Streamflow Report for the Quebrada Cuecha in Monteverde, Costa Rica
June 2004 – April 2006

Technical Report submitted to the Monteverde Institute

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1 September 2006

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Executive Summary

Monitoring streamflow on the Quebrada Cuecha in Monteverde, Costa Rica began in June 2004 and continues to this day. A stream gaging station consisting of a staff gage and pressure transducers was established to obtain a continuous record of discharge. Details of the measurement methodology are provided in Appendix A. Streamflow records from the following periods are included in this study:

Period 1.	11 Jun – 1 Sep 2004
Period 2.	25 Jun – 28 Jul 2005
Period 3.	6 Jan – 1 May 2006

The first two periods fall during the rainy season, and investigators from Smith College were in Monteverde making hydrologic measurements for most of this time. During the third period, which straddles the transitional and dry seasons, two pressure transducers were used to record stage (for redundancy), and investigators from Smith College were on-site to make discharge measurements in January and April. While the focus of this report is on these three time periods, Appendix B contains a record of all direct discharge measurements, including those outside of these time periods.

The distribution of flow rates for the Quebrada Cuecha is highly skewed due to a few large events of relatively short duration, and the streamflow data reflect the effects of both natural hydrologic processes and water withdrawals for human use and consumption. Average streamflows were 230 liters/second, 280 liters/second, and 100 liters/second for time periods 1, 2, and 3, respectively, and median streamflows were 210 liters/second, 240 liters/second, and 80 liters/second. The 7-day minimum flow is of particular utility in the assessment of water resources because it indicates the lowest flow in a stream or river. To determine the 7-day minimum flow, a 7-day moving average of discharge is calculated for a time period of interest, and the smallest value is selected. From 6-Jan-06 to 1-May-06, the 7-day minimum flow was 40 liters/s, which is less than one-third of what is observed in the rainy season. The data, statistics, and figures presented in this report reflect the conditions for the periods of measurement. Given the seasonal and year-to-year variability in precipitation, however, these data should not be presumed to be representative of streamflow for all time. Continued monitoring and measurement is necessary to fully characterize streamflow for the Quebrada Cuecha.

Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Monteverde

Monteverde, Costa Rica (84°48' W Long., 10°18' N Lat.), is home to tropical montane cloud forests in the volcanic mountain range of the Cordillera de Tilarán. The rich biological diversity sustained by the regional climate and habitat has attracted many visitors to the community, and Monteverde has experienced an economic shift from agriculture and milk production to ecotourism over the past two decades. While the community has experienced tremendous growth, numerous efforts strive to promote sustainable development and preserve Monteverde's valuable resources.

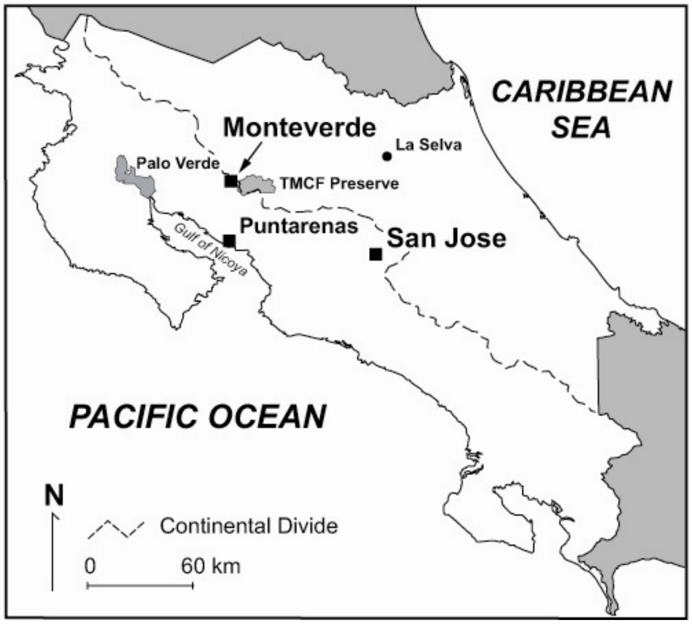

Figure 1. Monteverde, Costa Rica, is located on the Pacific slope of the Cordillera de Tilarán.

The Costa Rican climate is governed by the geographic position of the Intertropical Convergence Zone (ITCZ), a low-pressure region near the equator marked by heavy precipitation. The climate is typically divided into three seasons: the rainy season (May through October), when the ITCZ is positioned over Costa Rica, and the transitional (November through January) and dry (February through April) seasons when the ITCZ migrates south. Since water for supply is withdrawn directly from streams and springs, the seasonality of precipitation has major implications for the water resources of Monteverde. Although annual precipitation totaled 2404 mm in 2004 and 3791 mm in 2005, only 9% of the total precipitation in 2004 and 3% in 2005 fell during the dry season (Johnson et al. 2005, Guswa et al. 2006). An improved understanding and quantification of the temporal variability in streamflow can inform resource management and decision-making.

1.2 Smith College Involvement

A hydrological and geochemical investigation of the Guacimal Watershed (Figure 2) was initiated in 2001 by Professor Amy Rhodes (Geology) and Professor Andrew Guswa (Engineering) of Smith College in Northampton, Massachusetts, USA. The overarching purpose of this project is to improve understanding of the hydrologic and geochemical processes at work in the region. Activities have included the installation of a meteorological station on the roof of the Monteverde Institute (reports and data are available at www.mvinstitute.org and www.science.smith.edu/~aguswa/research.html), the quantification of throughfall variability (Guswa and Rhodes, 2004), geochemical characterization of stream water (Rhodes et al., in press a), and determination of the importance of dry-season orographic precipitation to streamflow (Rhodes et al., in press b). Current projects involve mapping the geology of the region to determine the geologic and anthropogenic processes affecting stream chemistry and the investigation of rainfall-runoff relationships to develop quantitative hydrologic models.

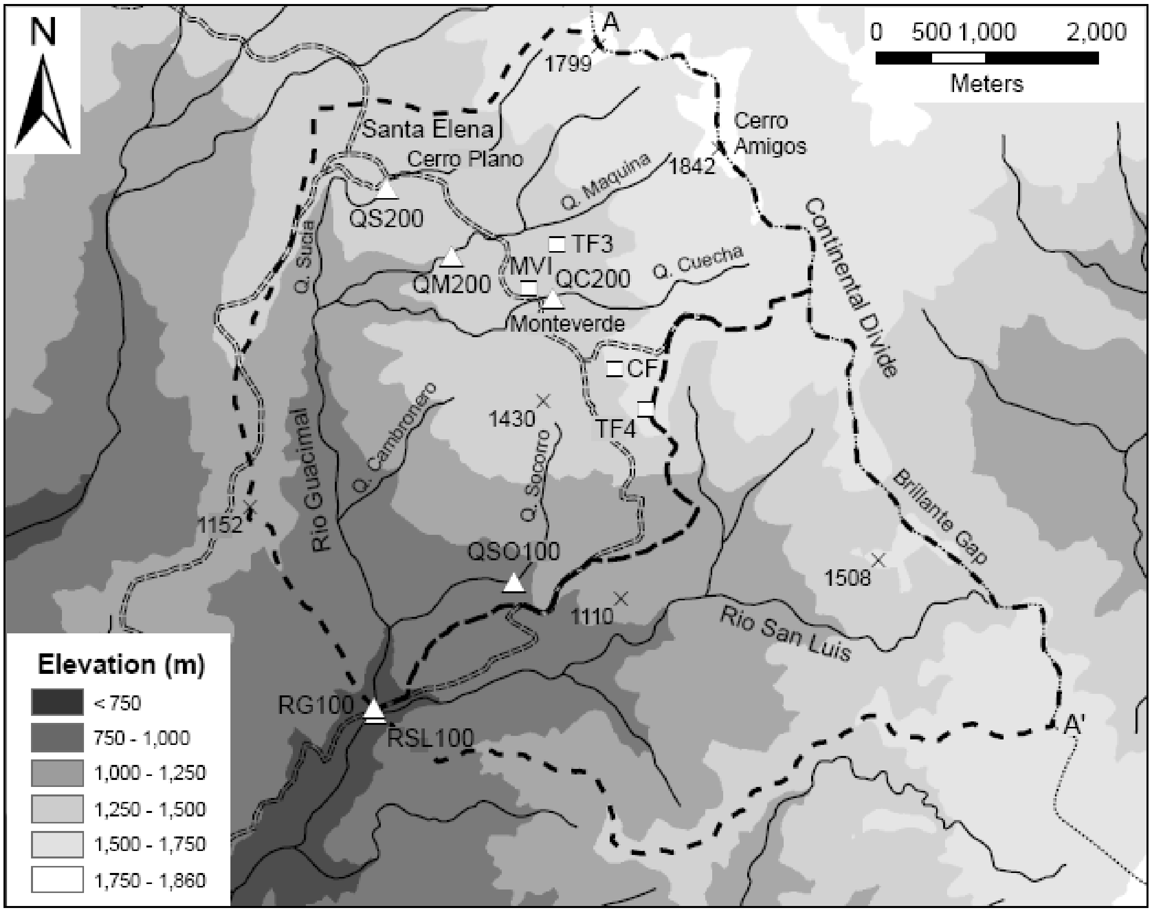

Figure 2. The Rio Guacimal watershed and the San Luis watershed in Monteverde, Costa Rica are depicted with the dashed boundaries. Triangles indicate sites of stream sample collection and squares indicate sites of precipitation collection and measurement. The Quebrada Cuecha and the site of the stream gaging station, QC200, are located above the center of the map.

1.3 Hydrological Concepts

Water flowing in a stream or river originates as precipitation, and the area of land that drains to a given point on a stream is known as the drainage basin or watershed associated with that point. The different paths taken by water as it moves to a stream channel affect both timing and magnitude of the stream response. During a precipitation event, some water moves quickly into the channel, leading to a rapid response in water level and discharge. Elevated streamflow induced by a precipitation event in this way is known as stormflow. Some of this stormflow is generated by water that quickly runs off over the ground surface. Other water infiltrates into the ground and makes its way to the stream more slowly. Between precipitation events, streamflow is sustained by the release of this stored water. Streamflow that is not directly associated with a specific precipitation event is known as baseflow.

The fate of rain falling on a land surface depends on factors such as land cover, soil hydraulic properties, and the geomorphology of the drainage basin. For example, the stormflow response for a basin with thick, vegetative cover and well-drained soil might be small, as much of the rain is absorbed by the soil. For the same storm, the rapid stormflow response for a steep basin with large areas of saturated or impervious surfaces could be much greater as it is more conducive to runoff.

The balance between rain that is stored in a watershed and rain that causes a rapid but short-lived response affects both the vulnerability of a community to flooding and the long-term supply of water to its streams. In Monteverde, flooding is less of an issue as the topography is steep and the stream channels are deeply incised. Due to the seasonality of precipitation, streamflow during the dry season is strongly dependent on the slow drainage of water that arrived during the rainy season.

1.4 Streamflow Monitoring of Quebrada Cuecha

The Quebrada Cuecha becomes the Rio Guacimal when it crosses under the road in Monteverde (Figure 2). As part of our scientific investigations, discharge on this stream has been measured since June 2004. A gaging station consisting of a staff gage and pressure transducers for acquiring continuous stage (water level) measurements has been set up and maintained just upstream of the road at a site named QC200. Upstream of this monitoring point, the area of land from which water drains to the Quebrada Cuecha is approximately 1.7 km^2. Within this watershed, water is withdrawn for supply, some of which is transferred out of the basin. This report summarizes the streamflow behavior at QC200 from June 2004 through April 2006, and these records reflect both natural hydrologic processes and the effects of the withdrawals.

2 Methodology

Stream discharge is the volume of water flowing through a channel cross section per unit of time; it is the product of the channel velocity and the cross-sectional area (Equation 1).

$$\text{Discharge} = \text{Average Velocity} \times \text{Area} \qquad (1)$$

While discharge can be determined by measuring depth and velocity at discrete points across a channel, the method is time consuming and impractical for long-term, continuous monitoring of streamflow. Water level (stage) is a more easily measured parameter. Measuring stage and discharge concurrently enables the development of correlations between these variables. Continuous records of stage can then be converted to discharge using these correlations known as rating curves. Detailed methods of acquiring stage and discharge records and the equipment involved are documented in Appendix A.

Changes in the channel profile and morphology in the vicinity of the stream gaging station could alter the stage-discharge relationship developed for a channel. Therefore, rating curves must be reassessed from time to time by making direct measurements and comparing the data with the existing rating curve. If a shift is apparent, a new rating curve must be developed. From June 2004 to April 2006, manual discharge measurements were performed primarily in January, June, and July. A record of all direct measurements of discharge at QC200 is included as Appendix B.

Since discharge is inferred from automated stage records for most of the year, changes in channel conditions could render the stage data unreliable. Retaining only the most reliable data, the following time periods were included in this study:

Period 1.	11 Jun – 1 Sep 2004
Period 2.	25 Jun – 28 Jul 2005
Period 3.	6 Jan – 1 May 2006

The first two periods fall during the rainy season, and investigators from Smith College were in Monteverde making hydrologic measurements for most of this time. During the third period, which straddles the transitional and dry seasons, two pressure transducers were used to record stage (for redundancy) and investigators from Smith College were on-site to make discharge measurements in January and April. While the focus of this report is on these three time periods, Appendix B contains a record of all direct discharge measurements made at QC200, including those outside of these time periods.

Rating curves for the three periods were developed based on both a power-law equation and a second-order polynomial (quadratic) equation:

Quadratic Model $$\text{Discharge} = a(\text{stage})^2 + b(\text{stage}) + c \tag{2}$$

Power Law $$\text{Discharge} = a(\text{stage} - c)^b = a(\text{fitted stage})^b \tag{3}$$

Results from both models were compared to determine the more appropriate fit for the data. The resulting rating curves for each period are presented in Figures 3-5 below. Note that the rating curves were developed for the stage and discharge measurements in English units (ft and cubic feet per second). Details of the rating-curve determination and the associated uncertainty are available in Appendix C.

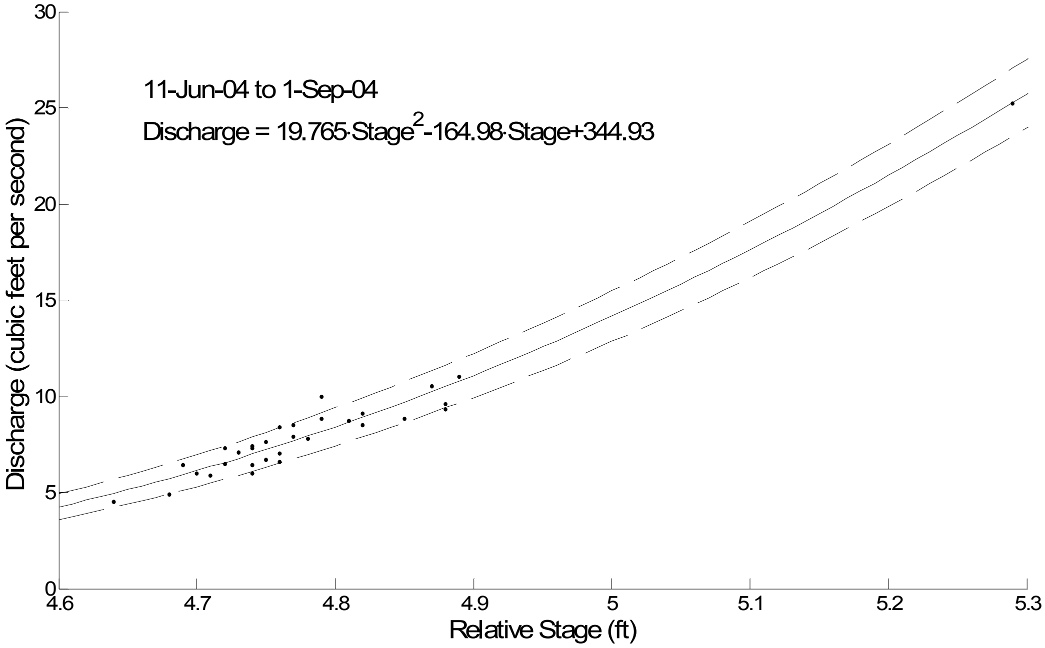

Figure 3. QC200 direct discharge measurements and rating curve for the period 11-Jun-04 to 1-Sep-04. The points indicate the direct discharge measurements performed to develop the rating curve (solid line) for the stated period (see Table B1 in Appendix B). The uncertainty in the rating-curve predictions is given by the dashed lines. Stage is measured relative to a consistent point on a staff gage (see Appendix A).

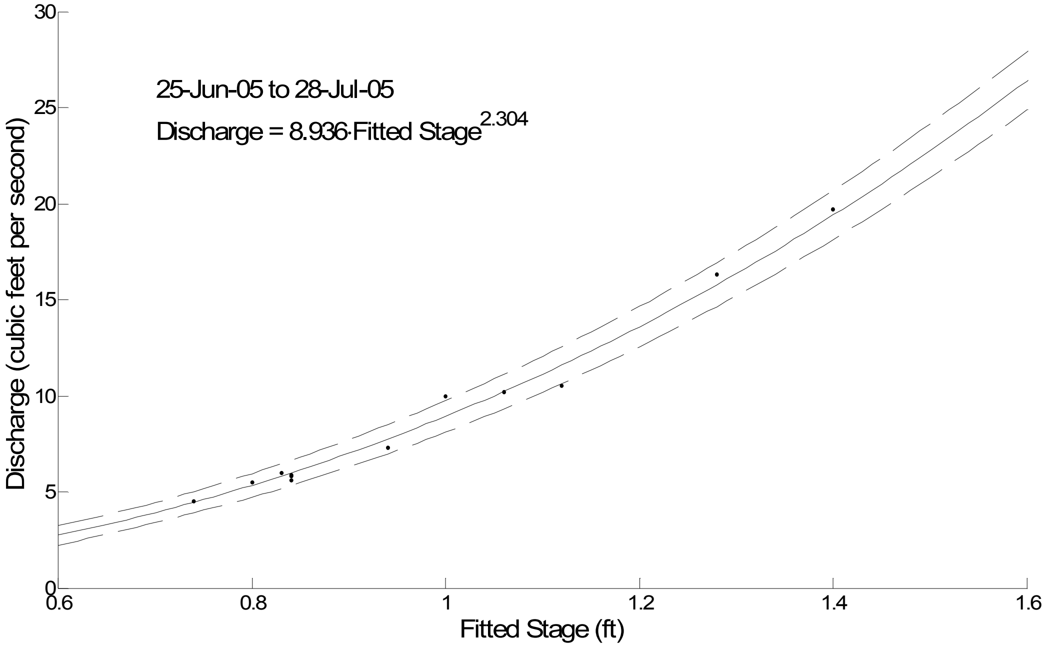

Figure 4. QC200 direct discharge measurements and rating curve for the period 25-Jun-05 to 28-Jul-05. The points indicate the direct discharge measurements performed to develop the rating curve (solid line) for the stated period (see Table B1 in Appendix B). The uncertainty in the rating-curve predictions is given by the dashed lines. Stage is measured relative to a consistent point on a staff gage (see Appendix A).

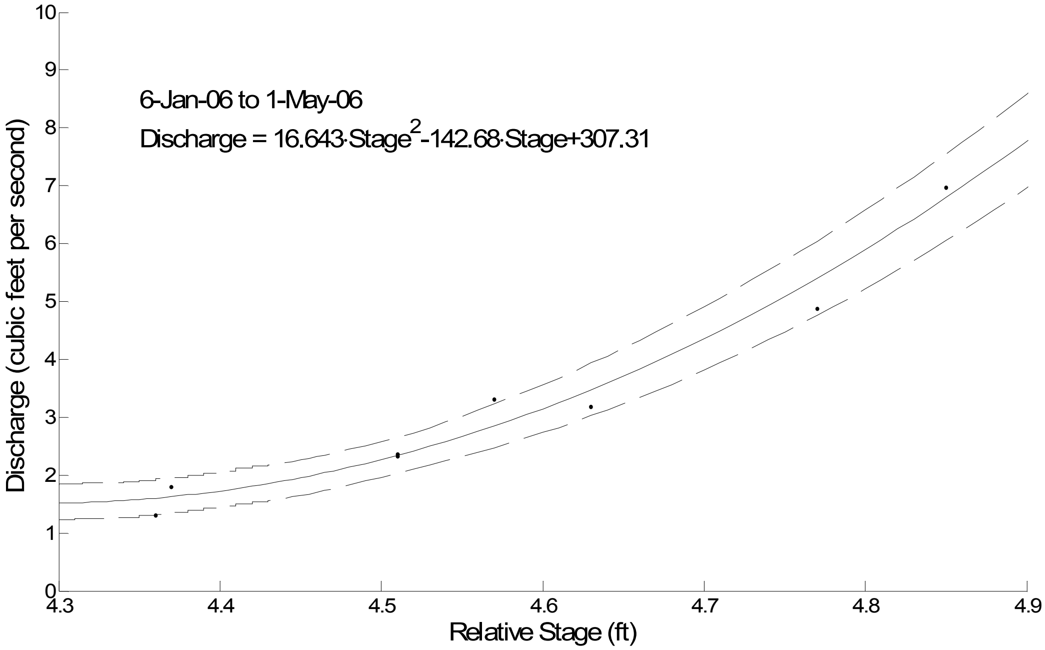

Figure 5. QC200 direct discharge measurements and rating curve for the period 6-Jan-06 to 1-May-06. The points indicate the direct discharge measurements performed to develop the rating curve (solid line) for the stated period (see Table B1 in Appendix B). The uncertainty in the rating-curve predictions is given by the dashed lines. Stage is measured relative to a consistent point on a staff gage (see Appendix A).

3 Results

Figures 6-8 show the time series of discharge for the three periods of interest. The stage records were derived from pressure-transducer measurements, and the discharge records were generated using the appropriate rating curves. The circles indicate direct discharge measurements and the horizontal lines indicate the maximum and minimum discharge measurements within each period. Discharge estimates beyond the range of measured flows require the extrapolation of the rating curves and, therefore, are associated with larger uncertainties. Note that the vertical scale for 2005 (Figure 7) differs from the other periods because of a large rain event and corresponding high flow in July 2005. Daily average streamflow data are presented in tabular form in Appendix E. Precipitation data are from the meteorological station on the roof of the Monteverde Institute (Johnson et al. 2005, Guswa et. al. 2006).

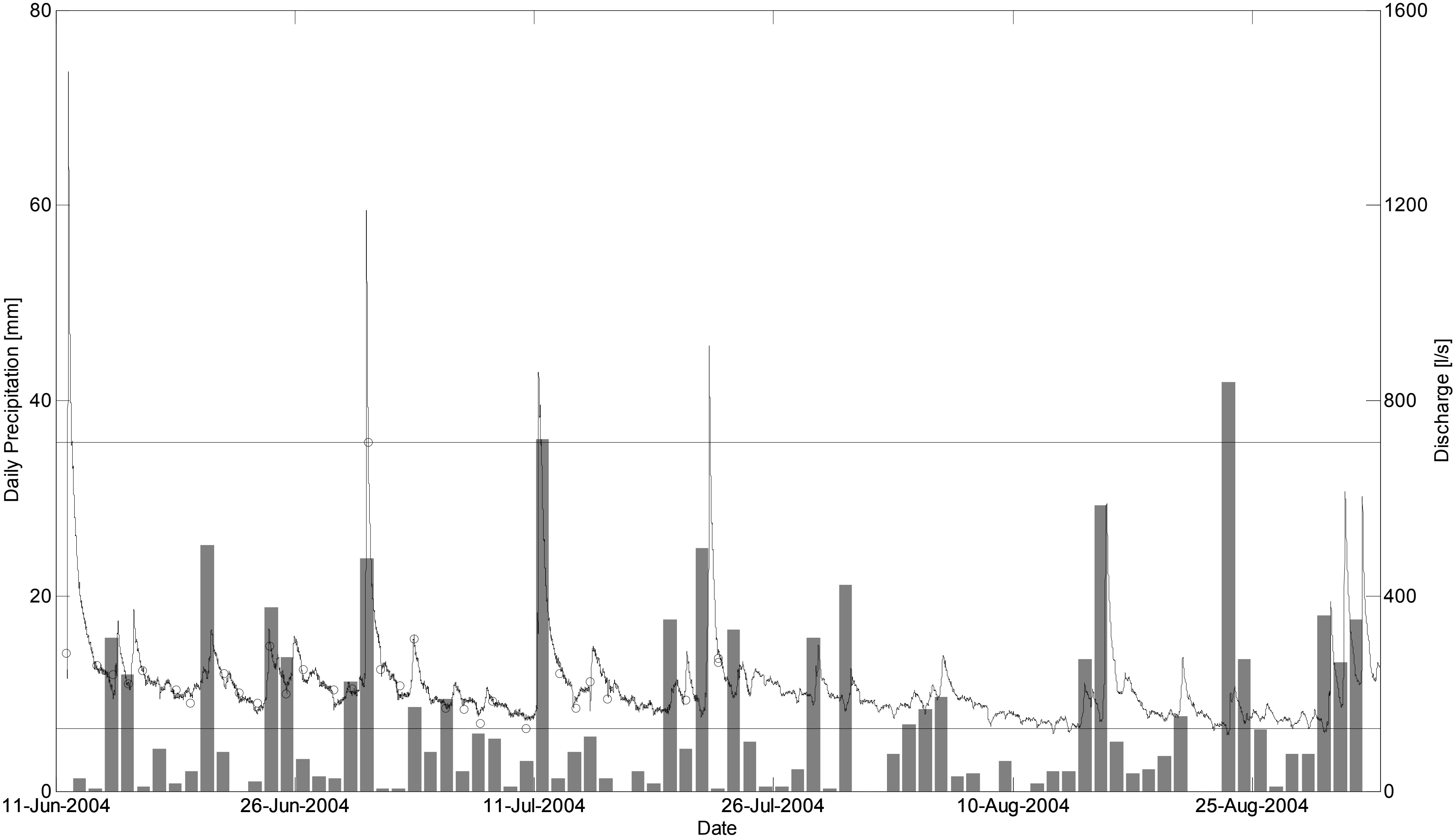

Figure 6. Time series of discharge at QC200 for the period 11-Jun-04 to 1-Sep-04. The circles represent direct discharge measurements; the horizontal lines indicate the maximum (710 l/s) and minimum (130 l/s) direct discharge measurements for the period. The average streamflow over this period was 230 l/s.

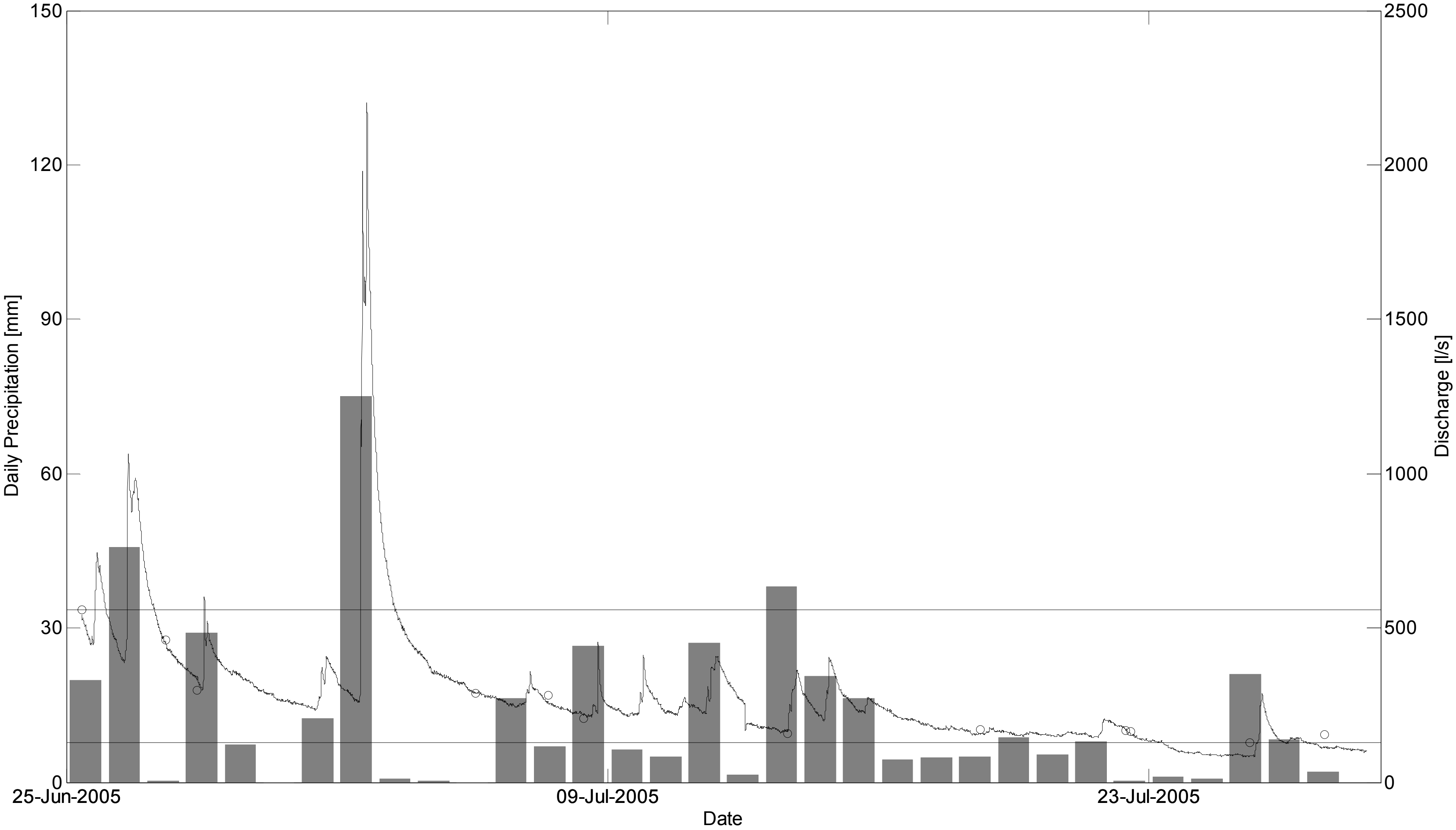

Figure 7. Time series of discharge at QC200 for the period 25-Jun-05 to 28-Jul-05. The circles represent direct discharge measurements; the horizontal lines indicate the maximum (560 l/s) and minimum (130 l/s) direct discharge measurements for the period. The average streamflow over this period was 280 l/s.

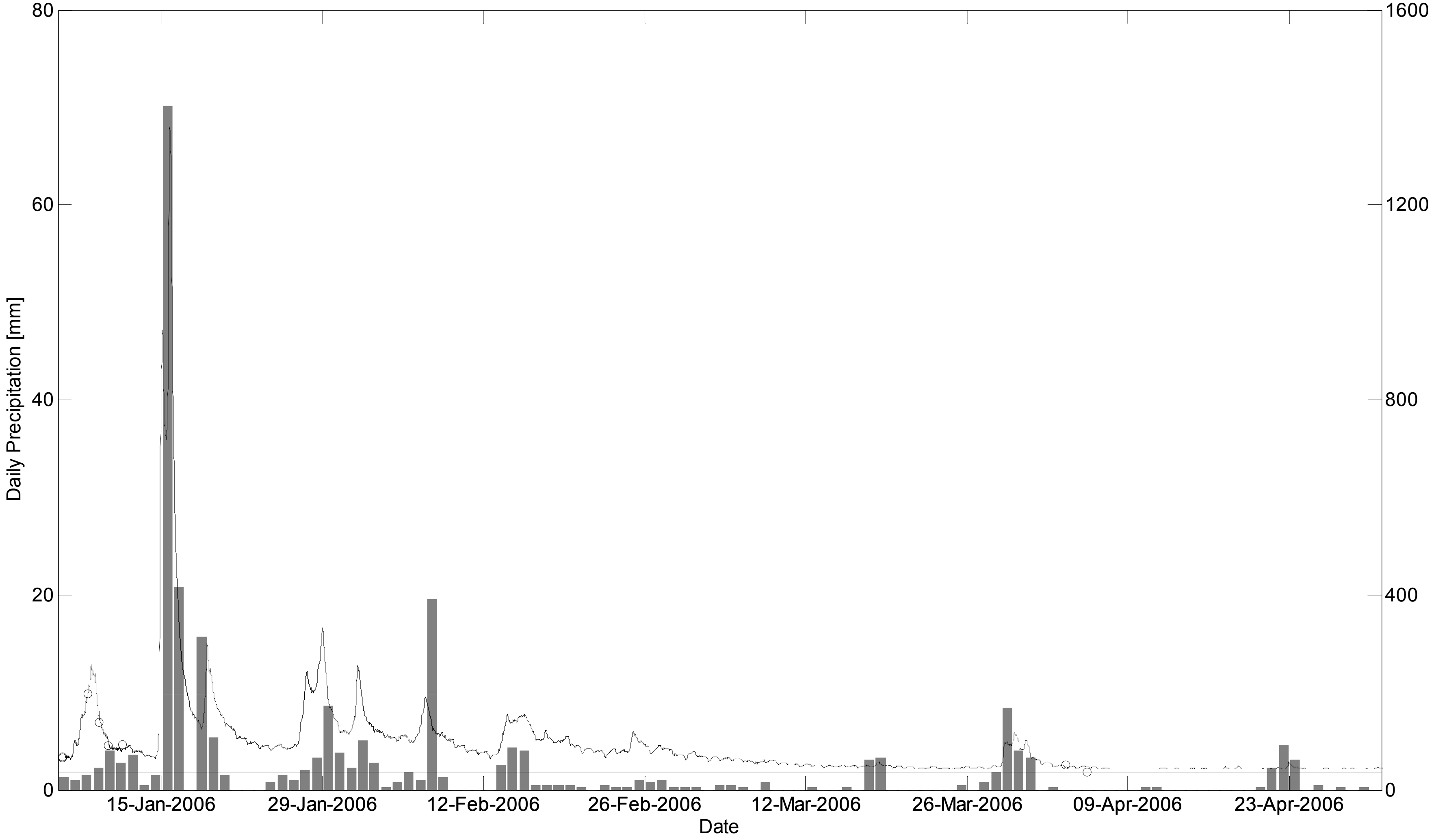

Figure 8. Time series of discharge at QC200 for the period 6-Jan-06 to 1-May-06. The circles represent direct discharge measurements; the horizontal lines indicate the maximum (200 l/s) and minimum (40 l/s) direct discharge measurements for the period. The average streamflow over this period was 100 l/s.

On all three figures, the streamflow response to precipitation is apparent. Precipitation is typically coupled with a rapid rise in discharge followed by a recession as stormflow subsides and the stream returns to baseflow conditions. Figure 8 shows a gradual decrease of baseflow over several months due to the relatively low precipitation during the transitional and dry seasons. Further work is required to understand the interaction between rainfall, runoff, and the groundwater storage capacity within the region.

Table 1 provides summary statistics for streamflow and precipitation during the three periods of interest. The representative streamflow for each period can be quantified by the median, which is the value of discharge for which half of the time the flowrate is higher and for half of the time the flowrate is lower. The mean, or average, discharge is useful as a measure of the total amount of water discharged by the stream, but is less helpful as a measure of a typical flowrate due to a few large events of relatively short duration that skew the distribution of flows. The 7-day minimum flow is of particular utility in the assessment of water resources because it indicates the lowest flows in a stream or river. To determine the 7-day minimum flow, a 7-day moving average of discharge is calculated for a time period of interest, and the smallest value is selected. From 6-Jan-06 to 1-May-06, the 7-day minimum flow was 40 liters/second, which is less than one-third of what is observed in the rainy season.

Table 1. Summary statistics for discharge at QC200 for the three periods of interest.

	11 Jun 04 – 1 Sep 04	25 Jun 05 – 28 Jul 05	6 Jan 06 – 1 May 06
Season	Rainy	Rainy	Transitional/Dry
Average Precipitation (mm/day)	7.2	13.3	2.1
Mean Streamflow (l/s)	230	280	100
Median Streamflow (l/s)	210	240	80
7-day Minimum Streamflow (l/s)	150	130	40
Max Direct Discharge Measurement (l/s)	710	560	200
Min Direct Discharge Measurement (l/s)	130	130	40

Figure 9 shows the frequency distributions of streamflow on the Quebrada Cuecha for the three time periods. As shown on the figure, the discharge at QC200 is much lower during the dry and transitional season than during the rainy season. The effect of stormflow explains the positive skewness of the data (i.e., the few very large values of discharge) shown in Figure 9. During and immediately after a rain event, streamflow is very high and then quickly subsides. Not surprisingly, the highest flows are observed during the rainy season.

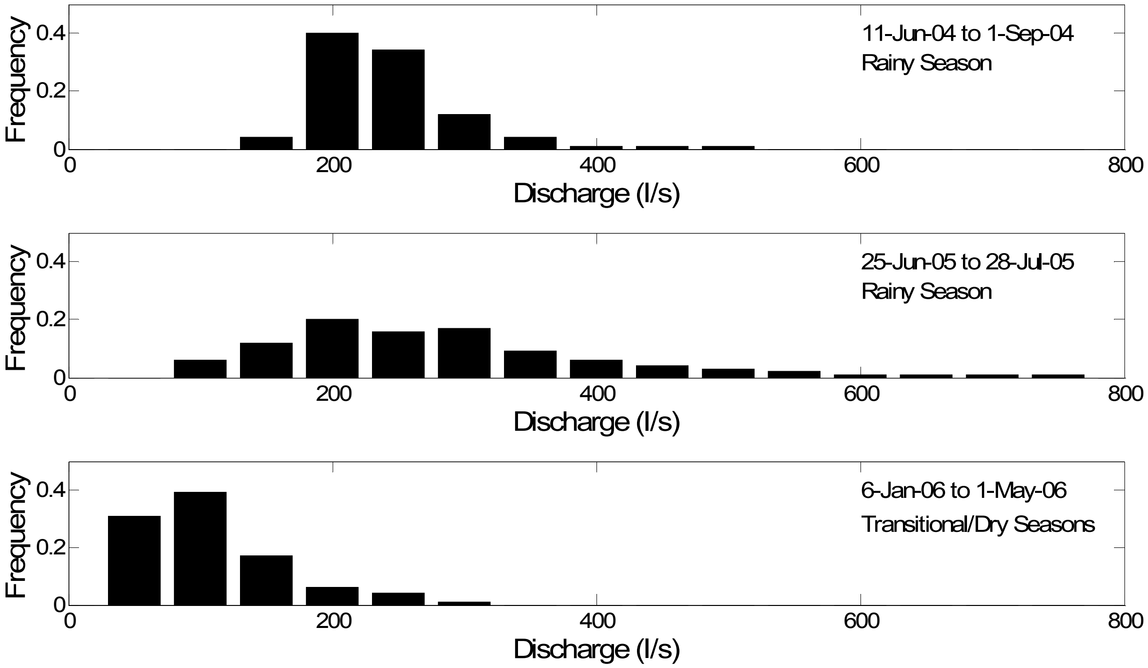

Figure 9. Frequency distributions for QC200 streamflow for the three periods of interest. The width of each bar represents 50 liters/s.

Flow-duration curves (Figure 10) present the same information as the frequency distribution curves (Figure 9), but present it in a different manner. In a flow-duration curve, stream discharge is plotted against the frequency of time for which streamflow is *greater than or equal to that value*. Figure 10 presents flow-duration curves for the Quebrada Cuecha. This figure shows that streamflow in excess of 200 l/s is not uncommon during the rainy season; discharge at QC200 met or exceeded 200 l/s 56% of the time during period 1 and 62% during period 2. During the transitional and dry seasons of 2006, however, the median flow rate was 80 l/s and discharge exceeded 200 l/s only 7% of the time.

The different geometries of the flow-duration curves are due to the different distributions of the streamflow data (see Figure 9); the slope for the dry season in 2006 is steeper than those for the other two periods because the range of flows was relatively small, suggesting that streamflow did not deviate significantly from baseflow conditions. Note that the median streamflow is the discharge that corresponds to a frequency of 0.5 on Figure 10.

The data, statistics, and figures presented in this report reflect the conditions for the periods of measurement. Given the seasonal and year-to-year variability in precipitation, however, these data should not be presumed to be representative of streamflow at QC200 for all time. Continued monitoring and measurement is necessary to fully characterize streamflow for the Quebrada Cuecha.

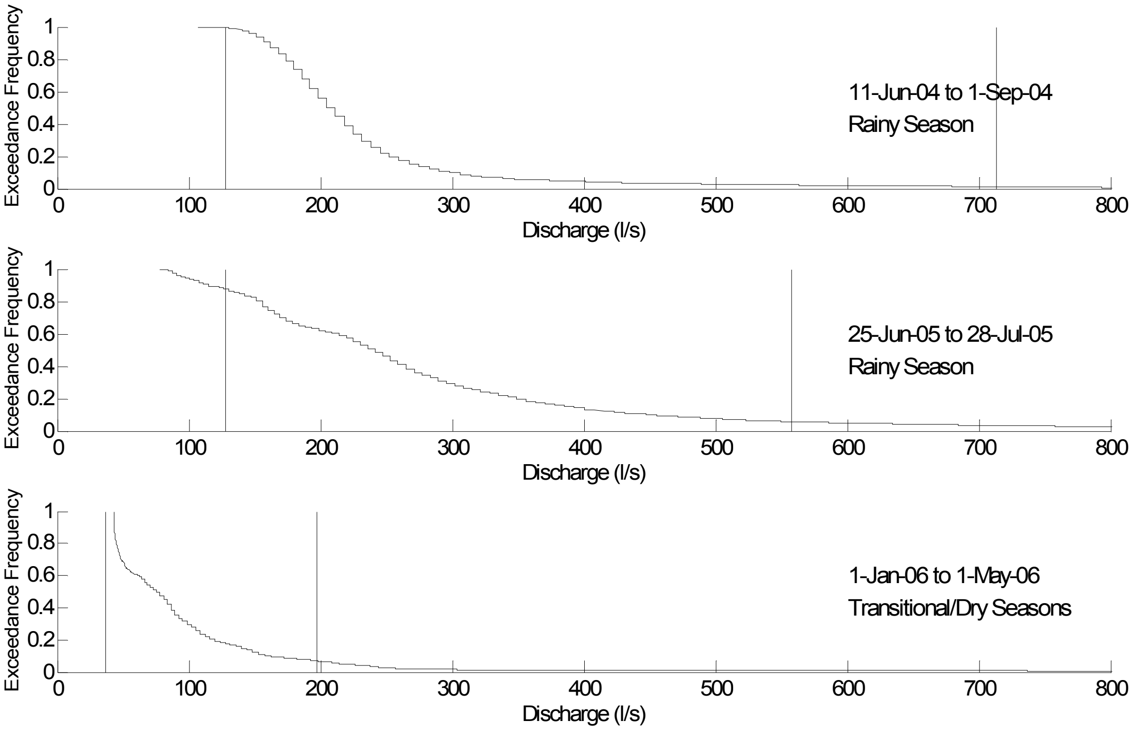

Figure 10. Flow-duration curves for QC200. These plots present discharge versus the frequency with which that value was exceeded during each of the three periods. The vertical lines represent the maximum and minimum manual discharge measurements; these values correspond to 710 and 130 liters/second for 2004, 560 and 130 liters/second for 2005, and 200 and 40 liters/second for 2006. The ‘staircase’ pattern in the curves is due to the finite resolution of the stage measurements.

Acknowledgments

The authors would like to thank the many individuals who contributed to the completion of this report. The Rockwell family provides access to site QC200 through their property. The Monteverde Institute provides logistical support during our visits to Monteverde. Smith students Silvia Newell ‘04, Elizabeth Koenig ’05, Ilona Johnson ’06, Mai Kobayashi ’06, and Merilie Reynolds ’08 made manual discharge measurements at QC200 and helped to generate the rating curves. We are grateful for all of these specific contributions and the general support of the Monteverde community.

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APPENDIX A. Methods for Discharge Determination

Discharge can be determined by measuring the depth and the vertically-averaged flow velocity at discrete points along a channel cross section. In this study, a Swoffer flowmeter (Figure A1) is used to measure velocity and depth. Velocity is typically measured twice at each location and the results are averaged; velocity measurements are accurate to approximately 3%. At each location, velocity is measured at six-tenth of the total depth because the velocity at this depth is theoretically equal to the vertical average. These measurements are typically performed at 15-20 locations across a channel cross section. Measurements from these locations are then numerically integrated to determine total discharge (Figure A2).

Figure A1. Photo of flowmeter wand and digital meter. The flowmeter consists of a metal rod with marked increments for depth measurement and a propeller for velocity measurement.

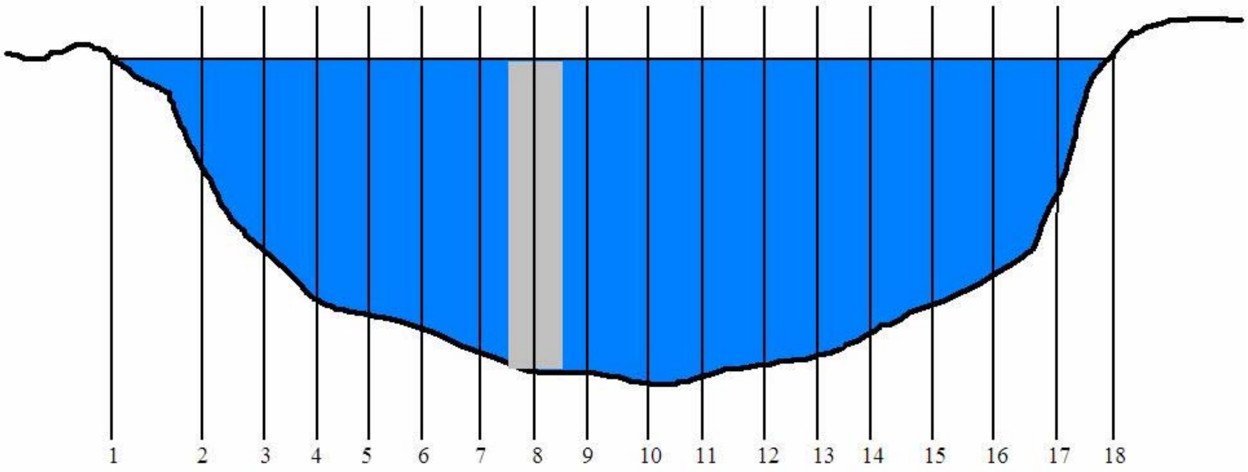

Figure A2. Illustration of the numerical method used to calculate discharge through a channel cross section. Numbers 2-17 represent locations of depth and velocity measurements; the tagline of numbers 1 and 18 are recorded to indicate the banks. Example of the numerical method: The depth and velocity measurements at 8 are assumed to be representative of the depth and velocity of the entire shaded rectangle; the product of the shaded area and the representative velocity measurement at 8 is the discharge through the rectangle (Equation 1). The width of the rectangle is determined by summing ½ of the distance between 7 and 8 and ½ of the distance between 8 and 9. The sum of all such rectangles across the channel is the total discharge through the entire cross section. Depth and velocity are typically measured at 15-20 locations across a channel.

Direct discharge measurements are time consuming and field conditions do not allow for the implementation of this method when flows are extremely high or low. A more practical approach is to establish an empirical relationship relating discharge and a more easily-monitored parameter such as water level (stage). Manual staff gage readings are obtained when direct discharge measurements are performed. Based on direct discharge measurements and corresponding manual staff-gage readings, rating curves are developed to relate stage and discharge. Automated measurements of stage can then be converted to records of discharge using the rating curves.

To obtain a continuous record of stage at QC200, a gaging station consisting of a staff gage and pressure transducers has been maintained since June 2004. The staff gage (Figure A3) is a large metal ruler with marked increments of 0.01 ft (3.0 mm); it is installed within the channel and water level above an arbitrary point can be read from the gage. There are two pressure transducers: a levelogger and a barologger (Figure A3). The levelogger is installed near the staff gage in a vertical PVC pipe with slits that allow for water to pass through; this instrument measures both the atmospheric pressure and water pressure above the point of measurement. The barologger is installed out of the water; it measures only atmospheric pressure. The subtraction of the barologger readings from the levelogger readings yields the water pressure; the latter can be converted to equivalent staff gage readings by comparing with available manual staff-gage measurements. Both loggers were manufactured by Solinst, Inc.; the accuracies of the levelogger and barologger measurements are 0.1% and 0.3%, respectively.

Figure A3. [Left] The water level above an arbitrary point is measured using a staff gage. [Right] Two pressure transducers (levelogger and barologger) installed at QC200. The subtraction of the barologger readings from the levelogger readings yields the water pressure; the latter can be converted to equivalent staff-gage readings by comparing with manual staff-gage measurements.

APPENDIX B. Discharge Measurements at QC200

Table B1. Record of all direct measurements of discharge (to the nearest 10 liters/second) made at QC200 from June 2004 through June 2006.

Date	Time (CST)	Discharge (liters/s)	Date	Time (CST)	Discharge (liters/s)	Date	Time (CST)	Discharge (liters/s)
11-Jun-04	16:45	280	28-Feb-05	14:45	90	23-Jun-06	8:30	180
13-Jun-04	14:00	260	15-Mar-05	13:47	40	23-Jun-06	13:02	160
14-Jun-04	13:50	240	31-Mar-05	10:45	20	28-Jun-06	13:21	500
15-Jun-04	13:30	220	23-Jun-05	8:42	200	28-Jun-06	15:17	450
16-Jun-04	10:30	250	25-Jun-05	10:00	560	29-Jun-06	16:38	310
18-Jun-04	13:38	210	27-Jun-05	13:57	460	30-Jun-06	8:40	700
19-Jun-04	10:30	180	28-Jun-05	9:20	300	30-Jun-06	8:59	790
21-Jun-04	13:35	240	5-Jul-05	14:21	290	30-Jun-06	9:21	810
22-Jun-04	11:45	200	7-Jul-05	11:03	280	30-Jun-06	11:16	840
23-Jun-04	15:40	180	8-Jul-05	9:06	210	30-Jun-06	15:20	870
24-Jun-04	10:40	300	13-Jul-05	15:48	160			
25-Jun-04	10:22	200	18-Jul-05	15:19	170			
26-Jun-04	12:00	250	22-Jul-05	9:50	170			
28-Jun-04	10:45	210	22-Jul-05	12:40	160			
29-Jun-04	13:15	210	25-Jul-05	14:55	130			
30-Jun-04	13:55	710	27-Jul-05	13:13	160			
01-Jul-04	9:30	250	6-Jan-06	8:57	70			
02-Jul-04	13:13	220	6-Jan-06	10:01	70			
03-Jul-04	11:43	310	8-Jan-06	14:34	200			
05-Jul-04	11:20	170	9-Jan-06	14:13	140			
06-Jul-04	13:40	170	10-Jan-06	8:46	90			
07-Jul-04	14:50	140	11-Jan-06	13:38	90			
08-Jul-04	8:50	180	3-Apr-06	13:28	50			
10-Jul-04	11:20	130	5-Apr-06	9:55	40			
12-Jul-04	13:20	240	9-Jun-06	9:00	140			
13-Jul-04	15:13	170	10-Jun-06	13:34	120			
14-Jul-04	11:55	220	10-Jun-06	14:30	140			
15-Jul-04	14:45	190	11-Jun-06	15:35	210			
20-Jul-04	11:45	190	13-Jun-06	10:11	100			
22-Jul-04	12:00	270	14-Jun-06	13:36	200			
22-Jul-04	12:01	260	15-Jun-06	10:32	90			
04-Nov-04	13:45	170	16-Jun-06	9:33	320			
10-Jan-05	12:25	720	16-Jun-06	12:39	270			
10-Jan-05	13:45	720	16-Jun-06	14:59	240			
30-Jan-05	15:10	200	19-Jun-06	8:18	90			
16-Feb-05	14:25	90	19-Jun-06	16:22	90			
23-Feb-05	14:30	220	21-Jun-06	8:16	70			
23-Feb-05	15:25	170	21-Jun-06	14:45	60			
24-Feb-05	13:15	160	22-Jun-06	17:20	560			

APPENDIX C. Rating Curve Determination

Two mathematical models were assessed to describe the relationship between water level and stream discharge:

Quadratic Model $\text{Discharge} = a(\text{stage})^2 + b(\text{stage}) + c$ (2)

Power Law $\text{Discharge} = a(\text{stage} - c)^b = a(\text{fitted stage})^b$ (3)

The quadratic model (Equation 2) is purely empirical; it is based solely on the correlation of the measured stage and discharge data. This model could be desirable because it is not based on any inherent assumptions about the data.

The power law model (Equation 3) is based on a theoretical assumption; the parameter ‘c’ indicates the staff-gage level which corresponds to a discharge of zero. The choice of this parameter is based on qualitative comparisons of the data with the existing rating curves. Different values of the parameter ‘c’ can be used within a period of interest. If any changes in the channel morphology in the vicinity of the stream gage are known and their impact on the water level is quantifiable, ‘c’ could be altered to reflect this change. This was applicable in period 2 (25-Jun-05 to 28-Jul-05); a flow obstruction was in place downstream of the staff gage from 12-22 Jul 05 and stage was consequently elevated throughout the period. A new ‘c’ was used for the period when the obstruction was in place and another was used for when it was removed. The initial and the final parameters within the period are not equal (Table C1) because the system did not return to its initial conditions.

Model assessment was based on a comparison between the correlation factors (R^2), the root mean square (RMS) error, and a graphical assessment of residuals vs. time and residuals vs. discharge. The results of the model selection are summarized in Table C1 below. Continuous discharge records for each period of interest were generated using the chosen rating curves. Figures 3-5 illustrate the direct discharge measurements and the rating curves selected for each period. Note that the rating curves were developed for the stage and discharge measurements in English Units (ft and cubic feet per second).

Table C1. Summary of the rating-curve selections for QC200. Assessment was based on a comparison between the correlation factors (R^2), the root mean square (RMS) errors, and a graphical assessment of residuals vs. time and residuals vs. discharge. The quadratic model was selected for the first and third periods, and the power-law model was selected for the second. The parameters, a, b, and c, refer to those in Equation 2 (quadratic) and Equation 3 (power law). More than one parameter 'c' was used in the second period because a flow obstruction was in place downstream of the stream gaging station from 12-22 Jul 05.

	11 Jun 04 – 1 Sep 04		**25 Jun 05 – 28 Jul 05**			**6 Jan 06 – 1 May 06**	
	Power Law	**Quadratic**	**Power Law**		**Quadratic**	**Power Law**	**Quadratic**
Parameters							
A	17.009	19.765	8.936		24.218	7.802	16.643
B	2.149	-164.98	2.304		-207.49	1.77	-142.68
C	3.38	344.93	3.73	for 25-Jun to 12-Jul	447.22	3.48	307.31
			3.57	for 12-Jul to 22-Jul			
			3.66	for 22-Jul to 28-Jul			
Statistics							
R^2	0.92	0.97	0.99		0.93	0.95	0.97
Root Mean Square (cfs)	0.65	0.65	0.51		1.19	0.46	0.31
Mean of the Residuals (cfs)	0.0	0.0	0.0		0.0	0.0	0.0
Any trends in…							
Residual vs. Discharge	None	None	None		None	None	None
Residual vs. Time	Weak, negative correlation (R^2 = 0.47)	Weak, negative correlation (R^2 = 0.47)	None		None	None	None
Chosen Model	Quadratic		Power law			Quadratic	

APPENDIX D. Error Assessment for Discharge Predictions

There are two major sources of uncertainty associated with discharge values predicted from a rating curve: 1. Variability of the direct discharge measurements about the rating curve and 2. Uncertainty in discharge predicted by the rating curves due to uncertainty in the continuous record of stage. The former is quantified by the root mean square (RMS) error, and the latter is calculated as follows:

$$\Delta Q(S) = \frac{dQ(S)}{dS}\Big|_{s} \times \Delta S \qquad (4)$$

where Q is the discharge predicted from a rating curve, ΔQ is the uncertainty associated with the predicted discharge, S is stage, and ΔS is the uncertainty in the continuous stage record (a conservative estimate of 0.04 ft was used)

The larger of the two errors at each value of stage was used to quantify the uncertainty in the rating-curve predictions; the calculated uncertainties are indicated by the dashed lines on Figures 3-5.

APPENDIX E. Daily Average Streamflow Data

Table E1. Daily average streamflow at QC200 (reported to the nearest 10 liters/second) from 12-Jun-04 through 31-Aug-04 determined from a continuous record of stream stage.

Date	liters/s	Date	liters/s	Date	liters/s
12-Jun-04	450	12-Jul-04	270	11-Aug-04	140
13-Jun-04	270	13-Jul-04	210	12-Aug-04	140
14-Jun-04	240	14-Jul-04	240	13-Aug-04	140
15-Jun-04	260	15-Jul-04	230	14-Aug-04	170
16-Jun-04	250	16-Jul-04	200	15-Aug-04	240
17-Jun-04	220	17-Jul-04	180	16-Aug-04	250
18-Jun-04	200	18-Jul-04	170	17-Aug-04	210
19-Jun-04	210	19-Jul-04	190	18-Aug-04	160
20-Jun-04	260	20-Jul-04	220	19-Aug-04	160
21-Jun-04	240	21-Jul-04	230	20-Aug-04	190
22-Jun-04	200	22-Jul-04	350	21-Aug-04	170
23-Jun-04	180	23-Jul-04	220	22-Aug-04	140
24-Jun-04	250	24-Jul-04	230	23-Aug-04	160
25-Jun-04	240	25-Jul-04	230	24-Aug-04	160
26-Jun-04	260	26-Jul-04	210	25-Aug-04	160
27-Jun-04	230	27-Jul-04	200	26-Aug-04	150
28-Jun-04	190	28-Jul-04	220	27-Aug-04	140
29-Jun-04	200	29-Jul-04	210	28-Aug-04	150
30-Jun-04	400	30-Jul-04	190	29-Aug-04	160
1-Jul-04	280	31-Jul-04	200	30-Aug-04	280
2-Jul-04	210	1-Aug-04	180	31-Aug-04	300
3-Jul-04	240	2-Aug-04	170		
4-Jul-04	200	3-Aug-04	180		
5-Jul-04	180	4-Aug-04	190		
6-Jul-04	200	5-Aug-04	230		
7-Jul-04	180	6-Aug-04	200		
8-Jul-04	190	7-Aug-04	180		
9-Jul-04	170	8-Aug-04	160		
10-Jul-04	160	9-Aug-04	160		
11-Jul-04	420	10-Aug-04	150		

Table E2. Daily average streamflow at QC200 (reported to the nearest 10 liters/second) from 26-Jun-05 through 26-Jul-05 determined from a continuous record of stream stage.

Date	liters/s
26-Jun-05	650
27-Jun-05	500
28-Jun-05	390
29-Jun-05	340
30-Jun-05	270
1-Jul-05	300
2-Jul-05	780
3-Jul-05	630
4-Jul-05	370
5-Jul-05	300
6-Jul-05	260
7-Jul-05	270
8-Jul-05	240
9-Jul-05	240
10-Jul-05	250
11-Jul-05	290
12-Jul-05	250
13-Jul-05	210
14-Jul-05	280
15-Jul-05	260
16-Jul-05	220
17-Jul-05	180
18-Jul-05	160
19-Jul-05	160
20-Jul-05	160
21-Jul-05	160
22-Jul-05	160
23-Jul-05	120
24-Jul-05	90
25-Jul-05	120
26-Jul-05	150

Table E3. Daily average streamflow at QC200 (reported to the nearest 10 liters/second) from 7-Jan-06 through 30-Apr-06 determined from a continuous record of stream stage.

Date	liters/s	Date	liters/s	Date	liters/s	Date	liters/s
7-Jan-06	90	6-Feb-06	140	8-Mar-06	60	7-Apr-06	40
8-Jan-06	190	7-Feb-06	140	9-Mar-06	60	8-Apr-06	40
9-Jan-06	170	8-Feb-06	110	10-Mar-06	50	9-Apr-06	40
10-Jan-06	100	9-Feb-06	90	11-Mar-06	50	10-Apr-06	40
11-Jan-06	80	10-Feb-06	80	12-Mar-06	50	11-Apr-06	40
12-Jan-06	80	11-Feb-06	80	13-Mar-06	50	12-Apr-06	40
13-Jan-06	70	12-Feb-06	70	14-Mar-06	50	13-Apr-06	40
14-Jan-06	120	13-Feb-06	100	15-Mar-06	50	14-Apr-06	40
15-Jan-06	940	14-Feb-06	140	16-Mar-06	50	15-Apr-06	40
16-Jan-06	380	15-Feb-06	150	17-Mar-06	50	16-Apr-06	40
17-Jan-06	180	16-Feb-06	110	18-Mar-06	50	17-Apr-06	40
18-Jan-06	160	17-Feb-06	110	19-Mar-06	50	18-Apr-06	40
19-Jan-06	210	18-Feb-06	100	20-Mar-06	50	19-Apr-06	40
20-Jan-06	140	19-Feb-06	100	21-Mar-06	40	20-Apr-06	40
21-Jan-06	110	20-Feb-06	80	22-Mar-06	50	21-Apr-06	40
22-Jan-06	100	21-Feb-06	80	23-Mar-06	50	22-Apr-06	40
23-Jan-06	90	22-Feb-06	70	24-Mar-06	40	23-Apr-06	50
24-Jan-06	90	23-Feb-06	80	25-Mar-06	50	24-Apr-06	40
25-Jan-06	90	24-Feb-06	80	26-Mar-06	50	25-Apr-06	40
26-Jan-06	90	25-Feb-06	100	27-Mar-06	40	26-Apr-06	40
27-Jan-06	190	26-Feb-06	80	28-Mar-06	50	27-Apr-06	40
28-Jan-06	230	27-Feb-06	90	29-Mar-06	90	28-Apr-06	40
29-Jan-06	210	28-Feb-06	80	30-Mar-06	100	29-Apr-06	40
30-Jan-06	130	1-Mar-06	70	31-Mar-06	80	30-Apr-06	40
31-Jan-06	140	2-Mar-06	70	1-Apr-06	60		
1-Feb-06	180	3-Mar-06	60	2-Apr-06	50		
2-Feb-06	130	4-Mar-06	60	3-Apr-06	50		
3-Feb-06	110	5-Mar-06	60	4-Apr-06	50		
4-Feb-06	110	6-Mar-06	60	5-Apr-06	50		
5-Feb-06	100	7-Mar-06	60	6-Apr-06	40		