve as road drains directing runoff towards detention pond 1 near the top of the main access road. Traps 1 and 2 consistently have had significant amounts of sediment during all the visits (Figure 26). Traps 3-10, all located on road segments below the top detention pond, rarely collect significant amounts of sediment, mainly because the road has lost the insloping grade (i.e., inward tilting) that was originally achieved during road improvements. Therefore, runoff along these road segments continues down the road and is therefore not being directed towards the traps (Figure 30). Traps 11-15 drain to the lower pond, located about one-third of the way up into Punta Aloe. These are some of the most effective traps due to the depth of the ditch and the effective road inslope tilting in this road section (Figure 31). Traps 16-23 receive the greatest amounts of runoff and sediment, but these were destroyed during the two hurricanes and have lost their trapping efficiency (Figures 32 and 33). Maintenance is required for these traps to perform at an acceptable level. Overall, the energy dissipating structures trap some sediment but periodical maintenance is required to sustain its effectiveness.

Figure 31: *Sediment trap 1 at Punta Aloe*

Figure 32: *Runoff flowing through the center of the road and not being delivered to the ditch on the right were the sediment traps are located*

Figure 33: *Traps 11-15 are located on the ditch on the left.*

Figure 34: *Trap 19, note how the sediment goes over the energy dissipating*

Figure 35: *Damaged sediment trap*

8 PROJECT COSTS

The work completed in Culebra for FY 2016 in the subwatersheds of Puerto del Manglar, Almodovar and Manzanillo was performed for a total combined cost of $201,475 including $120,550 (cash, Table 4) and $80,925 (non-cash, Table 7). From this amount, $91,475.00 was provided by NOAA CRCP (Table 5), and $29,075 was provided by the Punta del Viento Estates Homeowner Association (Table 6). A total in-kind (non-cash) match of $80,925 was estimated on this effort from contributing entities, including the DNER, PDC, Culebra Municipality and local community volunteers, as described in Table 7.

Table 4. Summarized Global Costs

CATEGORY	COST
Labor and Manpower	$10,000
Rental Equipment and Materials Transportation	$10,400
Supplies	$46,000
Project Management, Coordination, Design and Engineering	$36,200
Travel (gas, flights, ferry, per diem, etc.)	$5,450
Monitoring	$12,500
TOTAL	**$120,550**

Table 5. Summarized NOAA Funding Costs

CATEGORY		COST
Labor and Manpower		$6,800
Rental Equipment and Materials Transportation		$8,600
Supplies (costs include 8-12", 2-4', ¾/1 ½", size stones, Vetiver plants, other mis.)		$25,000
Project Management, Coordination, Design and Engineering		$34,000
Travel (gas, flights, ferry, per diem, etc.)		$4,575
Monitoring		$12,500
	TOTAL	**$91,475**

Table 6. Summarized PVEHA Funding Costs

CATEGORY		COST
Labor and Manpower		$ 3,200
Rental Equipment and Materials Transportation		$ 1,800
Supplies (Concrete, rebar, lumber, and other mis. materials)		$ 21,000
Project Management, Coordination, Design and Engineering		$ 2,200
Travel (gas, flights, ferry, per diem, etc.)		$ 875
	TOTAL	**$ 29,075**

Table 7. Estimated In-Kind Match Contributions from Project Partners

ENTITY	ACTIVITY	UNITS	COST/UNIT	TOTAL COST
DNER	Lodging for 8 persons at a rate of 1500/Month	12	$1,502	$18,025
Culebra Municipality	HD Hammer for Bob Cat at a rate of $1,450/month	6	$1,450	$8,700
Culebra Municipality	Hours labor	35	$30	$1,050
Omar Villanueva	Backhoe at a rate of $400/day	60	$400	$24,000
PDC	Dozer at a rate of $650/day	7	$650	$4,550
PDC	Dump truck at a rate of $450/day	8	$450	$3,600
PDC	Small water truck at a rate of $350/day	35	$350	$12,250
PDC	Skid Loader at a rate of $250/day	7	$250	$1,750
PDC	Uncompensated hours at a team mean cost/hour	60	$75	$4,500
PDC	Office space and materials at a cost of $1,500/year	1	$1,500	$1,500
PDC	Landscaping Supplies (hand tools, soil enhancements, auger drill, generator, etc.)	60	$100	$1,000
			TOTAL ESTIMATED	***$80,925***