A study of stream flow and measurements of sediment load in the Terciopelo Creek of the Firestone Center for Restoration Ecology in southwest Costa Rica

By Sam Scott

Pitzer College

Abstract

Terciopelo Creek is a small stream that runs through the property of the Firestone Center for Restoration Ecology in Baru, Costa Rica. Quebrada Cacao is a larger stream that runs down the eastern boundary of the property. During several episodes of heavy rain, stream velocity and vertical depth were measured. By multiplying these measurements, stream flow could be determined. Sediment load was also measured during these rain events by taking water samples from each stream at various time intervals and using vacuum filtration the water to mass the amount of sediment in each sample. The behavior of stream velocity, vertical depth, flow and sediment load were analyzed in response to heavy rainfall. A significant increase in vertical depth were observed in both streams after the rain events, while velocity data did not follow any consistent pattern in response to rainfall. A significant increase in turbidity, and therefore sediment load, were observed in water samples taken from both streams in response to heavy rainfall. Flow and sediment export were calculated in Terciopelo Stream.

Introduction

Streams respond in a variety of ways to heavy rainfall (Robson et al. 1993). Factors that influence this response include but not limited to such factors as location of stream, duration and intensity of rainfall, the period of time during which the rainfall occurs and the surrounding land-use. Stream flow – the volume of water passing through the stream over a given duration of time – has been known to change with heavy rainfall, and this change has been shown to vary according to various spatial and temporal factors (Singh 1996). Correspondingly, factors such as stream velocity and stream height, which together determine stream flow, also vary during heavy rain.

Being able to quantify the change in stream flow that occurs during a heavy rain is useful for a variety of reasons. Such an estimation could have important engineering implications by providing an assessment of potential stream volumes that any structure built on or in a stream should take into consideration. Additionally, this estimation would be useful in any attempts to estimate the capacity of a stream to function as a source of hydroelectric power.

One method that has been suggested to quantify stream flow is the "velocity – area" method of stream flow measurement (Herschy 1985). This method uses the height of the stream over a given geometry of a cross-section of a stream with the velocity of the stream at that cross-section to quantify the amount of water passing through that cross-section over a given period of time. These calculations can be simplified by using a mathematically known cross-section geometry, such as that provided by a cylindrical culvert.

Another component of the physical response of a stream to heavy rainfall is the mass of sediment contained in the water. The role of heavy rainfall in soil erosion has been shown to vary according to a number of factors similar to those that influence stream flow, such as land use, and soil conditions (Pla Sentis 1997). Due to agricultural implications, a number of models have been proposed to predict and/or quantify the mass of soil that will/has eroded from a given landscape, such as the Revised Universal Soil Loss Equation (RUSLE) (Renard et al. 1991). Soil erosion is of particular interest in the tropics, where poor land use has resulted in a large amount of soil erosion

Theoretically, directly quantifying soil erosion over a watershed is possible by measuring the amount of soil carried in a stream emerging out of that watershed. Since, as previously discussed, heavy rainfall has been shown to stimulate soil erosion, the periods of time which would be most useful for quantifying soil erosion would be during or immediately after large rain events.

The purpose of this research has been to provide a baseline assessment of quantifiable changes in stream flow and sediment load that occur with heavy rainfall in two streams whose watersheds include tropical montane deciduous secondary forest located at the Firestone Center for Restoration Ecology in Baru, Costa Rica. Additionally, this research allowed for an assessment of the effectiveness, accuracy, and practicality of various proposed methods by which these two quantities could be measured.

Materials and Methods

MAPPPP???

Data was collected from two culverts located at the eastern edge of the Firestone Center for Restoration Ecology (FCRE) located in Baru, Costa Rica. FCRE is located at 9.279 N, 83.862 W. The smaller culvert channeled water from a stream known as Terciopelo Stream, whose watershed consisted of an area of mixed primary and secondary forest towards the inside of the property. In general, most of the rainforest 20 – 30 meters from Terciopelo stream was left uncut by the previous owner of the FCRE, while the forest surrounding the area immediately around the stream was highly disturbed secondary forest that used to function as cow pasture. The larger culvert channeled water from a stream known as Quebrada Cacao, which ran along the northwestern boundary of the property. On the eastern side of the stream, the side contained in the FCRE, the stream is bordered by areas of secondary forest and small human settlements near the culvert, while further upstream it is bordered by thin strips of primary forest and secondary forest further in, similar to condition of Terciopelo Stream. The western edge of the stream consisted of highly disturbed secondary growth towards the south, featuring a road and a cow pasture lay, and less disturbed primary/secondary forest. The headwaters of Quebrada Cacao lay far outside the property lines for the Firestone Center for Restoration Ecology, so the quality of the surrounding land far upstream of the culvert has not been determined.

Weather data was collected using a Davis VantagePro2 Weather Station mounted on the roof of the program house, which collected data on barometric pressure, temperature highs and lows, wind speed and direction, humidity, dew point, heat index, thw index, rainfall, rain velocity and a variety of other weather-related measurements .

Collection of Velocity and Height Data

For Terciopelo Stream, velocity data was collected using a Greyline Stingray Flowmeter. The apparatus consisted of a bolt fitted into the cement culvert at the lowest height possible, upon which a bracket was attached. The flowmeter was placed into this bracket carefully, to assure that the apparatus was parallel to the bottom of the culvert.

The cord, which comes out of the flowmeter, was led up the sides of the culvert and attached to the orange data logger box, which was then placed inside of a wooden box that was locked and chained to a tree that neighbored the culvert. Over the course of the summer, the specifics about the velocity data recorded by the flowmeter changed. For the rainfalls that occurred on June 13th and June 28th, data was recorded in units of feet/sec at a five minute interval. For the month of July, data was recorded in units of meters/sec at a two minute interval for the rainfall on the 13th of July, and a one minute interval for the 24th of June. After loading the data from the logger on to the computer using the Greyline Stingray software, the data was converted into a format viewable Microsoft Excel using the "Export Data" function located under the "File" menu when viewing the data in the program.

The Greyline Stingray Flowmeter could not be dispensed in Quebrada Cacao due to the threat of large rocks passing through the stream that could potentially damage the flowmeter. Therefore, velocity data for this stream was collected using a method popularly known as "the float method". A passion fruit was dropped on the upstream side of the culvert, a stopwatch was started when the fruit crossed over the northern boundary of the culvert and stopped when the fruit was seen emerging from the culvert downstream.

Height data was collected from both Terciopelo Stream and Quebrada Cacao using gauges placed on the circumference of the culvert, and supplemented by measurements from a bamboo pole painted with centimeter heights when the stream height rose above the top of the gauge. On Terciopelo Stream, the gauge consisted of 36 inch long ruler, while for Quebrada Cacao, the gauge was five centimeter intervals up to

120 centimeters. The measurements from the gauges were converted into vertical depth measurements (in centimeters) and wetted area measurements (in centimeters^2) based on the following equations: **EQUATION EDITOR??**

For height data from Terciopelo Stream[1]:

Radius of Terciopelo Culvert = 63 centimeters

Depth on gauge in inches x 2.54 centimeters/inch = Depth on gauge in cms.

Depth on gauge in cms + 21 cms between "zero" on gauge and bottom of culvert

= Circumferential Depth (cms.)

Wetted arc length (s) = Circumferential Depth (cms) x 2

Theta = Wetted arc length (s) /(Radius of Terciopelo Culvert)

Vertical depth = Radius of Terc. Culvert (63 cms) – {(Radius of culvert) x COS(Theta/2)}

Wetted area = (Radius of Terc. Culvert)^2 x [(Theta – SIN(Theta))/2]

For height data from Quebrada Cacao:

Radius of Cacao Culvert = 145 centimeters

Depth on gauge in centimeters + 94 centimeters between "zero" on gauge and bottom of culvert =

Circumferential Depth (cms)

Once circumferential depth is calculated, vertical depth and wetted area can be calculated according to the same equations as used for the height data from Terciopelo Stream, substituting the radius of Radius of Cacao Culvert for the Radius of Terciopelo Culvert.

For the measurements taken directly as vertical depths, using the bamboo pole method described above, the following equations were used to calculate wetted area (in centimeters^2):

d = Radius of culvert from which measurement was taken – Vertical depth in centimeters

Theta = 2 * [ACOS(d/Radius of respective culvert)]

Wetted area was calculated using Theta in the same way as seen in the above equation.

All of these equations were condensed into spreadsheet form by Donald McFarlane.

Interpolation Algorithm

Since height and velocity measurements were not taken at every minute during the storm, data analysis for height and velocity data relied on an interpolation routine written in Visual Basic for use in Microsoft Excel. The routine was written with the assistance of Timothy Lykes.

Essentially, the routine consisted of an outer loop that took the difference between two sequential manually taken data points and divided that difference by the number of minutes between the two manually taken data points, and an inner loop that progressively accumulated that difference, or incremental value, on to each minute between the two points. Therefore, a number representing a height and velocity could be produced for every minute during a period in which data was collected. For a more complete explanation of the logic used in the routine and the complete text of the routine, see the appendix.

Calculation of Flow Using Interpolated Data

Using the interpolation routine, a velocity measurement and a wetted area measurement were created for every minute during which data was collected. By multiplying a velocity value (in cm/min) for a given minute by a wetted area value (in cm^2) for the same minute to produce a flow value (in cm^3/min or ml/min). The flow values were converted to l/min. Flow values for successive minutes were then added together to produce a value for the quantity of water that flowed through the stream over a given interval. A period known as “high flow” was ambiguously defined as the period from the beginning of both velocity and height data collection to two hours after rainfall ceases, due to the tendency for this period to repeatedly show especially high levels of flow.

Measurement of Turbidity and Sediment Load

Water samples were collected during the storm using Nalgene plastic bottles of various sizes that were rinsed with tap water prior to use. All samples were collected at the front and center of the respective culverts of each stream; during high flow conditions, water was collected as close to this point as was safely reachable. At these points, the sample water was collected by submerging the Nalgene bottles just beneath the surface of the stream. For all dates except the 28^{th} of June, three replicates were taken for each time a sample is listed as collected. On the 28^{th} of June, only one sample was taken at each stream, and the turbidity of each sample was measured three times, using three different portions of water collected in the same bottle.

Turbidity was measured using a LaMotte 2200e Turbidimeter that was calibrated prior to use according to the manual instructions. A 1 FTU sample made by AMCO was used as the turbidity standard. Before taking the turbidity of a sample, the glass bottle in which turbidity is measured was rinsed three times with the sample water prior to measuring the turbidity of that sample water. Before adding the water to the glass bottle, the sample bottle was thoroughly shaken to suspend as much sediment as possible. Water was added from the sample water bottle less than ten seconds after it was shaken using a 10 ml glass pipette, which was rinsed with deionized water between collections. For samples with turbidities higher than 80 NTU’s, the sample was diluted in half using deionized water. Since the glass turbidity bottle called for 10 ml of sample water, for these highly turbid samples, 5 ml of deionized water would be added to 5 ml of sample water. The glass bottle would then be rinsed three times with the diluted water, and turbidity would be measured according to the procedure in the manual.

Sediment content of the water samples was measured in water taken from Terciopelo Stream on July 13th and water taken from Quebrada Cacao on July 21st. Number 2 filters were heated at a temperature of approximately 60^{o} Celsius in an incubator for 24 hours. After drying, these filter papers were massed on a balance accurate to +/- 0.005 grams. The filter papers were then placed in a vacuum filter apparatus, and 25 to 500 ml of the sample water was run through the vacuum filter, depending on the relative sediment content of each sample – more water from samples with less sediment content was needed in order to produce a measurable amount of sediment on the filter paper. After filtration, the filter papers were heated at a temperature of approximately 60^{o} Celsius in an incubator for 24 hours, then massed using the same balance. The mass of the filter paper pre-filtration was subtracted from the mass of the filter paper post-filtration and all measurements were converted to grams of sediment per liter, based on the quantity of sample water filtered through each paper.

Based on the measurements of turbidity and sediment content in the samples taken on July 13th and July 21st, a trend line was produced in Microsoft Excel for each respective stream with turbidity values in NTUs on the x-axis and grams of sediment per liter values on the y-axis.   Using the equation for this trend line, the other turbidity measurements for each sample from each stream were converted into a value in grams of sediment per liter.

As was done for the velocity and height measurements, the interpolation routine for Microsoft Excel was used for the sediment load measurements to produce a value for grams of sediment per liter of water for each minute during which data was taken. Then, the amount of sediment which passed through the stream during a given minute was calculated by multiplying the flow value (in liters/min) for that given minute by the value for grams of sediment per liter. The amount of sediment which passed through the stream over a time interval was calculated by summing all of the values for the amount of sediment which passed through the stream during each minute in the interval.

Results and Discussion

Weather Monitoring on Storm Days

Data was collected on June 13th, June 28th, July 13th, July 21st, and July 24th. Figure 1 presents a broad overview of the data collected from each day. Weather data is missing for June 28th due to a power loss during the storm, which prevented the Davis Weatherlink system from collecting data.

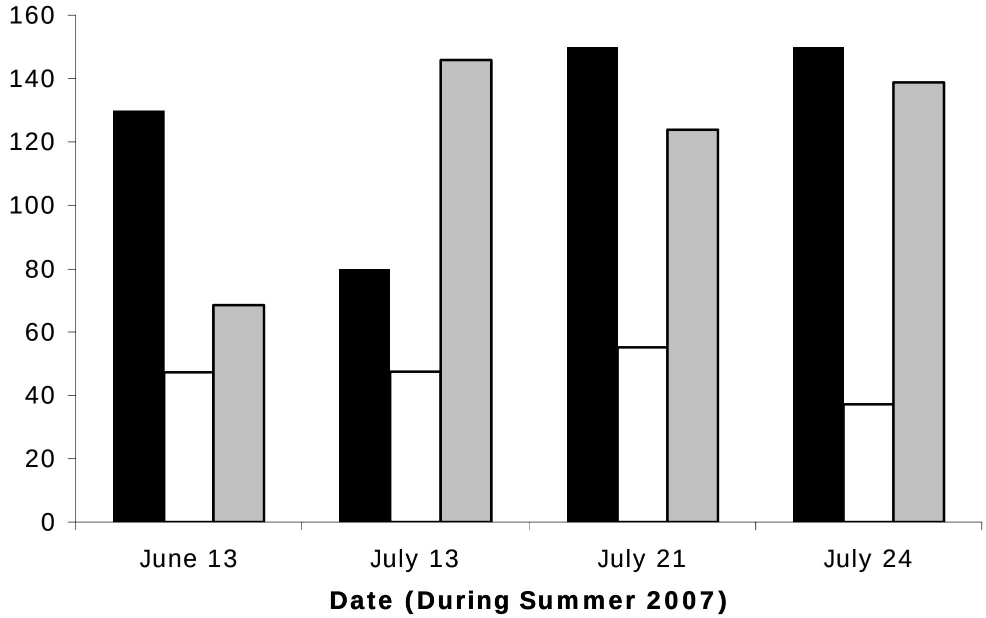

Figure 1. Data collected by Davis Weatherlink System for four days on which heavy rainfall occurred and stream data was collected. A black bar indicates the duration of the storm (minutes) falling on a respective date, a white bar total rainfall (centimeters) and a grey bar peak rainfall rate (centimeters/hour).

In general, the weather data did not prove very useful to use at a more specific level than presented above due to the large logging interval of the Davis Weatherlink system (10 minutes) in comparison to rapid rate of change occurring in the stream during rainfall, and the variety of problems that appeared due to power loss in the Davis Weatherlink system.

When power was lost, as frequently occurred during heavy rain and lightning, the system would cease collecting data. When power and data collection resumed, the Weatherlink system would automatically assign the first measured data to a time interval ten minutes after the previous data point was measured, even though the period in which data was not collected could have exceed ten minutes substantially. For example, it appears likely that a short power outage occurred on July 13 and July 21, since the duration of rainfall recorded by the system is shorter than the duration of an increase in stream height. Additionally, if any power outage occurred before a storm in which height and velocity data was collected, the time component of the logger would appear offset; the storm would appear to occur earlier than manual measurements would show. However, it is difficult to trust the “time” component of the Davis Weatherlink System to a high degree of precision and to pair data recorded by the machine with manually recorded height, velocity, and water sample data.

Data Analysis and the Interpolation Routine

Table 1 shows a portion of stream velocity measurements taken at Terciopelo Stream by the Greyline Flowmeter. Table 2 shows a corresponding portion of interpolated stream velocity measurements, in which the minutes between the manually taken data points were assigned a velocity value based on the interpolation routine (see above – *Interpolation Algorithm)*.

Table 1 – Sample of stream velocities recorded at Terciopelo Stream on June 13, 2007 by Greyline Stingray Flowmeter. Logging interval set to five minutes.

Time	Velocity (ft/sec)	Velocity (cm/sec)	Velocity (m/min)
4:32 PM	2.432	74.13	44.47
4:37 PM	2.117	64.53	38.72
4:42 PM	1.471	44.84	26.90

Table 2 – Sample of interpolated velocities taken from Terciopelo Stream on June 13, 2007. Red text indicates data from Greyline Logger (also displayed above), and black text indicates data produced by the interpolation routine.

Time	Velocity (ft/sec)	Velocity (cm/sec)	Velocity (m/min)
04:32 PM	2.432	74.13	44.47
04:33 PM			43.32
04:34 PM			42.17
04:35 PM			41.02
04:36 PM			39.87
04:37 PM	2.117	64.53	38.72
04:38 PM			36.35

04:39 PM			33.99
04:40 PM			31.63
04:41 PM			29.26
04:42 PM	1.471	44.84	26.90

Table 3 shows a portion of circumferential depth measurements taken at Terciopelo Stream at June 13, 2007 converted into vertical depth and wetted area measurements. Table 4 shows a corresponding section of these vertical depth and wetted area measurements after applying the interpolation routine. Since the interpolated data can only be displayed to two significant figures, it appears that there are not equal intervals between all of the interpolated data points; however, the interpolation routine calculated these values to a higher degree of precision and these more precise values for vertical depth and wetted area were used in any flow calculations. **DISPLAY SAMPLE EQUATION**

Table 3 – A sample of stream height measurements taken manually at Terciopelo Stream and converted to vertical depth and wetted area measurements.

Time	Circumferential Depth Taken From Gauge (inches)	Vertical Depth (cm)	Wetted Area (m^2)
4:30 PM	2.0	5.3	1.8
4:40 PM	4.0	7.6	3.0

Table 4 – An interpolated portion of stream height measurements taken at Terciopelo Stream corresponding to data presented in Table 2.1. Red text indicates data produced by manual measurements (also displayed above), while black text indicates data produced by the interpolation routine.

Time	Circumferential Depth Taken From Gauge (inches)	Vertical Depth (cm)	Wetted Area (cm^2)
04:30 PM	2.0	5.3	1.8
04:31 PM		5.5	1.9
04:32 PM		5.8	2.0
04:33 PM		6.0	2.2

04:34 PM		6.2	2.3
04:35 PM		6.4	2.4
04:36 PM		6.7	2.5
04:37 PM		6.9	2.7
04:38 PM		7.1	2.8
04:39 PM		7.3	2.9
04:40 PM	4.0	7.6	3.0

As can be seen in Tables 2 and 4, the interpolation routine proved an effective way to "connect the dots" in the manually taken data, and the numbers generated by the routine are essential to later calculations of flow and sediment export. However, throughout all further analysis it is very important to remember that the data generated by the interpolation routine is no more than an approximation based on an assumption about stream behavior that is almost certainly false – that changes in velocity and height can be mapped as a series of linear functions. Actual stream behavior might have deviated substantially from the interpolated values, especially when the interval between the two sequential data points was a long amount of time, such as what occurred in overnight periods. However, effort was taken to take height measurements at a very frequent interval (3-5 minutes) when stream height was changing rapidly, as during the first two hours of a storm. Additionally, once the logging interval on the Greyline Stingray Flowmeter was decreased to one minute, the interpolation routine was not needed, and thus the data more accurately reflect actual stream behavior. Despite the uncertainties inherent in the method of data generation, the interpolation routine proved to be a valuable tool in data analysis.

Mapping Stream Height and Velocity

Figures 2, 3, 4, and 5 show the response of stream velocity and vertical depth to heavy rainfall in Terciopelo Stream on four days in which data was taken. Interpolated data has been used to produce the graphs.

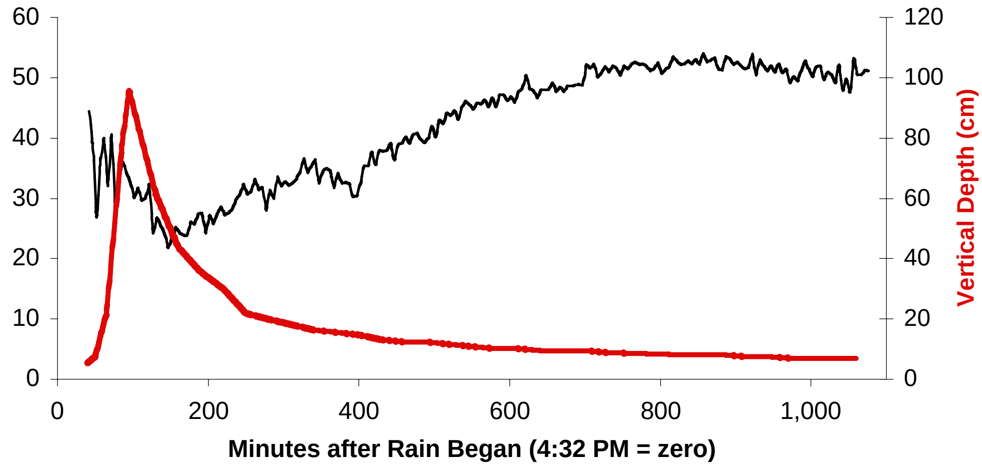

Figure 2. Velocity and vertical depth in Terciopelo Stream after heavy rainfall on June 13, 2007. Velocity (m/min) is shown in black and vertical depth (cm) is shown in red. Storm duration is recorded as approximately 130 minutes. Both velocity and height data is missing for the first 42 minutes of the rainfall; 1.6 centimeters of rain are recorded to have fallen during this period of time.

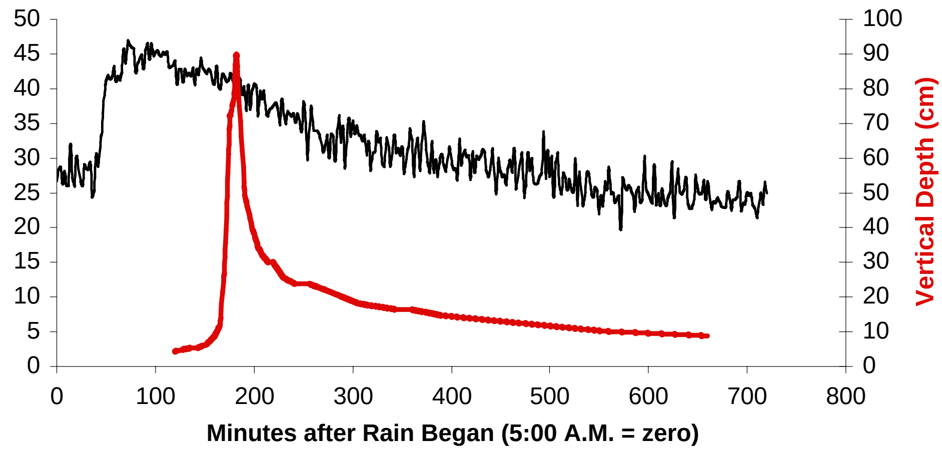

Figure 3. Velocity and vertical depth in Terciopelo Stream after heavy rainfall on June 28, 2007. Velocity (m/min) is shown in black and vertical depth (cm) is shown in red. Weather data are absent due to a power outage. Height data are absent for the first 120 minutes of the rainfall.

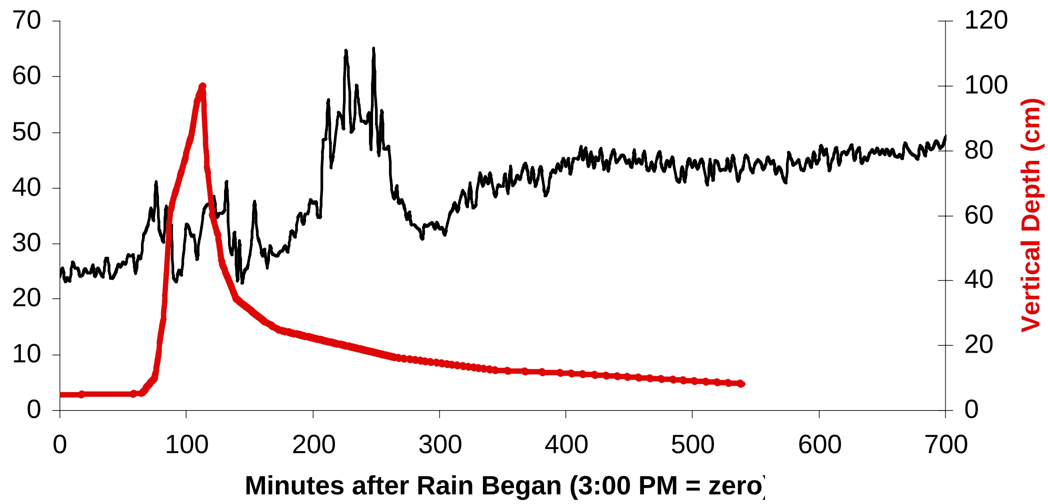

Figure 4. Velocity and vertical depth of Terciopelo Stream after heavy rainfall on July 13, 2007. Velocity (m/min) is shown in black and vertical depth (cm) is shown in red. Storm duration is recorded as 90 minutes; however, it appears likely that a short power outage occurred during the storm that would artificially reduce the recorded storm duration by ten or more minutes.

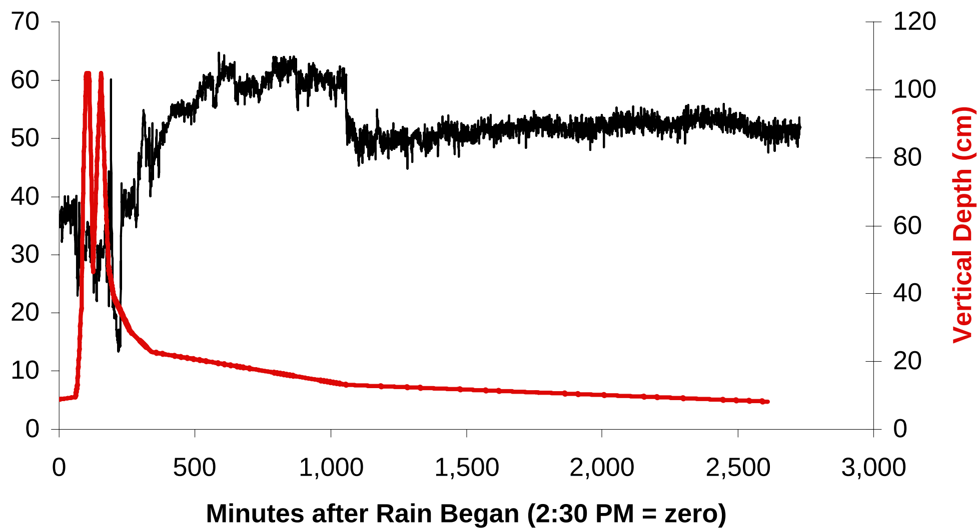

Figure 5. Velocity and vertical depth of Terciopelo Stream after heavy rainfall on July 24, 2007. Velocity (m/min) is shown in black and vertical depth (cm) is shown in red. Storm duration is recorded to be 150 minutes.

These figures reveal the variability in the response of stream velocity to rainfall; in fact, velocity shows a different response on each date. In Figure 2, velocity is seen to decrease as the storm progresses, and then to increase after the storm ceases. In Figure 3, velocity is seen to increase as the storm progresses and then gradually diminish after the peak velocity is reached. In Figure 4, velocity is seen to remain somewhat steady throughout the storm, and then to increase and decrease approximately 100 minutes after heavy rain stopped, seemingly responding to factors distinct from the storm. In Figure 5, velocity is seen to strongly decrease at the beginning of the storm, to increase after the storm ceases and then to sharply decrease approximately 1,000 minutes after rain began to a level at which it remains near for the duration of data collection. Perhaps the particular response of stream velocity hinges on the specific nature of each storm; however, such an analysis would require more precise and reliable rainfall data than that provided by the Davis Weatherlink system.

Another interesting phenomenon to note in the data is the relative thickness of the line showing stream velocity in the storm occurring July 24 (Figure 5), compared to that of the other days (Figures 2, 3, 4). The logging interval in the Greyline Stingray Flowmeter was set to one minute on July 24, while on the other days the logging interval was either five minutes (Figure 2) or two minutes (Figures 3 and 4). More frequent velocity data show a greater variation in velocity from minute to minute. This phenomenon reveals the potential weakness of the interpolation routine, which would not account for such variation from minute to minute.

In contrast to the variability seen in the velocity data, stream height seems to follow a more reliable pattern. In all figures, a “lag” period between 50 and 150 minutes is seen at the beginning of a storm, where stream height does not change substantially. It is likely that the duration of this “lag” period depends on rainfall intensity as the storm progresses. After this “lag” period, stream height dramatically increases; this increase is observed to occur for between ten and twenty-five minutes, likely dependant on the duration of heavy rainfall or the period of time until rainfall ceases. After the increase, a decrease in stream height is observed that follows a reliable pattern reminiscent of an exponential or logarithmic function. This function approaches a minimum close to the initial stream height. Figures 3 and 4 show that the initial stream height has not been reached approximately 400 – 500 minutes (6-8 hours) after the peak height was reached. Figures 2 and 5 show that the initial height is very nearly reached approximately 1,000 – 1,200 minutes (16-20 hours) after the peak height was reached.

Figure 6 shows the response of vertical depth in Quebrada Cacao to heavy rain on July 21, 2007. (Note: Due to significant uncertainties in the velocity data from Quebrada Cacao, what data that has been collected will be displayed and explained further in a later section.) Figure 7 shows the responses of stream heights of both Quebrada Cacao and Terciopelo Stream to the same heavy rainfall on July 24, 2007.

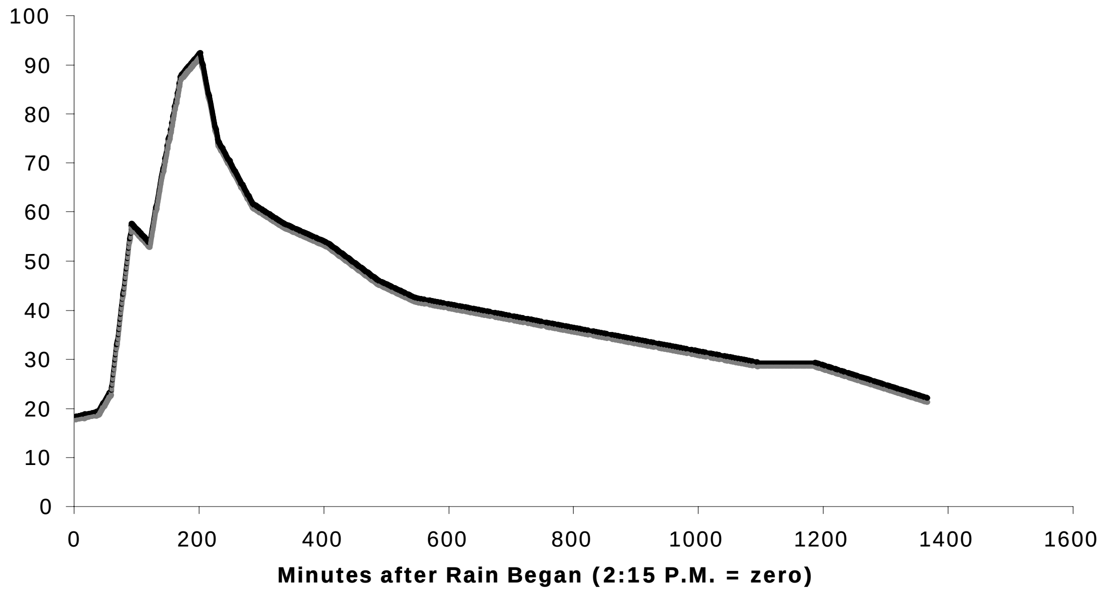

Figure 6. Vertical depth of Quebrada Cacao during and after heavy rainfall on July 21, 2007. Weather data indicate the storm lasting approximately 150 minutes; however, it appears likely that a power outage occurred during the storm that reduced the recorded storm duration by ten or more minutes.

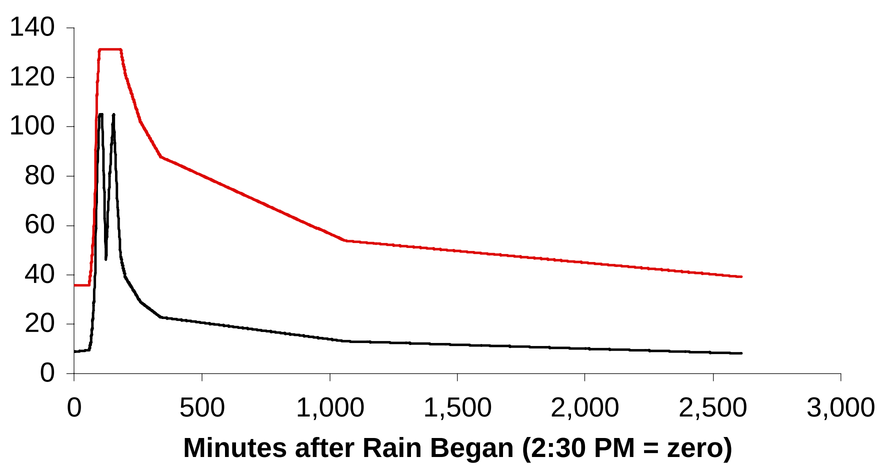

Figure 7. Vertical depths of Terciopelo Creek and Quebrada Cacao in response to the same heavy rainfall on 24 July 2007. Data from Terciopelo Stream is shown in black; Quebrada Cacao in red. (Note: The peak vertical depth of Quebrada Cacao exceeded the maximum height measurable by the gauge. In this graph, the peak vertical depth measurable by the gauge is shown in place of the vertical depths that exceeded the capacity of the gauge.)

Stream height appears to behave similar in response to heavy rain in both Terciopelo Stream and Quebrada Cacao. Figure 6 shows the characteristic stream height behavior described for Terciopelo Stream. Figure 7 shows that the response of stream height in both streams is synced – that is, they respond in roughly the same ways at roughly the same times.

Velocity Data from Quebrada Cacao

Table 7 shows the result of velocity data collected at Quebrada Cacao for the purpose of evaluating the effectiveness of the "fruit-dropping" method of data collection (described above; see "Collection of Height and Velocity Data" in Methods & Materials). Figure 8 shows how the average velocity of the measured data changes as the number of trials performed increases.

Table 5. A sample of velocity data collected at Quebrada Cacao for the purpose of evaluating the "fruit-dropping method". (Note: Velocity calculated using 10.1 meters as the distance traveled by the fruit through the culvert (measured length of Cacao Culvert))

Trial #	Time measured (sec.)	Measured Velocity (m/s)	Average Velocity after "n" Number of Trials	Standard Deviation after "n" Number of Trials
1	6.32	95.9	95.9	
2	6.08	99.7	97.8	1.33
3	10.00	60.6	85.4	6.68
4	5.14	117.9	93.5	5.46
5	7.44	81.5	91.1	4.82
6	6.68	90.7	91.0	4.36
7	6.36	95.3	91.6	3.99
8	6.38	95.0	92.1	3.70
9	7.19	84.3	91.2	3.48
10	6.24	97.1	91.8	3.28
11	7.12	85.1	91.2	3.13

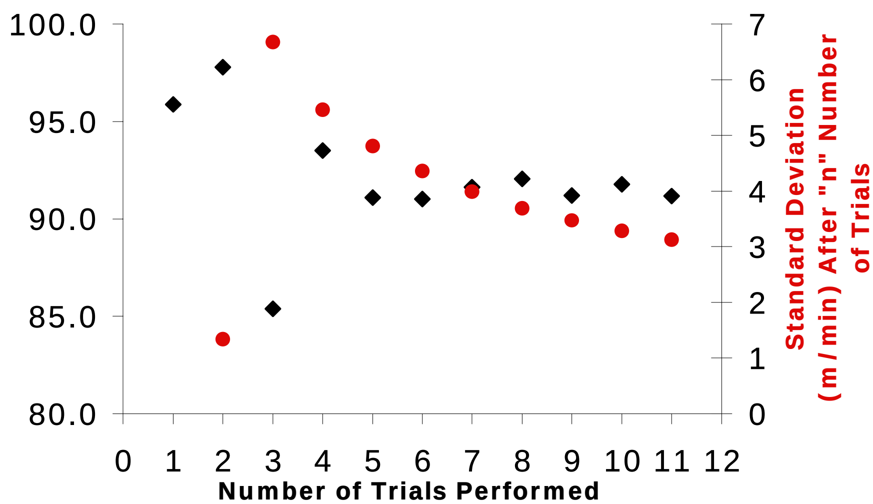

Figure 20. Average velocity (shown in black) and standard deviation (shown in red) measured in Quebrada Cacao after "n" number of trials performed.

From these trial results, it would appear that the "fruit dropping" method proves effective after a minimum of five trials; after that point, the measured average velocity remains relatively consistent. Even after five trials, the standard deviation of the dataset is higher than it could optimally be, which appears to be around three. Although the standard deviation seen in Table 5 is comparatively low after only two trials, the discrepancy in average velocity at this point from that produced after more trials renders the low standard deviation a moot point.

Table 6 shows velocity data taken from Quebrada Cacao on July 21 using the fruit-dropping method. Height data is included to give a sense of the progression of the storm. The data was collected at large time intervals (30-45 minutes) due to the amount of time it took to properly execute the method three or four times (the amount deemed necessary to establish a fair degree of precision), which was roughly fifteen minutes. If a large interval of time was not provided between data collection, data collection would be nearly continuous, and one would be unable to distinguish velocity data between time values.

Table 6. Velocity data taken at Quebrada Cacao during heavy rain on July 21, 2007.

Time	Vertical Depth (cm)	Measured Times for Fruit to Travel Length of Culvert (sec)	Average Velocity (m/min)	Standard Deviation (m/min)
2:15 PM	19	8.74, 9.97, 15.47, 9.51, 9.27, 15.29	53.3	13.4
2:53 PM	20	9.74, 9.38, 13.09, 6.74	62.2	18.0
3:13 PM	24	5.51, 5.85, 5.55	107.5	3.48
3:45 PM	58	>30, >30, >30	-----------	---------

These data show the difficulty in execution of the "fruit-dropping" method and the unreliability of the data produced from this technique compared to the data produced by the Greyline Stingray Flowmeter, even after four or five trials are performed. Even though six trials were performed at 2:15 P.M., standard deviation is seen to be 13.4 meters per minute, extremely high in comparison to that seen in the trial data. Such a large standard deviation calls into question the accuracy of the average velocity measured at this time. Especially notable is the lack of accurate and usable data produced by the trial performed at 3:45 P.M. At this point, stream height had doubled the level it was at a little over a half-hour ago; since stream height and flow follow a similar relationship (see below - *Measuring Flow*), it is likely that stream flow was rapidly increasing at this point. Although the water appeared to be moving rapidly, or at the very least, not substantially slower than it had appeared to be moving in the previous trials, the measured time for the fruit to travel the length of the culvert was measured to be more than three times the times measured in any of the previous trials. Since velocity has not been observed to decrease three-fold during storm conditions in Terciopelo Stream (see above – *Mapping Velocity and Stream Height*), it is likely that this measured time is the result of high flow conditions distorting the path of the fruit through the culvert, perhaps keeping it trapped against the side. For all trials performed at 3:15 P.M. the fruit was seen to emerge from the far sides of the culvert, where water was seen to move much slower than the water emerging from the center of the culvert. The unlikelihood of the measured times reflecting the actual velocity of the stream is high.

Measuring Flow

Table 7 shows a portion of flow data for Terciopelo Stream measured on June 13, 2007. The data includes both interpolated and manually taken samples. The data are only displayed to two significant figures due to the limitations imposed by the measurements of wetted area; however, more precise values for wetted area were used in the calculated values for flow.

Table 7. A portion of flow data for Terciopelo Stream measured on June 13, 2007.

Time	Velocities (m/min)	Wetted Area (m^2)	Flow (m^3 x 10^1/min)	Flow (l x 10^2/min)
4:32 PM	44.5	2.0	9.1	9.1
4:33 PM	43.3	2.2	9.4	9.4
4:34 PM	42.2	2.3	9.6	9.6
4:35 PM	41.0	2.4	9.9	9.9
4:36 PM	39.9	2.5	10	1.0
4:37 PM	38.7	2.7	10	1.0

Figures 8, 9, 10 and 11 show the response of stream flow to heavy rain in Terciopelo Stream on various days on which heavy rain fell. Due to the lack of velocity data for Quebrada Cacao, no flow data is shown for that stream. The graphs were made using interpolated data.

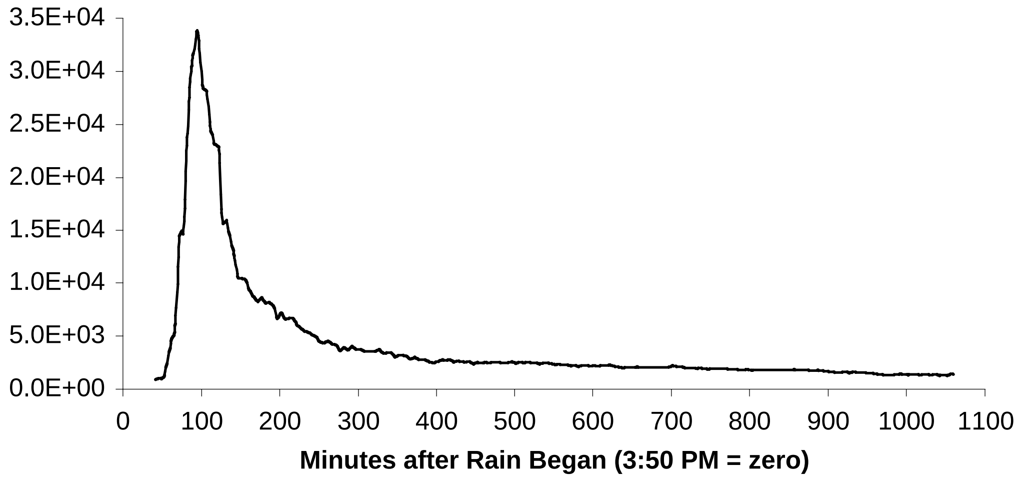

Figure 8. Stream flow in Terciopelo Stream after heavy rainfall on June 13, 2007. Weather data indicate the storm lasting 130 minutes. Flow data is absent for the first 42 minutes of the storm; less than 2 centimeters of rain fell during this period of time.

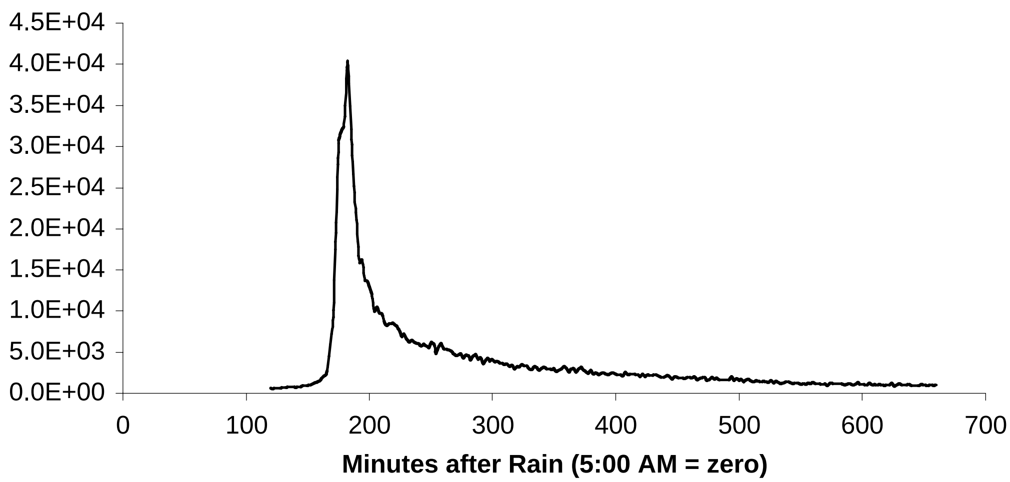

Figure 9. Stream flow in Terciopelo Stream after heavy rainfall on June 28, 2007. Flow data are missing for the first 120 minutes of the rainfall. Weather data indicate a light rainfall beginning at 5:00 A.M.; however, weather data is missing later in the storm due to a power outage.

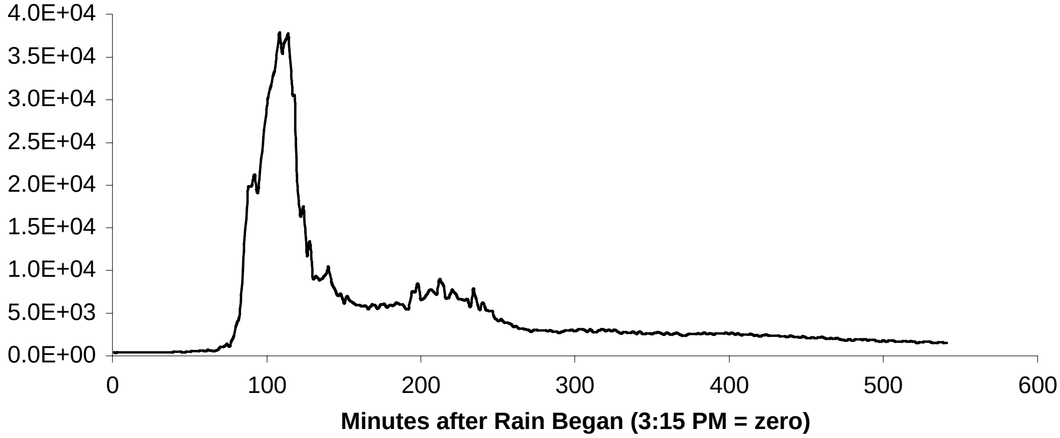

Figure 10. Stream flow in Terciopelo Stream after heavy rain on July 13, 2007. Storm duration is recorded as 90 minutes; however, it appears likely that a short power outage occurred during the storm that would artificially reduce the recorded storm duration by ten or more minutes.

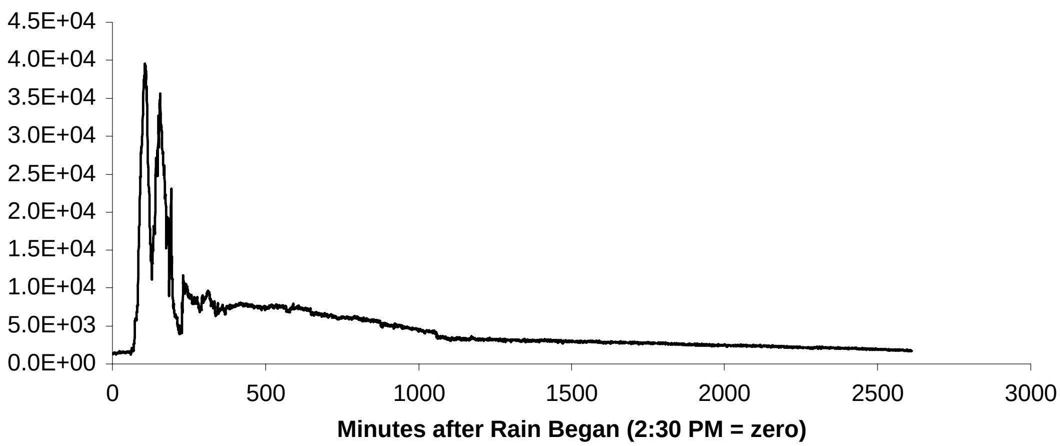

Figure 11. Stream flow in Terciopelo Stream after heavy rain on July 24, 2007. Storm duration is recorded to be 150 minutes.

Figure 8, 9, 10 and 11 show that stream flow behaves with some regularity between the days in which data was taken. Stream flow rapidly increases at a certain time, which varies between the storm days. After peaking, stream flow rapidly decreases to a certain flow level, which also varies between the storm days, at which it gradually decreases.

As can be seen by comparing Figures 2, 3, 4 and 5 with Figures 8, 9, 10 and 11, respectively, flow more closely mimics the pattern displayed by vertical depth than stream velocity (see above – *Mapping Stream Height and Velocity*). This makes mathematical sense as vertical depth has a bearing on wetted area, which has more of a weight on the outcome of flow than velocity; flow is calculated by multiplying wetted area, given in units of square meters, by velocity, given in units of meters per unit of time, so each meter increase or decrease in wetted area would have a larger impact than each meter increase or decrease in velocity on the flow product.

Despite the larger bearing of wetted area on flow, the impact of velocity can be seen by comparing Figure 10 with Figure 4, which both show data collected from the storm on July 13, 2007. The rise and fall in stream flow that occurs between approximately 200 – 250 minutes after rain began can be explained by the rise in velocity that is seen around that time.

In terms of the change in the quantity of water that passes through Terciopelo Stream after a storm, the rate of stream flow (meters/min) increases approximately 36-fold from it's initial amount to it's peak on June 13 (Figure 8), 68-fold on June 28 (Figure 9), 98-fold on July 13 (Figure 10) and 29-fold on July 24 (Figure 11). Table 8 shows the calculated total stream flow from Terciopelo Stream during "high flow" conditions, defined as the period from the beginning of both velocity and height data collection to two hours after rainfall ceases (see above – *Calculation of Flow*).

Table 8. "Peak Flow" at Terciopelo Stream on four days during which heavy rain occurred.

Date of Storm (Summer 2007)	Duration of "High Flow" (min)	Total Flow during "High Flow" (liters × 10^6)
June 13	178	2.4
June 28	290	1.5

July 13	305	2.2
July 24	490	5.2

Table 8 shows that the duration of the "high flow" period is not necessarily the most important factor that affects the total flow during this period, although July 24 displays both the largest duration of "high flow" and total flow. June 13 displays the smallest duration of high flow between the four days of data collection, yet also displays the second largest total flow value during this period. This data might show that Terciopelo Stream, on the various storm days on which data was taken, do not display the same behavior period ambiguously defined as high flow. In some days, a higher volume of flow might occur outside of the period of high flow. Additionally, this data may show that the rate of flow decrease is not consistent between the various days, with some days displaying more rapid decrease.

By comparing Table 8 with Figures 8, 9, 10 and 11, it is interesting to note that "high flow" is greater on June 13 than on June 28 or July 13, even though a higher peak flow rate is reached on the latter two days. Additionally, June 28 shares roughly the same maximum flow rate as July 24 (roughly 4.0 x 10^4 m^3) (Figures 9 and 11, respectively), yet the duration of "high flow" and the total flow during the "high flow" period is much greater on July 24.

Turbidity & Sediment Load

Turbidity was measured for samples collected at Terciopelo Stream during the storms on June 28, July 13, and July 24 (Figures 12, 13 and 14, respectively). Turbidity was measured for samples collected from Quebrada Cacao on July 21 and 24 (Figures 15 and 16, respectively).

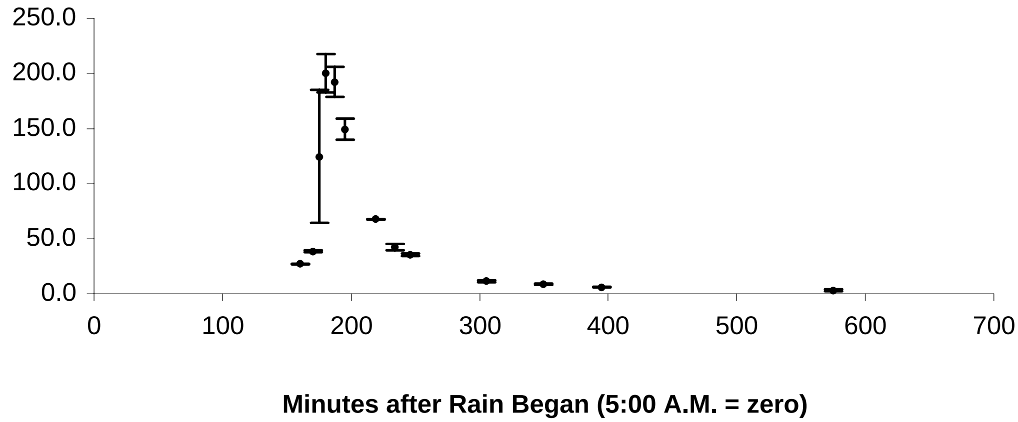

Figure 12. Measured turbidity of water samples taken from Terciopelo Stream during and after heavy rainfall on June 28. (mean ± SE, n=3)

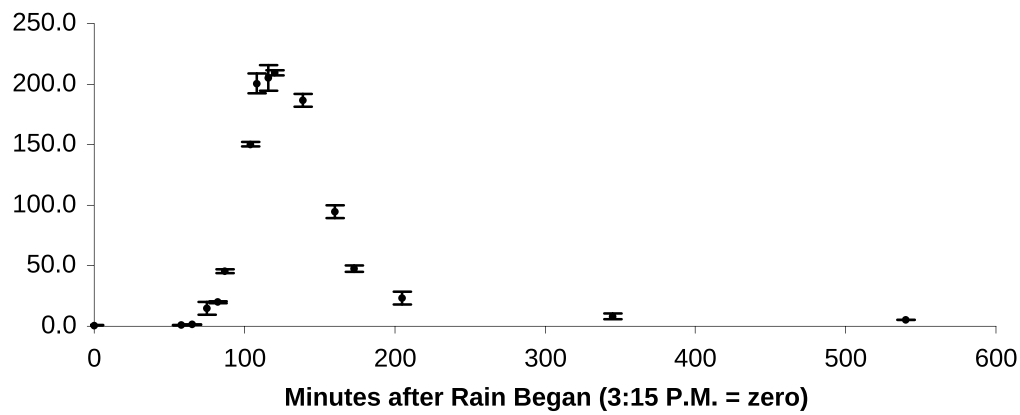

Figure 13. Measured turbidity of water samples taken at Terciopelo Stream during and after heavy rain occurring on July 13 (mean ± SE, n=3)

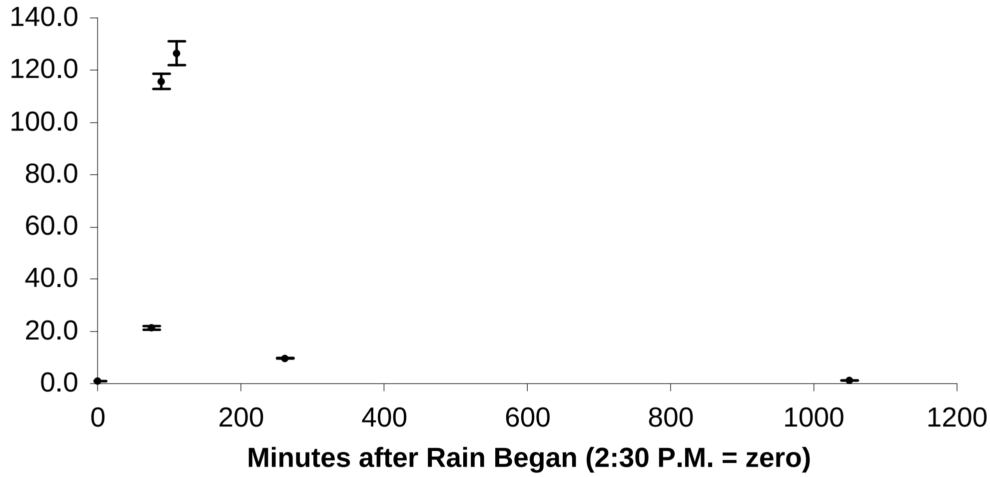

Figure 14. Measured turbidity of water samples taken at Terciopelo Stream during and after heavy rain occurring on July 24. (mean ± SE, n=3)

Turbidity was measured for samples collected from Quebrada Cacao on July 21 and 24 (Figures 17 and 18, respectively).

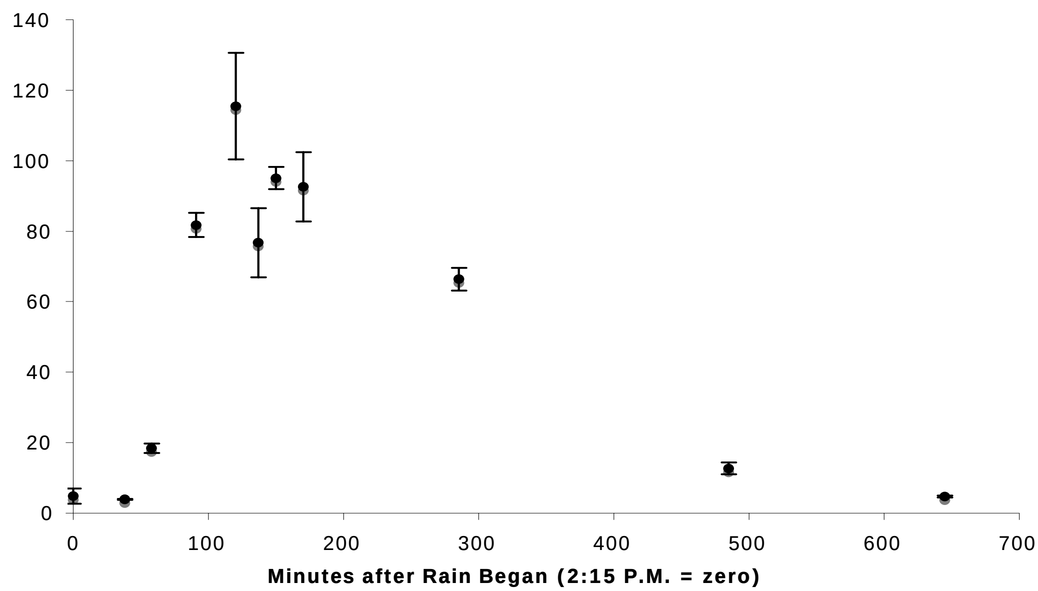

Figure 15. Measured turbidity of water samples taken at Quebrada Cacao during and after heavy rain on July 21. (mean ± SE, n=3)

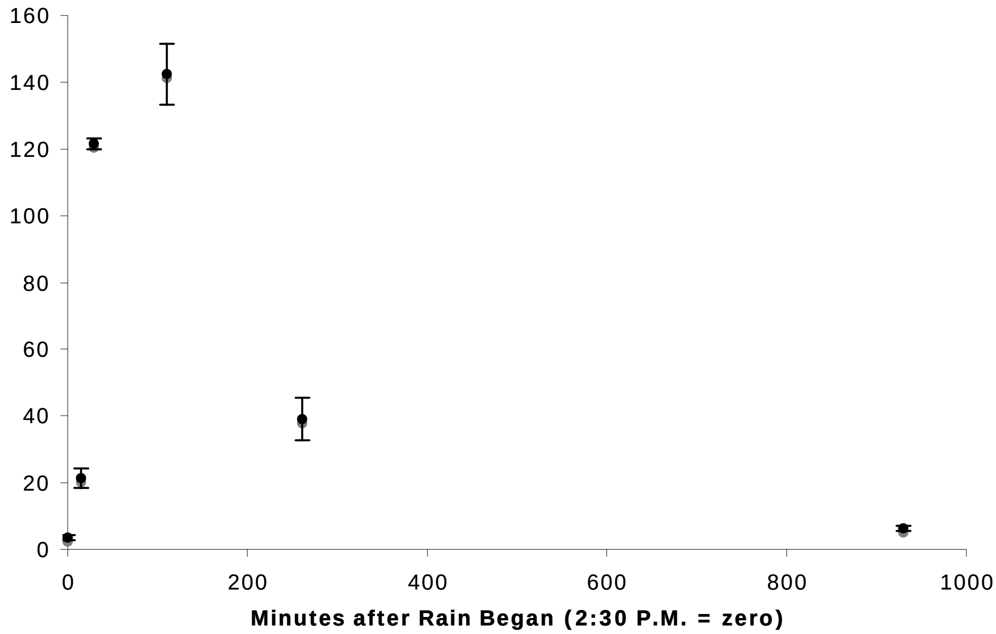

Figure 16. Measured turbidity of water samples taken at Quebrada Cacao during and after heavy rain on July 24. (mean ± SE, n=3)

Turbidity changes in a way that is similar to flow, and appears to exhibit the pattern described in reference to vertical depth; a period of "lag" with relatively little change, followed by a strong increase, followed by a decrease that seems to mimic an exponential or logarithmic function.

Turbidity in Terciopelo Stream is higher on June 28 and July 13 (Figures 12 and 13, respectively) than is seen on July 24 in that stream (Figure 14) or either of the two measured days in Quebrada Cacao (Figures 15 and 16). Additionally, measured turbidity on July 24 in Terciopelo Stream appears to be similar to that measured on either of the two days in Quebrada Cacao.

The sediment content was also measured for the samples taken at Terciopelo Stream during the heavy rain July 13, and for the samples taken at Quebrada Cacao during the heavy rain July 21. Figure 17 shows the relative sediment content of the samples of various turbidities taken at Terciopelo Stream on July 13 and an equation generated by Microsoft Excel that relates the relationship between the two, and the R^2 value for this equation; Figure 18 does the same but for water samples taken from Quebrada Cacao on July 21.

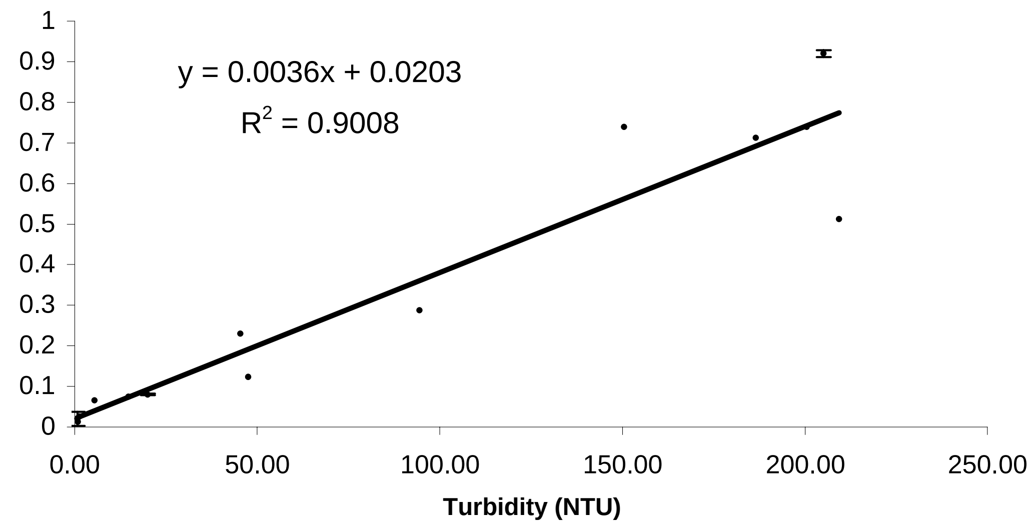

Figure 17. The relationship between average turbidity and average sediment load in water samples taken at Terciopelo Stream during and after heavy rain on July 13. (mean ± SE, n=3)

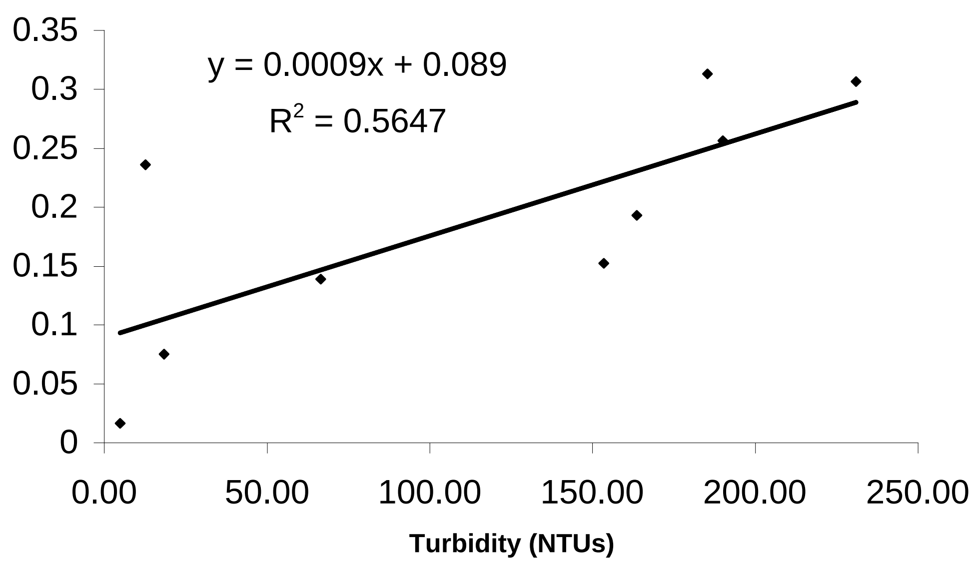

Figure 18. The relationship between average turbidity and average sediment load in water samples taken Quebrada Cacao during and after heavy rain on July 21 (mean ± SE, n=3)

The slope of the line produced from the data taken at Terciopelo Stream on July 13 is approximately four times larger than the slope produced from the data taken at Quebrada Cacao on July 21. This indicates that water from Terciopelo Stream carries significantly more sediment in it per unit of turbidity than water from Quebrada Cacao. A component other than the sediment measurable by the described methods (see above- *Measurement of Turbidity and Sediment Load*) is causing the water in Quebrada Cacao to be turbid.

Additionally, the R^2 value for the equation produced from the turbidity and sediment load data from Terciopelo Stream on that day is significantly higher than the R^2 value produced from the data taken at Quebrada Cacao on July 24. This means that the numbers generated by converting interpolated water turbidity values into sediment content values by means of these equations should be more reliable in Terciopelo Stream than in Quebrada Cacao; thus any estimations of total sediment export should be more accurate in Terciopelo Stream.

Table 9 shows a sample of data taken at Terciopelo Stream to demonstrate the variables used in the calculations of sediment export. By multiplying the flow value by the sediment load value, produced by converting the average turbidity in a sediment load value via the linear equation displayed above for Terciopelo Stream, a sediment export value is produced, which shows the amount of sediment exported through the stream during that minute.

Table 9. Sample of data involved in calculation of sediment export. Taken at Terciopelo Stream.

Date of Storm	Time	Flow (liters × 10^3/min)	Average Turbidity (NTUs)	Sediment Load (grams sediment/liter)	Sediment Export (kg/min)

06/28/07	7:40 AM	1.6	26.92	0.1173	0.18
06/28/07	7:41 AM	1.8	28.07	0.1215	0.21
06/28/07	7:42 AM	2.0	29.23	0.1257	0.25
06/28/07	7:43 AM	2.1	30.38	0.1298	0.27
06/28/07	7:44 AM	2.2	31.54	0.1340	0.29

By multiplying interpolated flow values for a given by sediment load values, generated by the conversion of interpolated average turbidity values into sediment load values by means of the equation shown in Figure 17, a sediment export value is produced, which reflects the total calculated mass of sediment passing through the stream at that time.

Table 10 shows the measured mass of sediment exported through Terciopelo Stream on three days during which data was collected. Data is unavailable from Quebrada Cacao due to an inability to calculate flow as a result of a lack of velocity data.

Table 10. Calculated mass of sediment exported through Terciopelo Stream on three days during which heavy rain fell.

Date of Storm (Summer 2007)	Duration of Data Collection Period (min)	Mass of Sediment Exported (kg)
June 28	410	5.9 × 10^1
July 13	540	9.2 × 10^1
July 24	930	1.3 × 10^2

In considering these measured values, it is extremely important to remember that these numbers are likely substantially lower than the actual mass of sediment exported. This is due to the inability of the method used to take into account the larger items passing through the stream during heavy rainfall, such as large rocks, logs, fallen branches and large leaves that were observed to pass through each of the culverts on all of the storm days. This is because the only objects that were measured via vacuum filtration were the ones small enough to fit into the mouth of the bottles used, which had radii approximately between 1 and 4 inches. These larger objects would undoubtedly contribute substantially to the total mass of sediment exported through the stream during peak rain.

Conclusions & Future Suggestions

The objectives for this research – namely, that stream height and velocity in Terciopelo Stream and Quebrada Cacao be measured for the purpose of measuring flow in response, and that turbidity and sediment load should be measured for the purpose of calculating sediment export in response to rainfall – were met by the methodology used for Terciopelo Stream, but with a high degree of uncertainty. The objectives of this research were not met in Quebrada Cacao.

The results show a consistent pattern in stream height, characterized by a “lag” period, a sharp increase, and an exponential decrease after rain ceases; this was seen in both streams (see above – *Measuring Stream Height and Velocity*). A consistent pattern was not observed in velocity data between the four days on which data was collected by the Greyline Stingray Flowmeter. Velocity data from Quebrada Cacao was incomplete and riddled with uncertainties, which prevented the calculation of flow and sediment export in that stream. Stream flow shows a pattern similar to that observed in stream height, though flow behavior was not observed to be precisely consistent between the three days on which it is measured, with some days showing longer periods of increased flow after rain ceases. Turbidity data from Terciopelo Stream shows a strong increase in water turbidity with rainfall. By calibrating turbidity with sediment load, it was observed that the water in Terciopelo Stream has more sediment per unit of turbidity than Quebrada Cacao. Sediment export calculations can be observed in Table 10.

There are a variety of sources from which the uncertainty comes. In stream measurements, the velocity of the stream at a certain section is not necessarily consistent within the stream as a whole (i.e., could it be faster at the top than at the bottom). In order to eliminate this uncertainty, a method would have to be designed that not only calculates the different velocities of the stream at the same time, but factors in the relative amount of water in the stream that is moving at this velocity. Additionally, it is by no means certain that velocity remains consistent for an entire minute, although the data is considered in minute intervals. Thirdly, and this factor holds true for velocity, height, and turbidity data, the data produced by the interpolation routine is inherent uncertain, and functions on a assumption of linearity in stream behavior that is almost certainly untrue.

For stream height data, the level of precision provided by the circumferential depth gauge proved very limiting, and the data was sometimes difficult to read. Additionally, it is possible that stream height varied within a minute, and that the data that was recorded did not necessarily reflect the average stream height over that period. Again, the interpolation routine generated data that had an inherent degree of uncertainty.

For turbidity and sediment load data, the size of the mouth of the Nalgene Bottles proved very limiting, as larger pieces of sediment moving down the stream, such as large leaves or fallen sticks, were not collected and factored into turbidity and sediment load measurements in my methods, though they undoubtedly contributed significantly to the mass of sediment moving down the stream. Additionally, the assumption of “uniformity” described in the uncertainties inherent in velocity data described above was a factor in this data as well; it is very possible that the stream water could be more or less turbid or could contain more or less sediment at different depths of the stream, yet samples were collected by submerging the bottle just beneath the surface of the stream. Of course, the uncertainty in the data produced by interpolating the turbidity data is to be considered here as well.

In considering future methodology, the data-logging intervals (in the Greyline Stingray Flowmeter and the Davis VantagePro2 Weather Station) should be set to one minute. There is no "good" reason why this step was not taken in the above research from the beginning. Secondly, more care should be taken to ensure the reliability of data produced by the Davis VantagePro2 Weather Station. Perhaps a secondary power source could be established for the weather station that is activated when power is lost to the FCRE establishment. Also, the time and data on the Weather Station should be reset every afternoon. Additionally, an effective way for measuring velocity in Quebrada Cacao should be developed, as data produced by the the "fruit-dropping" method proved too inaccurate and unreliable to use in flow calculations (see above – *Measuring Velocity in Quebrada Cacao*). Finally, velocity and height data should be taken more continuously throughout the day, so to see flow levels in the streams for a substantial duration of time before rain occurs. This might not necessitate frequent data collection, since stream height and velocity were seen to remain fairly steady in periods without rain.

Future studies should measure flow in Quebrada Cacao in response to heavy rainfall, and compare that data to flow in Terciopelo Stream. Data from both streams should be collected on the same day so that behavior can be compared in response to the same storm. Additionally, future research should further utilize data produced from the weather station, in order to provide a basis by which data collected on different days can be compared. Finally, other streams in the area, such as the Barú Stream found in nearby Hacienda Barú, may prove to be a source from which more data can be collected, as long as a method for measuring velocity that doesn't rely on the Greyline Stingray Flowmeter can be developed. Perhaps as data is collected in more streams in a variety of areas, land-use factors, such as the amount of secondary rainforest in the immediate watershed of a stream, can be considered in evaluating data produced between the streams.

Bibliography

Allan, JD., 1995. Stream Ecology: Structure and function of running waters. Kluwer Academic Publishers, Norwell, MA. pp. 45-82.

Herschy, R., 1995. Streamflow Measurement. Chapman and Hall, New York, New York. pp. 13-89

Larson W., Lindstrom, M., and Schumacher, T., 1997. The role of sever storms in soil erosion: A problem needng consideration. Journal of Soil and Water Conservation. Vol 52, 2:90-95.

Pla Sentis, I, 1997. A soil water balance model for monitoring soil erosion processes and effects on steep lands in the tropics. Soil Technology. Volume 1, 1:17-30.

Renard, K., Foster, G., Weesies, G., Porter, J., 1991. RUSLE. Revised universal soil loss equation. Journal of Soil and Water Conservation. Vol. 46, 1:30-33.

Robson, C., Neal S., Hill, C., Smith, J., 1993. Linking variations in short- and medium-term stream chemistry to rainfall inputs- some observations at Plynlimon, Mid-Wales. Journal of Hydrology (Amsterdam), Vol. 144, 1-4:291-310.

Singh, V., 1996. Effect of spatial and temporal variability in rainfall and watershed characteristics on stream flow hydrograph. Hydrological Processes, Vol 11, 12:1649-1669.

Appendix

For a more complete explanation of the logic and used in the routine to estimate stream velocity, please contact Dr. Cheryl Baduini at cbaduini@jsd.claremont.edu.