Development of Regional Hydraulic Geometry Curves for the Santa Cruz Mountains

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Abstract

This study was conducted to develop regional hydraulic geometry curves for the Santa Cruz Mountains that could be used in stream related and/or engineering projects. Data used to form these curves was collected from the USGS and by conducting stream geometry surveys. The resulting regional curves had high R^2 values ranging from .82 to .92. Compared to other regional curves in nearby areas, the Santa Cruz Mountains regional curve equations have higher exponents, meaning bankfull channel measurements increase at faster rates as drainage areas increases. Further measurements and analysis should be done before applying these curves to project sites.

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Acknowledgements

This project would not be possible without the assistance and encouragement of my advisor, Dr. Brian Dietterick, as well as graduate students Russell White, Lynette Niebrugge, Drew Perkins, and Drew Loganbill. The coordination with landowners and access to their properties was essential to my research. I greatly appreciate Roberta Smith, Kirk Toups, Satish Sheth, and Rick Labahn from CEMEX; Thomas Sutfin from the Soquel Demonstration Forest; Steve Auten and Susan Burgess from Swanton Pacific Ranch; Nadia Hamey from Big Creek Lumber Company; and Alicia Moss and Lea Haratani from the Resource Conservation District of Santa Cruz County. I also appreciate Lawrence Freeman and Emblele Awipl from USGS for providing me with data and information for the gaged sites. Finally, I would like to thank Dave Rosgen for personally answering my data analysis questions.

Introduction:

Regional hydraulic geometry curves compare bankfull channel dimensions with drainage area at various locations within a defined region. The channel geometry measurements are graphed on log-log plots and compare bankfull top width, mean depth, and cross-sectional area to the corresponding drainage area (NRCS, 2009). These curves are useful because bankfull channel geometry is often needed for stream related projects, but is difficult to measure. In-field measurements of bankfull characteristics can be error prone, tedious, or costly. Drainage area, on the other hand, is relatively easy to measure for a given site on a stream by using various tools such as the polar planimeter, dot grid or ArcMap. The curves can be used in future projects to estimate bankfull measurements by measuring the drainage area of the project site.

Regional hydraulic geometry curves are especially useful in stream restoration projects where the stream is so degraded that natural bankfull channel geometry can no longer be determined and a reference reach is unavailable. A well established regional curve can provide an estimate of the bankfull channel shape at a restoration project site. Regional curves can also be used on projects such as road, bridge or culvert construction, as well as scientific studies involving bankfull. Regional curves should only be applied to projects within the same region or to a region that has scientific evidence showing that it follows the same hydraulic geometry curves.

History:

The first data set of bankfull channel geometry was collected from the Upper Salmon River in Idaho in the early 1970's and arranged into hydraulic geometry curves by William Emmett in 1975 (Emmett, 1975). Luna Leopold assembled bankfull channel geometry data for the Upper Green River in Wyoming in the mid 1970's as well as data sets for the San Francisco Bay region and Southeastern Pennsylvania (Dunne and Leopold, 1978). These data sets were arranged into regional curves and published by Thomas Dunne and Luna Leopold (Dunne and Leopold,1978) in the late seventies. Since then, federal, state and local agencies have been working together to develop regional hydraulic geometry curves across the country. Hydrologists, engineers, foresters and natural scientists can use well developed regional curves for stream restoration projects, assessment of stream health, culvert construction and future project planning. In the future factors influencing the equation of the curve may be determined and possibly modeled by comparing Regional Hydraulic Geometry Curves.

Study Location:

Santa Cruz Mountains

The selected region for the development of the hydraulic geometry curves is the Santa Cruz Mountains. The mountain range runs down the southern San Francisco Peninsula from south of San Francisco to about 5 miles southeast of Gilroy. The mountains are bounded on the east by the Santa Clara Valley and on the west by the Pacific Ocean. The range is located in three counties: Santa Cruz, Santa Clara, and San Mateo. According to the NRCS region divisions, the Santa Cruz Mountains are part of the California Coast Ranges. The Santa Cruz Mountains have many streams ranging from small, unnamed ephemeral streams to large perennial streams such as Pescadero Creek.

Santa Cruz County has a temperate climate with a relatively uniform temperature throughout the county due to the marine influence and the mountain range that blocks winds. The Santa Cruz Mountains receive 60 inches of precipitation annually on average. Precipitation can range from 30 inches in the driest years to 90 inches in the wettest years. Snowfall is less than five inches and is limited to the highest points of the Santa Cruz Mountains. (SCS, 1976)

Measurement Sites

Data was collected from eight sites along streams in the Santa Cruz Mountains to develop the regional curves. Four sites are located at USGS stream gages and four sites are ungaged. The gaged sites all have at least ten years of peak streamflow records. The four gaged sites listed from north to south are: Pescadero Creek near Pescadero, San Lorenzo River near Boulder Creek, San Lorenzo River at Big Trees at Henry Cowell Redwoods State Park, and Soquel Creek at Soquel. The ungaged sites listed from north to south are: Opal Creek at Big Basin Redwoods State Park, East Branch of Soquel Creek at Soquel Demonstration Forest, Fall Creek at Felton, and San Vicente Creek at CEMEX near Davenport (Figure 1).

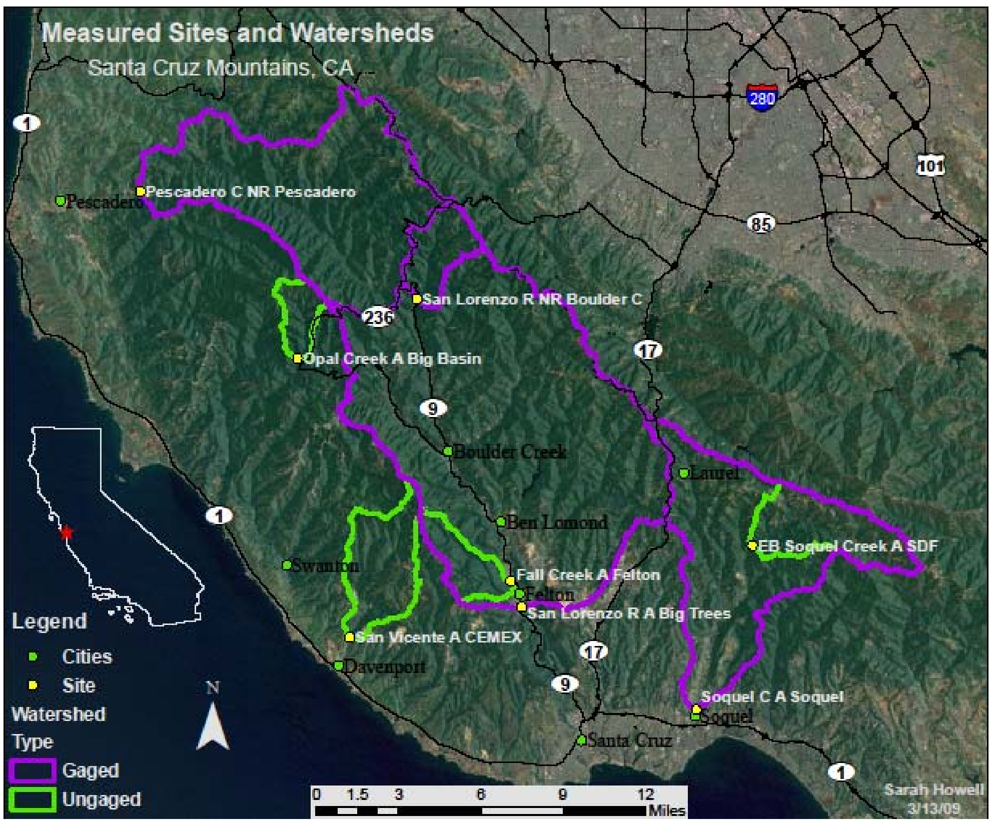

Figure 1-Map of Measured Sites and Watersheds in the Santa Cruz Mountains. Note how some watersheds encompass smaller watersheds.

The watershed of the Fall Creek site and the watershed of San Lorenzo River near Boulder Creek site are both part of the watershed of the San Lorenzo River at Big Trees site. The watershed of the site on the East Branch of Soquel Creek is part of the watershed of the site on Soquel Creek at Soquel. Maps of each site location are in Appendix A.

Bankfull Stage and Discharge:

Bankfull discharge, also known as effective discharge, has been identified as the dominant channel forming flow (Wolman and Miller, 1960). The most effective discharge over time is neither the very common low flows nor the very rare high flows. Instead, the effective discharge is a moderately high flow and has a return interval around 1.5 years (Leopold, 1994). This streamflow is most effective at moving sediment, forming or removing bars, forming or changing bends and meanders, and generally doing work that results in the average morphologic characteristics of channels (Dunne and Leopold, 1978). It is often the flow that just fills the channel to the top at the slope break between the bank and the floodplain.

Determination of the location of bankfull elevation in the field can be a challenge, even for experienced hydrologists and fluvial geomorphologists. Typical indicators of bankfull elevation are often used to locate the level of bankfull flow in the channel, but can sometimes be deceiving. Walking along a reach of the stream and taking multiple measurements can help give an idea of where bankfull is located. Some bankfull indicators according to Leopold (1994) include:

1. The point bar is the sloping surface that extends into the channel from the convex bank of a curve. The top of the point bar is at the level of the floodplain because floodplains generally result from the extension of point bars as a channel moves laterally by erosion and deposition through time.
2. The bankfull level is usually marked by a change in vegetation, such as the change from bare gravel bar to forbs, herbs or grass. Shrubs and willow clumps are sometimes useful, but can be misleading. Willows may occur below bankfull stage, but alders are above bankfull.
3. There is usually a topographic break at bankfull. The stream bank may change from a sloping bar to a vertical bank. It may change from a vertical bank to a horizontal plane on top of the floodplain. The change in topography may be as subtle as a change in slope of the bank.

4. Bankfull is often registered by a change in the size distribution of materials at the surface, from fine gravel to cobbles, from sand to gravel or even fine gravel material. It can change from fine to coarse or coarse to fine, but a change is common.
5. Even more subtle changes in the debris deposited between rocks, such as the amount of leaves, seeds, needles, or organic debris. Such indicators are confirmation rather than primary evidence. Flood-deposited debris alone should not be trusted.

Study Goal:

To create well-developed regional hydraulic geometry curves comparing drainage area to bankfull depth, width, area, and discharge that can be used for future projects in the Santa Cruz Mountains.

Study Objectives:

Before completion of this study, bankfull geometry measurements will be collected from four gaged stream locations by measuring bankfull stage height and using corresponding 9-207 form data. Bankfull geometry measurements will also be collected from four ungaged stream locations by performing full cross-section surveys as well as measuring slope and roughness (Manning's n). Bankfull measurements collected from the eight stream sites will be plotted on four separate graphs (one for each bankfull measurement) to develop regional hydraulic geometry curves for the Santa Cruz Mountains.

Procedures:

Measurements were collected from a total of eight stream sites within the Santa Cruz Mountains. At the four sites with gages, annual peak flow data was used to help calibrate the location of bankfull. Four sites with small drainage areas (<10 square miles) were selected in areas where land management projects are likely to be implemented. Due to the lack of stream gage data, more field measurements had to be taken at these locations. Full stream cross-section surveys were performed as well as measurements of slope and roughness.

Bankfull measurements at gaged stream sites:

At gaged stream sites, most of the needed channel measurements were already available in the USGS database. Bankfull stage needed to be estimated to determine the other bankfull geometry measurements. This was done by using rating curves and previously collected USGS data (9-207 forms). A field sheet was created for each site to aid in calibration of bankfull location. To create the field sheet, annual peak flow data (discharge, gage height and date) for gaged stream sites within the Santa Cruz Mountains was obtained from the USGS database. Data was ranked by discharge in descending order to determine the probability and recurrence interval for each peak flow. Streamflow verses return interval was graphed to find the equation of the best fit curve (Figure 2). Also, rating curves were created for each site (Figure 3) to be used with the equation for streamflow verses return interval to create the field sheet of discharge, gage height and elevation for return intervals from 1-3 years at every tenth of a year (Table 1). This field sheet helped with identifying bankfull since bankfull is usually around the 1.5 year return interval flow (Leopold, 1994).

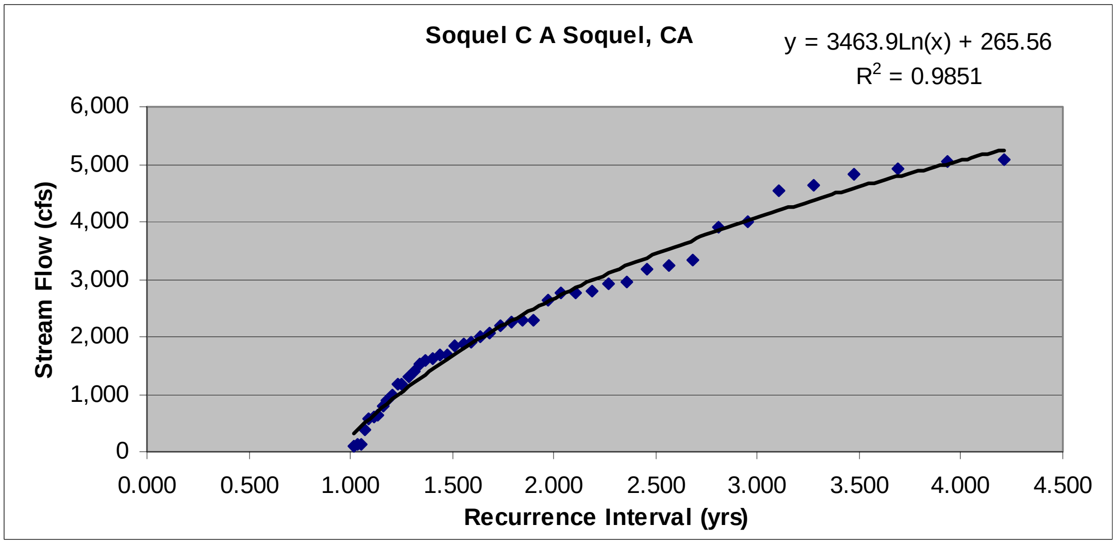

Figure 2 – Example Graph of Peak Streamflow verses Return Interval. The equation of the curve derived from this graph was used to estimate bankfull streamflow, which has a recurrence interval of about 1.5 years.

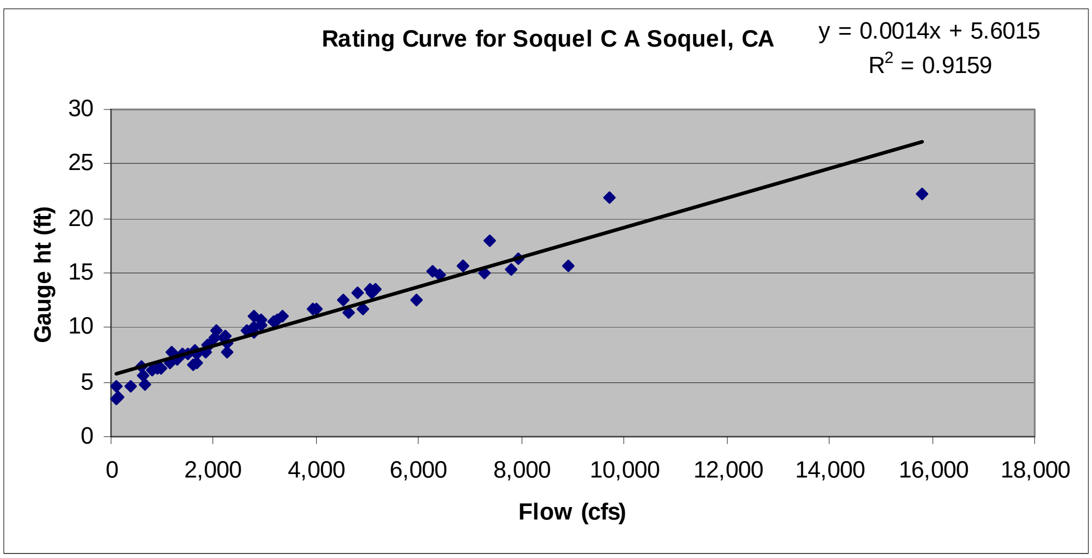

Figure 3 – Example Rating Curve. The equation of the rating curve was used to estimate bankfull gage height (see y-axis label above) from estimated bankfull streamflows.

Table 1 – Example Field Sheet. Flow and gage height are predicted for 1-3 year recurrence intervals using the streamflow vs. recurrence interval equation and rating curve equation.

Field Sheet for Soquel C A Soquel, CA			
Gauge datum (feet above NGVD) =			21.38
Recurrence Interval (yrs)	Flow (cfs)	Gauge Height (ft)	Feet above NGVD
1.0	**265.6**	**5.97**	**27.35**
1.1	595.7	6.44	27.82
1.2	897.1	6.86	28.24
1.3	1174.4	7.25	28.63
1.4	1431.1	7.60	28.98
1.5	**1670.1**	**7.94**	**29.32**
1.6	1893.6	8.25	29.63
1.7	2103.6	8.55	29.93
1.8	2301.6	8.82	30.20
1.9	2488.9	9.09	30.47
2.0	**2666.6**	**9.33**	**30.71**
2.1	2835.6	9.57	30.95
2.2	2996.7	9.80	31.18
2.3	3150.7	10.01	31.39
2.4	3298.1	10.22	31.60
2.5	**3439.5**	**10.42**	**31.80**
2.6	3575.4	10.61	31.99
2.7	3706.1	10.79	32.17
2.8	3832.1	10.97	32.35
2.9	3953.6	11.14	32.52
3.0	**4071.0**	**11.30**	**32.68**

In the field at the four gaged stream sites, bankfull stage was measured using an autolevel, tripod, and Philadelphia rod. Bankfull indicators were used first to locate bankfull stage and results verified with the field sheet. Bankfull discharge was calculated from gage height using the rating curve. USGS 9-207 forms for each gaged site were used to find the other bankfull measurements (Table 2). The data of each bankfull attribute was plotted with its corresponding discharge on separate graphs (Figure 4). The equations of the trend lines for these plots were used to calculate the bankfull measurements for the discharge calculated as bankfull discharge from field measurements. Drainage areas of gaged sites were provided in the USGS database. The data collected from these sites were then plotted on graphs to begin to form the regional curves.

Table 2 – Example 9-207 Form For Soquel Creek at Soquel, CA.

Measurement Number	Date	Width feet	Depth feet	Area sq. feet	velocity fps	Discharge cfs	Measurement Rating	Measurement Type
60	5/8/1952	25	0.828	20.7	1.72	35.5	G	WADING
61	6/16/1952	14	1.143	16	0.93	14.9	G	WADING
62	6/30/1952	18	0.994	17.9	1	17.9	G	WADING
63	7/29/1952	11.7	1.111	13	0.7	9.1	G	WADING
64	8/18/1952	16	0.731	11.7	0.6	7	G	WADING
65	9/5/1952	8.6	0.884	7.6	0.68	5.2	G	WADING
66	9/18/1952	8.4	0.845	7.1	0.87	6.2	G	WADING
67	10/16/1952	8.7	0.759	6.6	0.97	6.4	G	WADING
68	11/6/1952	8.6	0.826	7.1	0.75	5.3	G	WADING
69	11/27/1952	8.4	0.702	5.9	1.17	6.9	G	WADING
70	12/5/1952	26	1.388	36.1	2.05	74	G	WADING
71	12/8/1952	37	1.270	47	2.17	102	G	WADING
72	12/31/1952	33	1.585	52.3	2.89	151	G	WADING
73	2/18/1953	27	0.804	21.7	1.08	23.4	G	WADING
74	3/10/1953	18	0.956	17.2	1.78	30.9	G	WADING
75	3/22/1953	31	1.526	47.3	1.75	83	G	WADING
76	4/3/1953	16.6	1.253	20.8	1.38	28.8	G	WADING
77	4/22/1953	30	0.883	26.5	0.66	17.6	G	WADING
78	4/28/1953	33.5	1.299	43.5	2.26	98.1	G	WADING
79	5/8/1953	28	0.764	21.4	1.34	28.6	G	WADING
80	5/26/1953	30	0.723	21.7	0.82	17.7	G	WADING
81	6/20/1953	18.4	0.739	13.6	0.91	12.4	G	WADING
82	7/7/1953	17	0.612	10.4	0.69	7.15	G	WADING
83	7/24/1953	10.2	0.474	4.83	1.33	6.41	G	WADING
84	8/8/1953	8	0.436	3.49	1.36	4.76	G	WADING
85	9/22/1953	10.5	0.727	7.63	0.63	4.82	G	WADING

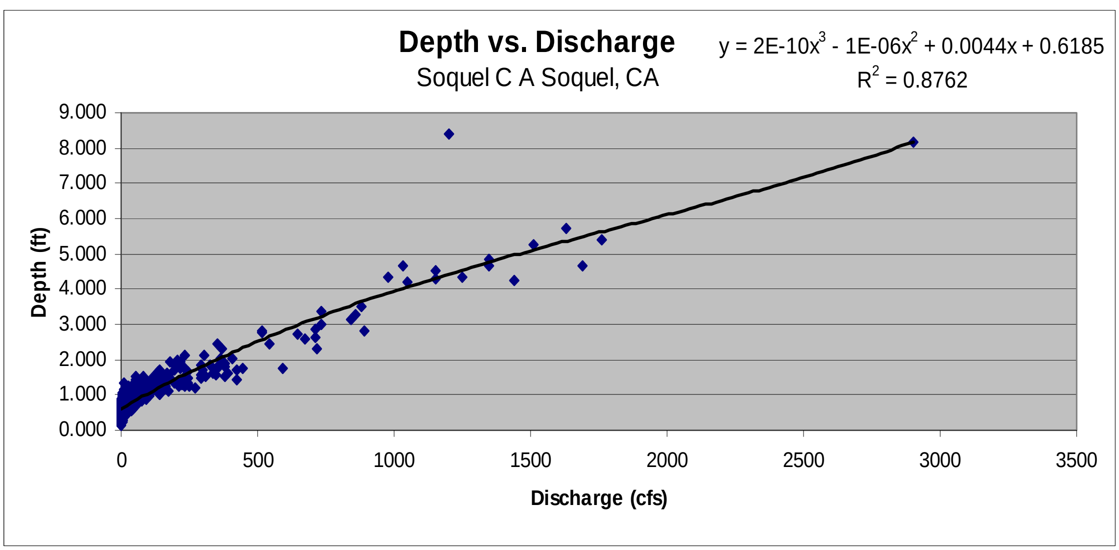

Figure 4 – Example Bankfull Measurement vs. Discharge Data Plotted From 9-207 Form.

Bankfull measurements at ungaged stream sites:

All bankfull channel geometry measurements were collected in the field at the ungaged sites. Stream channel geometry was measured using a laser level, tripod, receiver, Philadelphia rod, and cloth tape. Cross-section locations were chosen along a stream according to certain criteria such as a straight riffle reach between two meander bends, clear indicators of bankfull flow, presence of one or more terraces, channel section and form typical of the stream and a reasonably clear view of geomorphic features (NRCS, 2009). Cross-sections should measure two times the maximum channel depth in the cross-section at bankfull flow (NRCS, 2009). 15-25 measurements were taken across the channel at significant slope breaks as well as at bankfull left and bankfull right (Figure 5). Bankfull width, depth, and cross-sectional area were calculated from these measurements. Bankfull width is the distance between bankfull left and bankfull right. Bankfull cross-sectional area was calculated using the trapezoid equation. Bankfull depth was calculated by dividing the bankfull cross-sectional area by bankfull width. Table 3 shows an example of collected and calculated measurements of a cross-section. Summaries of the cross-section and site measurements for each ungaged site were placed in separate tables. Cross-section and site measurements were summarized for each ungaged site in separate tables (Table 4). See Appendix B for all ungaged site data.

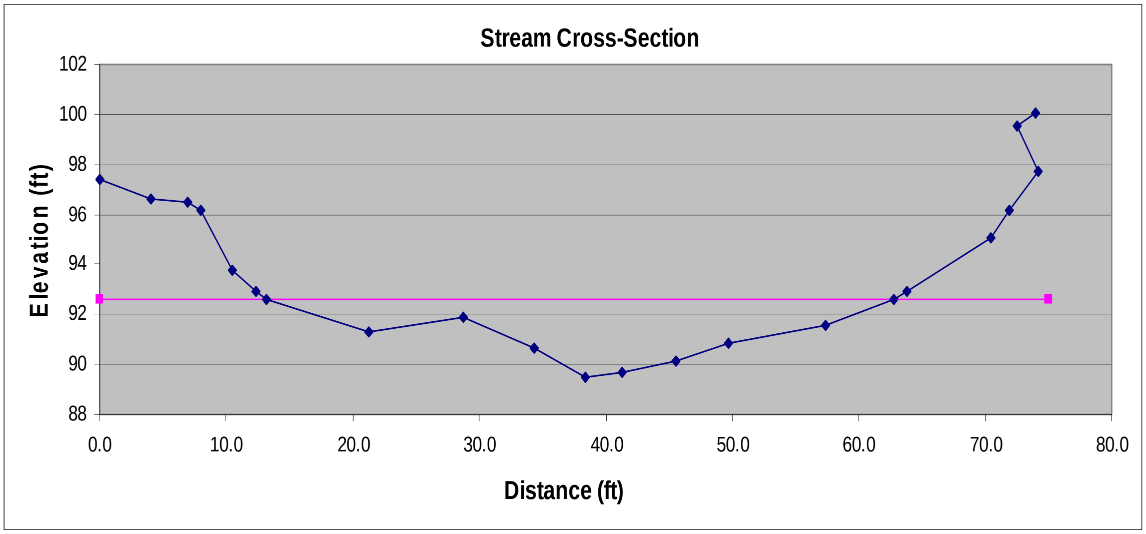

Figure 5 – Example Cross-section: East Branch of Soquel Creek at Soquel Demonstration Forest.

Table 3 – Example of Collected and Calculated Bankfull Measurements.

Distance (ft)	Elevation (ft)	Notes	Area (sq ft)	WP (ft)
0.0	97.38	RB pin		
4.0	96.62			
7.0	96.48			
8.0	96.14			
10.5	93.76			
12.3	92.94			
13.2	92.63	BFR		
21.3	91.33		5.27	8.20
28.7	91.91		7.47	7.42
34.3	90.66	WER	7.53	5.74
38.4	89.46		10.54	4.27
41.3	89.7		8.85	2.91
45.6	90.11		11.72	4.32
49.7	90.85	WEL	8.82	4.17
57.4	91.55		11.01	7.73
62.8	92.63	BFL	2.92	5.51
63.8	92.94			
70.5	95.07			
71.9	96.14	Bottom of UC		
74.2	97.69	UC		
72.5	99.56			
74.0	100.03	LB pin		
		Totals =	74.11	50.27

Table 4 – Example Summary of Cross-section and Site Measurements

Slope =	1.42%
n =	0.043
WP =	50.27
Cross-sectional area =	74.11
R =	1.47
Bank full width =	49.6
Bank full depth =	1.49
Bank full discharge =	395.57
Watershed area (sq mi) =	10.930

The slope of the stream channel and Manning's "n" were measured so that bankfull discharge can be calculated using Manning's equation:

$$Q = \frac{1.49}{n} S^{2/3} R^{1/2} A$$

Where:

R = $\frac{A}{WP}$

Q= discharge

S= slope

A= cross-sectional area

WP= wetted perimeter

Locations of the ungaged sites were well documented so that the study could be repeated and measurements could be verified. Photographs of the stream channel and bankfull indicators were taken while in the field for record (Appendix C). Detailed maps were drawn of the cross-section location including easily recognizable features, bearing of cross-section, temporary bench marks and north arrows (see Appendix D). Drainage areas were measured by digitizing the watersheds in ArcMap and calculating the geometry (Appendix A). These smaller sites were then plotted on the regional curves along with the gaged sites (Figures 5-9).

Results:

Bankfull geometry measurements collected from both gaged and ungaged sites are summarized in Table 5. Each bankfull attribute (cross-sectional area, width, depth and discharge) is plotted with respect to its corresponding drainage area on separate graphs (Figures 5-9). The regional curves presented are the least squares regression equation for each given data set. Hydraulic geometry curves from nearby regions are added for comparison purposes. Data collected from previous studies and watershed classes in Scotts Creek watershed in Swanton Pacific Ranch makes up the Scotts Creek regional curves. The Scotts Creek data was collected at different locations within the same watershed. The San Francisco Regional Curves, developed by Dunne and Leopold (1978), have also been added to the graphs and are shown by the red dashed lines. Unfortunately the only published San Francisco regional curve equation is the one for bankfull discharge, therefore all other San Francisco regional curves had to be added by copying the approximate locations of the endpoints from the text.

Table 5 – Summary of Measurements for all Sites

Type	Site	Drainage Area	Cross-Sectional Area	Width	Depth	Discharge	Recurrence Interval
Ungaged	Soquel	10.93	74.11	49.60	1.49	395.57	N/A
	San Vicente	10.50	55.71	25.40	2.19	491.62	N/A
	Opal	3.38	14.89	27.07	0.55	47.47	N/A
	Fall	4.97	30.80	19.10	1.61	212.15	N/A
Gaged	San Lor. BT	106	987.68	104.19	9.62	5136.56	2.69
	SanLor. BC	6.17	108.41	23.85	1.65	383.80	2.61
	Soquel	40.2	368.38	54.32	6.54	1827.50	1.57
	Pescadero	45.9	312.07	52.53	5.92	1352.16	1.50

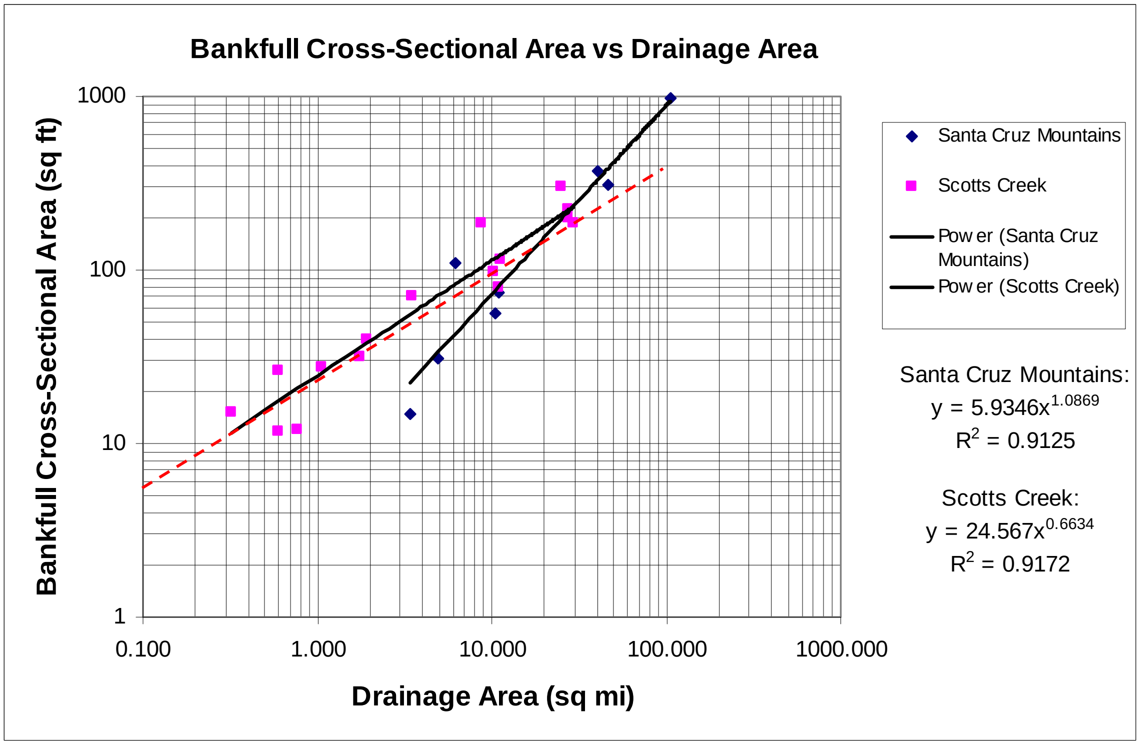

Figure 6 – Bankfull Cross-Sectional Area vs. Drainage Area Regional Curves

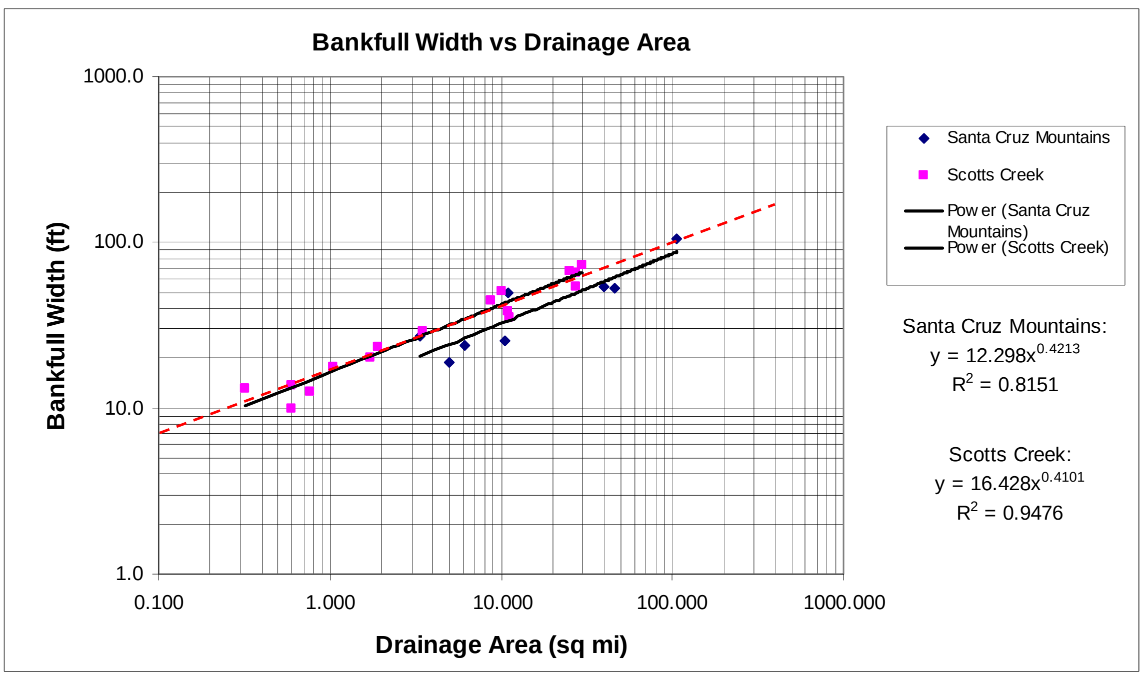

Figure 7 – Bankfull Width vs. Drainage Area Regional Curves

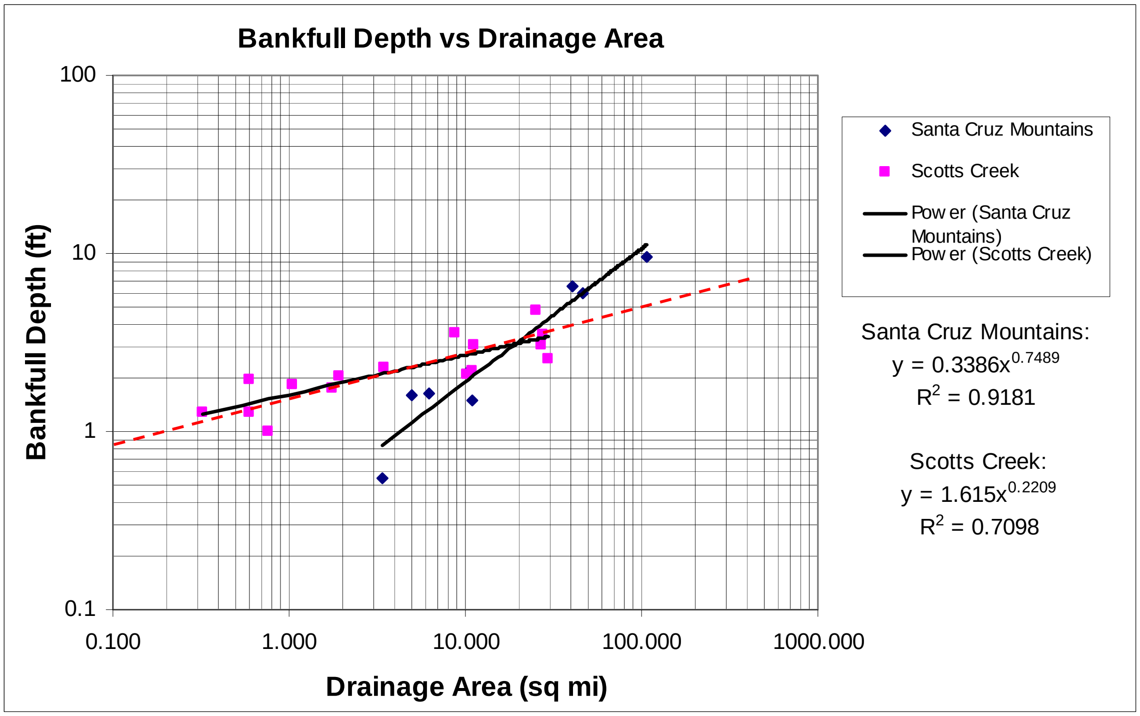

Figure 8 – Bankfull Depth vs. Drainage Area Regional Curves

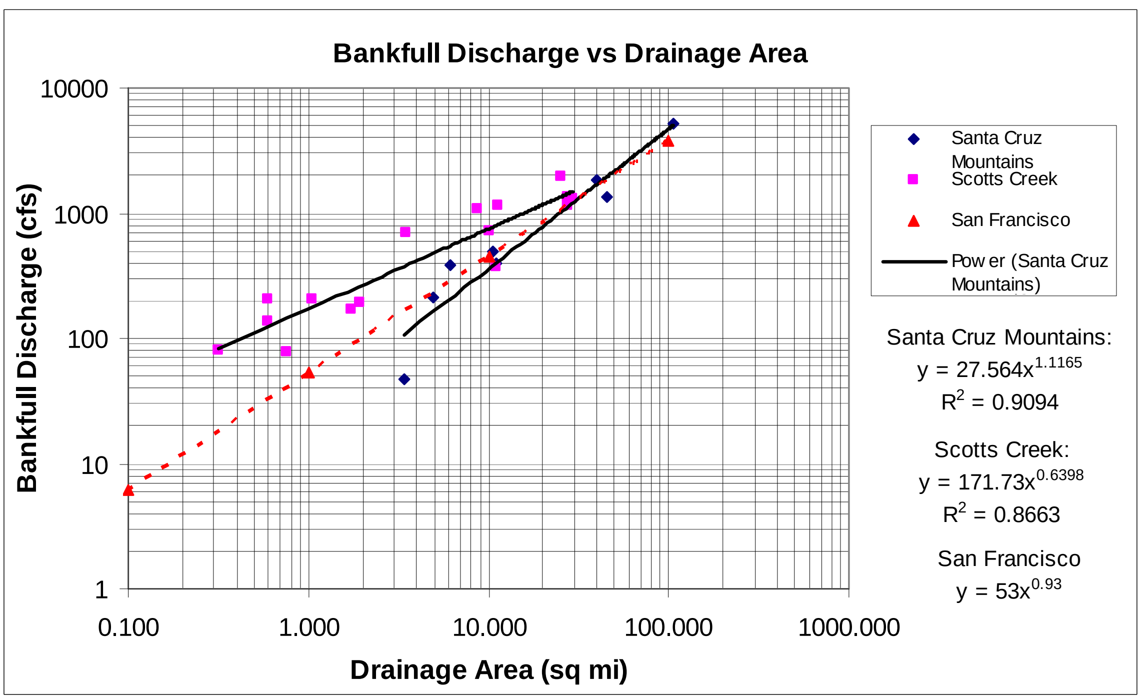

Figure 9 – Bankfull Discharge vs. Drainage Area Regional Curves

Analysis of Results:

Bankfull Calibration

Identifying bankfull levels can be a challenging task, as discussed earlier. Some issues related to bankfull determination involved unnatural stream banks, dense vegetation, and bedrock banks. The gage site at the San Lorenzo River at Big Trees was below a large bridge that caused the banks to become unnatural, making bankfull indicators difficult to find. Bankfull indicators were difficult to locate at Fall Creek and Soquel Creek at the Soquel Demonstration Forest due to dense bank vegetation and litter. A reach adjacent to the Fall Creek survey location had one bank limited by bedrock and did not reveal any clear bankfull indicators. Both Opal Creek and San Lorenzo River near Boulder Creek had clear point bars that were used as bankfull indicators.

The calibration procedure used USGS stream gage data as an aide in bankfull identification. The bankfull calibration procedure trained the surveyors in identifying bankfull at the gaged sites to make identifying bankfull at the ungaged less difficult. The recurrence intervals corresponding to the measured bankfull stages seem reasonable. Bankfull stage measured at Soquel and Pescadero Creek had corresponding recurrence intervals near 1.5 years (1.57 and 1.50 respectively). This is near the expected bankfull recurrence interval for most streams. Bankfull recurrence interval for San Lorenzo River was 2.69 at Big Trees and 2.61 near Boulder Creek. These values are at the high end of the range for expected bankfull recurrence intervals. Since the sites are on the same stream and measured very close bankfull recurrence intervals, there is good reason to accept these values.

The method of measurement of bankfull stage at the gaged locations may have incurred some error in the results. An auto level was used to measure to the bankfull level at the best bankfull indicators and then swung around to measure the corresponding stage. This method assumes that the bankfull follows a horizontal level throughout the stream, when actually it follows the same average slope of the stream. Error is magnified as distance from the bankfull indicator increases. At some of the gaged sites, multiple measurements were taken on either side of the stage plate and averaged, which may have removed some of the error. One way to account for the slope would be to measure the stage of multiple bankfull indicators on either side of the stage plate, measure the distance to the indicators from the stage plate, and then interpolate the bankfull stage at the stage plate.

Another source of error is the use of USGS 9-207 forms to determine bankfull geometry measurements because the exact location of the measurement is unknown. The method of using bankfull stage to determine other bankfull measurements using the 9-207 forms assumes that the measurement was made right at the stage plate. The cross section was probably measured some distance upstream or downstream of the stage plate, but was not recorded. Bankfull measurements may be slightly different from measurement right at the stage plate. Stream measurements were removed from the USGS online database due to this inaccuracy. According to the USGS, the stream measurements are not representative of the stream gaging station because the exact measurement location varies (USGS, 2008). The significance of this error is unknown, but could be studied by conducting cross-section surveys and comparing to the measurements from the 9-207 form.

Regional Curve Equations

Regional curve equations follow the same form (a power equation), but the coefficient and exponents differ. The values of the coefficients and exponents allow for quantitative comparison between regional curves. The equations can aid in analysis of the relationship between drainage area and the bankfull measurement. When analyzing the regional curve equations, the coefficient affects the line’s vertical position on the log-log plot while the exponent determines the slope of the line. A higher coefficient places the line higher on the plot and a higher exponent increases the slope of the line in a log-log plot. A higher coefficient causes the dependent variable to increase at a faster rate as the dependent variable increases. When the exponent is greater than one, it means that the dependent variable increases at an increasing rate as the independent variable increases. An example of this is found in the equation for Discharge vs. Drainage Area where discharge increases at an increasing rate as drainage area increases. When the exponent is less than one, such as in the equation for Depth vs. Drainage Area, it means that the dependent variable increases at a decreasing rate as the independent variable increases. If the exponent had equaled one, it would signify that the dependent variable increases at an even rate as the dependent variable increases. This also means that for regional curves with exponents greater than one, the bankfull measurement increases slowly at low drainage areas, but fast at large drainage areas and visa versa for exponents less than one.

Santa Cruz Mountains Regional Curves

Equations for the four regional curves for the Santa Cruz Mountains Region are shown on each respective graph along with their R^2 values. The R^2 value is the proportion of variability in the dependent variable that can be explained by the independent variable. The R^2 values for the Santa Cruz Mountains Regional Curves range from 0.82 to 0.92. This range of R^2 values demonstrates a reasonably high correlation between drainage area and bankfull geometry measurements.

All exponents in the regional curve equations are close to one or less than one. The exponent for the regional curve for discharge should be less than one because bankfull discharge does not increase as fast as drainage area (Dunne and Leopold, 1978). This is because storms do not occur evenly over a watershed, so the land area contributing to discharge must increase at a faster rate than the discharge. If discharge increases at a lower rate than drainage area, the regional curves for the other measurements should also have exponents less than one. This is because bankfull width, depth and cross-sectional area generally increase at a lower rate than discharge.

Because sample size is small (8), the power of the regression equation is fairly low. To increase the power of the regression equation, more measurements should be taken at various sites throughout the Santa Cruz Mountains. It would be best to measure sites with a wide range of drainage areas so that the regional curves could be applied to a wide range of project sites. It is not a good idea to extrapolate beyond the range of available data because it is uncertain how the variables will respond outside of the measured range.

The data points are not expected to all fall on the curves because streams naturally have different channel shapes. Some streams are deep and narrow while others are wide and shallow. A stream with a higher width-to-depth ratio will plot a relatively high width and low depth for its drainage area and visa versa. One way to reduce this variability about the regional curve is to classify the streams and develop separate curves for each stream classification. Stream channel classification categorizes streams by channel shape as well as other parameters.

Comparison with Pre-existing Regional Curves

Compared to the regional curves created for Scotts Creek, the slopes of the regional curves for the Santa Cruz Mountains are steeper, meaning higher exponents. The regional curves with the closest slopes are found in the plot of Width vs. Drainage Area. The exponents are 0.4213 for the Santa Cruz Mountains and 0.4101 for Scotts Creek. Regional curve equations with higher exponents mean that the bankfull measurement increases faster as drainage area increases than equations with lower exponents. The differences may be due to the fact that the Scotts Creek data only represents one watershed, while the Santa Cruz Mountains Data includes many watersheds. All streams have different channel geometry that may affect bankfull measurements. An incised or entrenched channel has less horizontal space to increase its width than a channel that is not incised. The relationship between cross-sectional area and discharge may change due to roughness of the channel. As roughness increases, cross-sectional area increases because velocity is decreased. Bankfull cross-sectional area measured in a stream with a high roughness coefficient will be greater than in a stream with a low roughness coefficient. Depth is dependent on both width and cross-sectional area and therefore, may be affected by either incision or channel roughness. A possible interpretation of the lower slope of Scotts Creek regional curves is that Scotts Creek is incised and has a low roughness coefficient throughout the stream compared to most of the streams measured for the regional curves for the Santa Cruz Mountains.

The regional curves for Scotts Creek fit better to the San Francisco Regional Curves both in slope and vertical placement than the regional curves for the Santa Cruz Mountains except for the regional curve for discharge. This may be because some data from Scotts Creek was discarded when plotting the regional curves due to error or uncertainty. It may be interesting to further investigate how the regional curves would change if some of this data was added back in to the graphs.

Conclusion:

The regional curves developed for the Santa Cruz Mountains have a reasonably high probability of correctly predicting bankfull measurements given drainage area, as is evident by the reasonably high R^2 values. Although the exponents in the regional curve equations are close to one, each exponent should all technically be less than one. With increased sample size, the regional curves should be able to more accurately predict bankfull measurements. Stream channel classification may help further define the regional curves according to channel shape.

The regional curves for the Santa Cruz Mountains have steeper slopes than both Scotts Creek and San Francisco regional curves due to higher exponents. This may be explained by differences in channel geometry and roughness or by the selection process of the data.

The regional curves of the Santa Cruz Mountains could be used for rough estimations of bankfull measurements, but should be further developed and analyzed before fully relying on these curves for engineering purposes. This study could be repeated to verify accuracy of cross-section measurements and bankfull identification. Multiple hydrologists well trained in identifying bankfull could assist surveyors in accurately identifying bankfull. At the gaged sites, full stream cross-sections could be conducted so that errors from the 9-207 forms can be avoided. Accuracy could also be increased by measuring bankfull stage at gaged sites by accounting for the slope of the stream according to the method described in the “Bankfull Calibration” section.

Additionally, more stream sites could be surveyed and added to the regional curves by following the same procedure. An analysis could be performed to determine how well the new site data aligns with the data collected in this study. A statistical analysis could be performed on the various regional curves once the Santa Cruz Mountains regional curves are further developed, to determine if the Santa Cruz Mountains regional curves are significantly different from the Scotts Creek and San Francisco regional curves.

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Appendices

Appendix A: Maps of All Site Locations

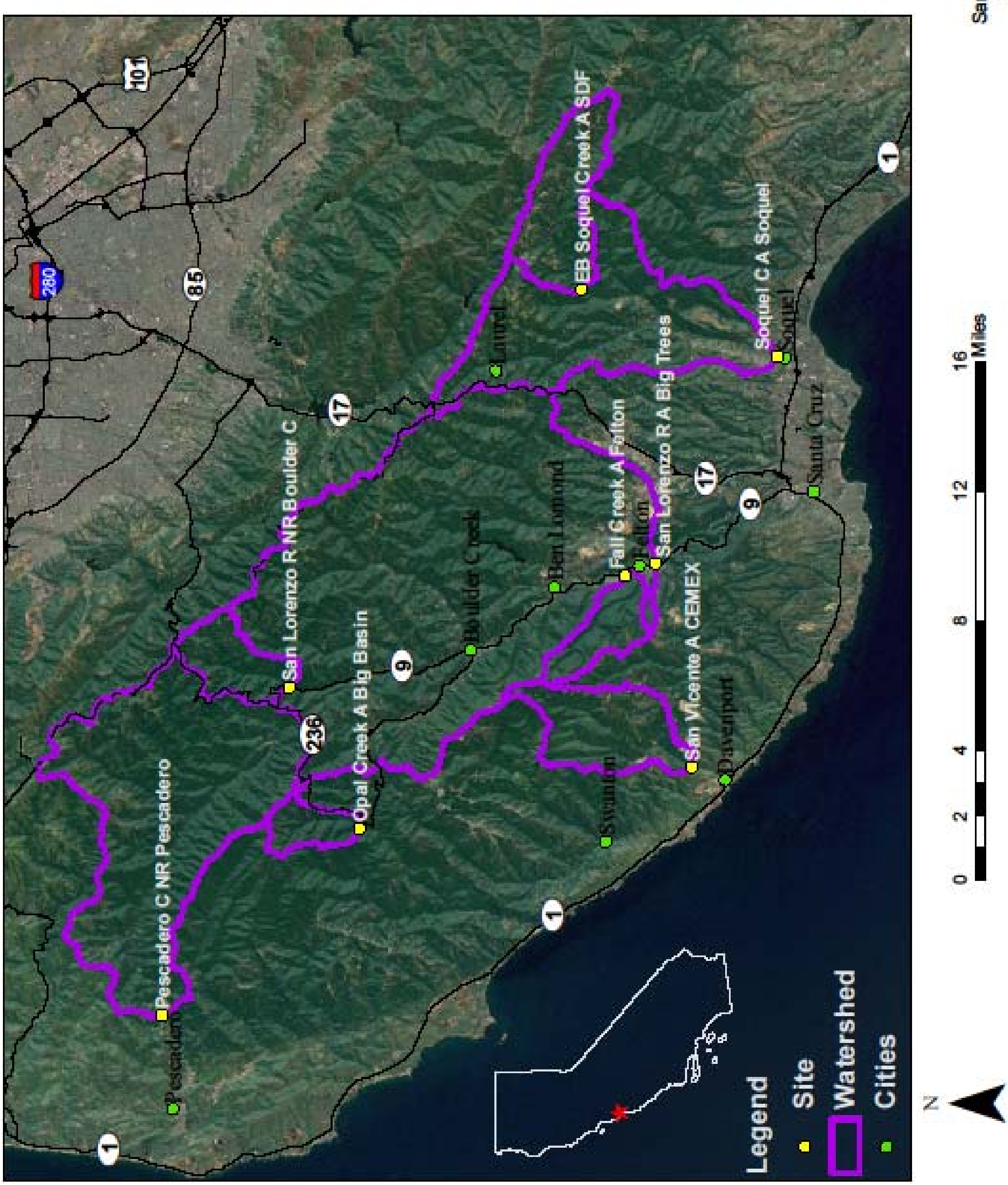
Appendix B: Cross-Section Data and Site Summaries for Ungaged Sites

Appendix C: Cross-Section Photos for Ungaged Sites

Appendix D: Detailed Hand Drawn Maps of Ungaged Sites

Appendix A

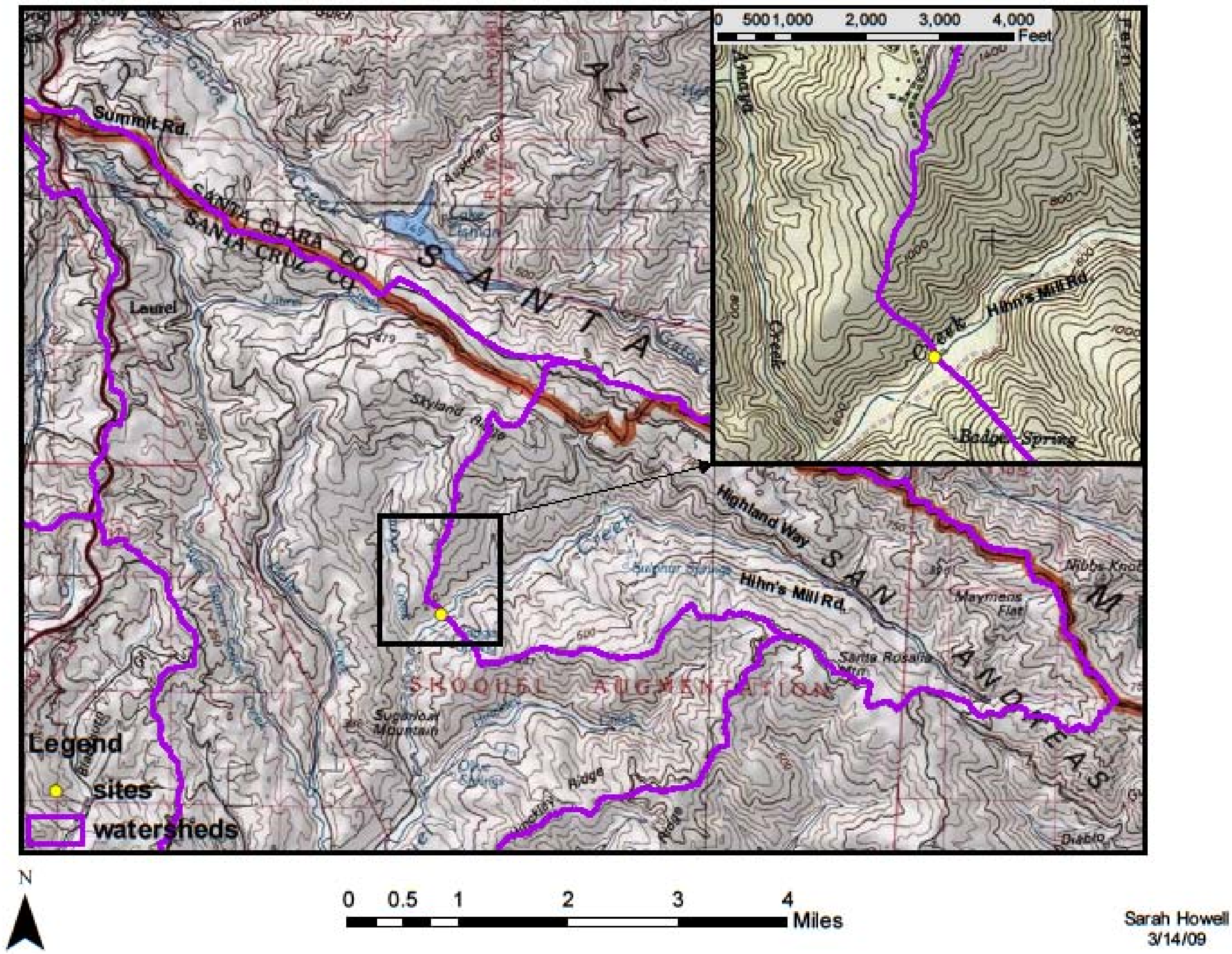
Measured Sites and Watersheds
Santa Cruz Mountains, CA



Sarah Howell
3/13/09

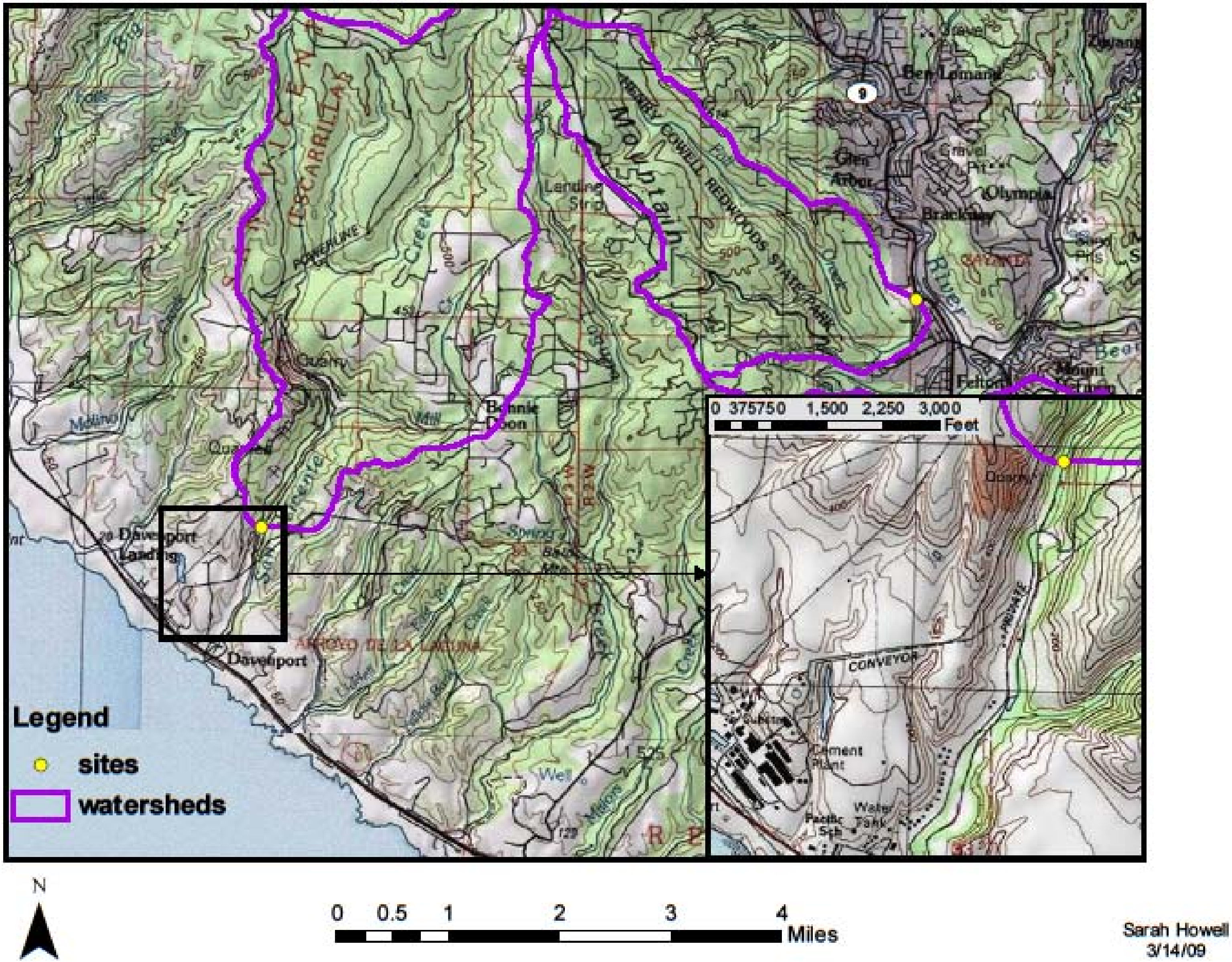
EB Soquel C A SDF, CA

Ungaged Site



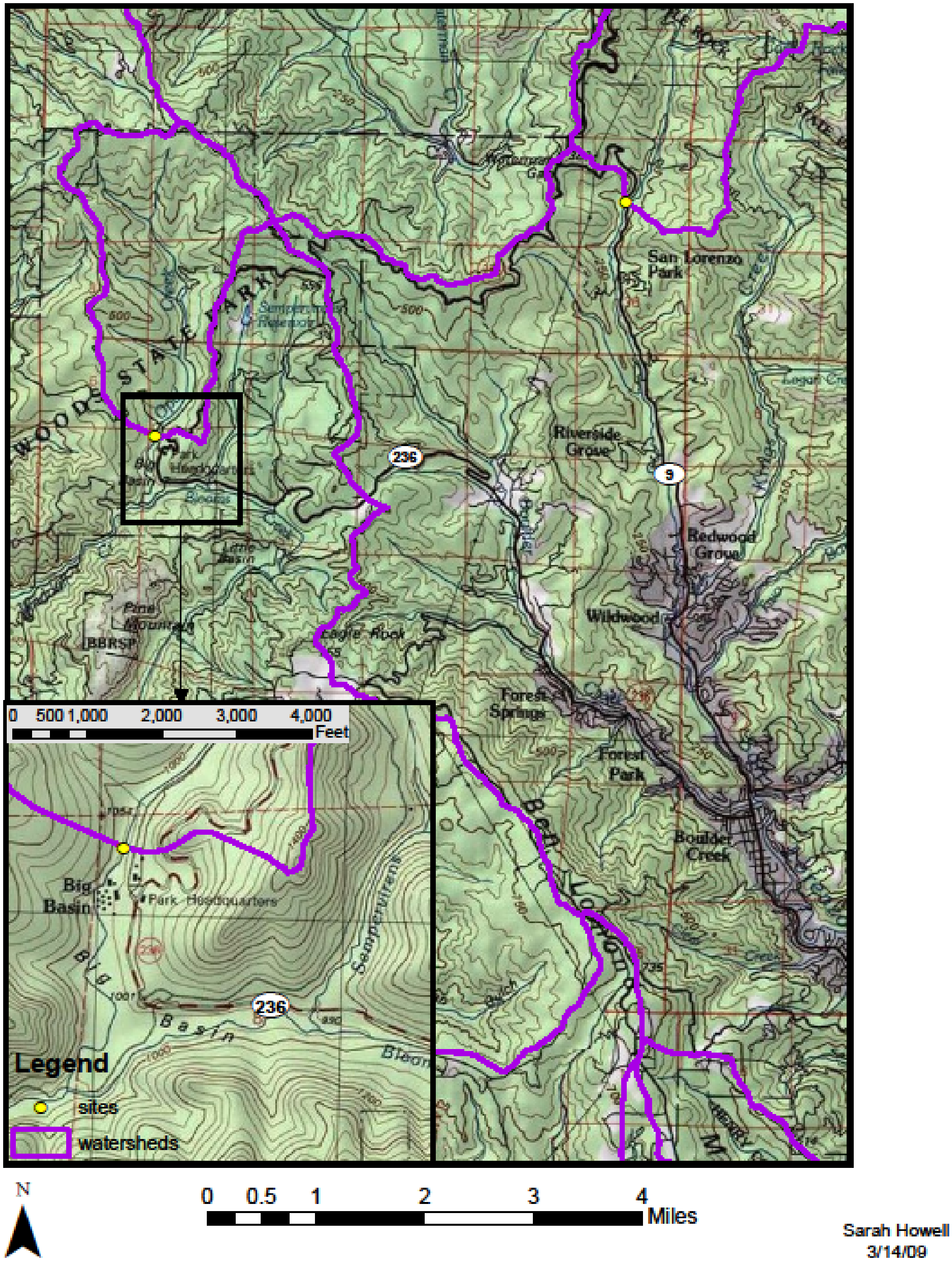
San Vicente A CEMEX

Ungaged Site



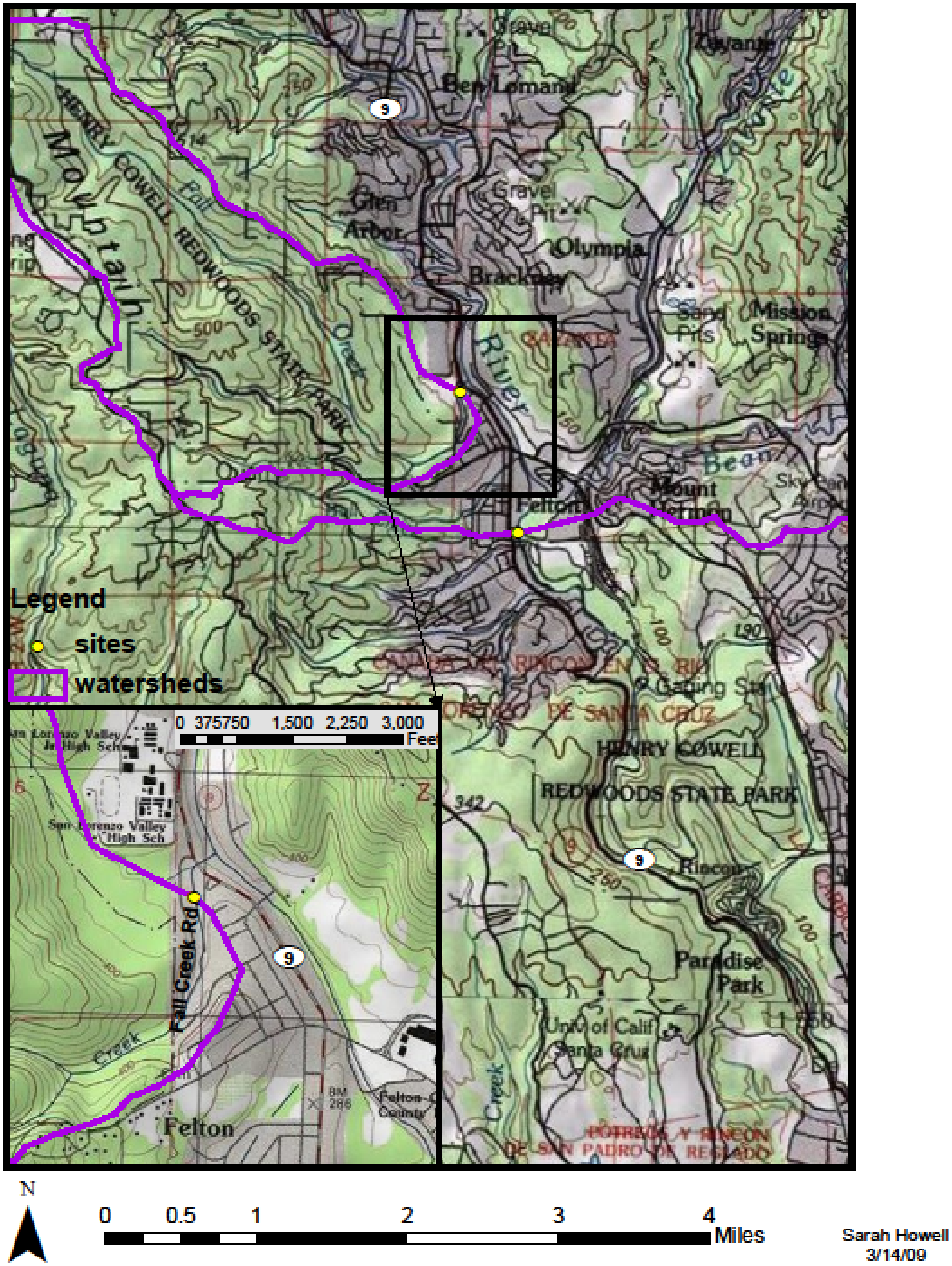
Opal Creek in Big Basin Redwoods State Park, CA

Ungaged Site



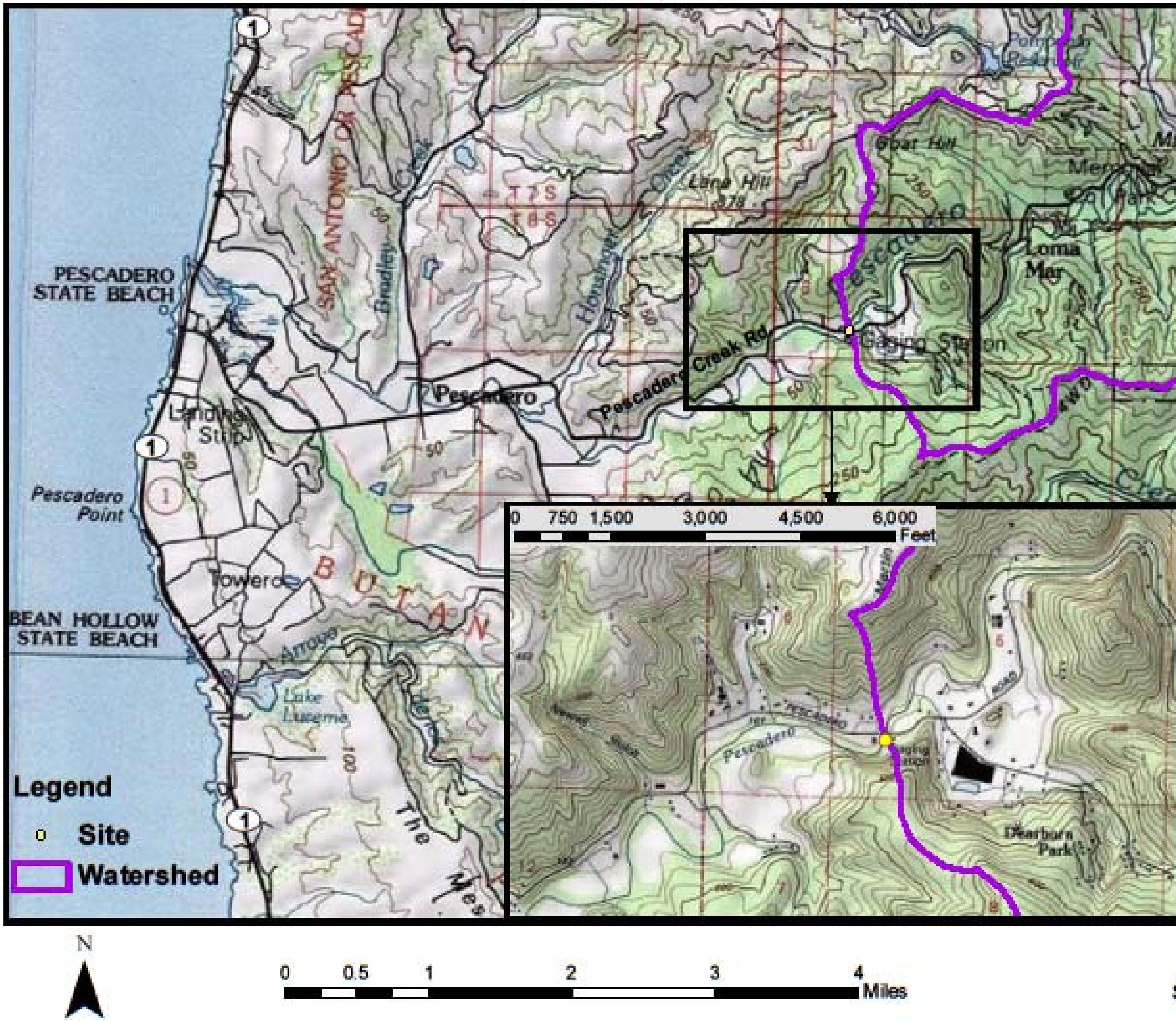
Fall Creek Near Felton, CA

Ungaged Site



Pescadero C NR Pescadero, CA

USGS Gaging Station 11162500



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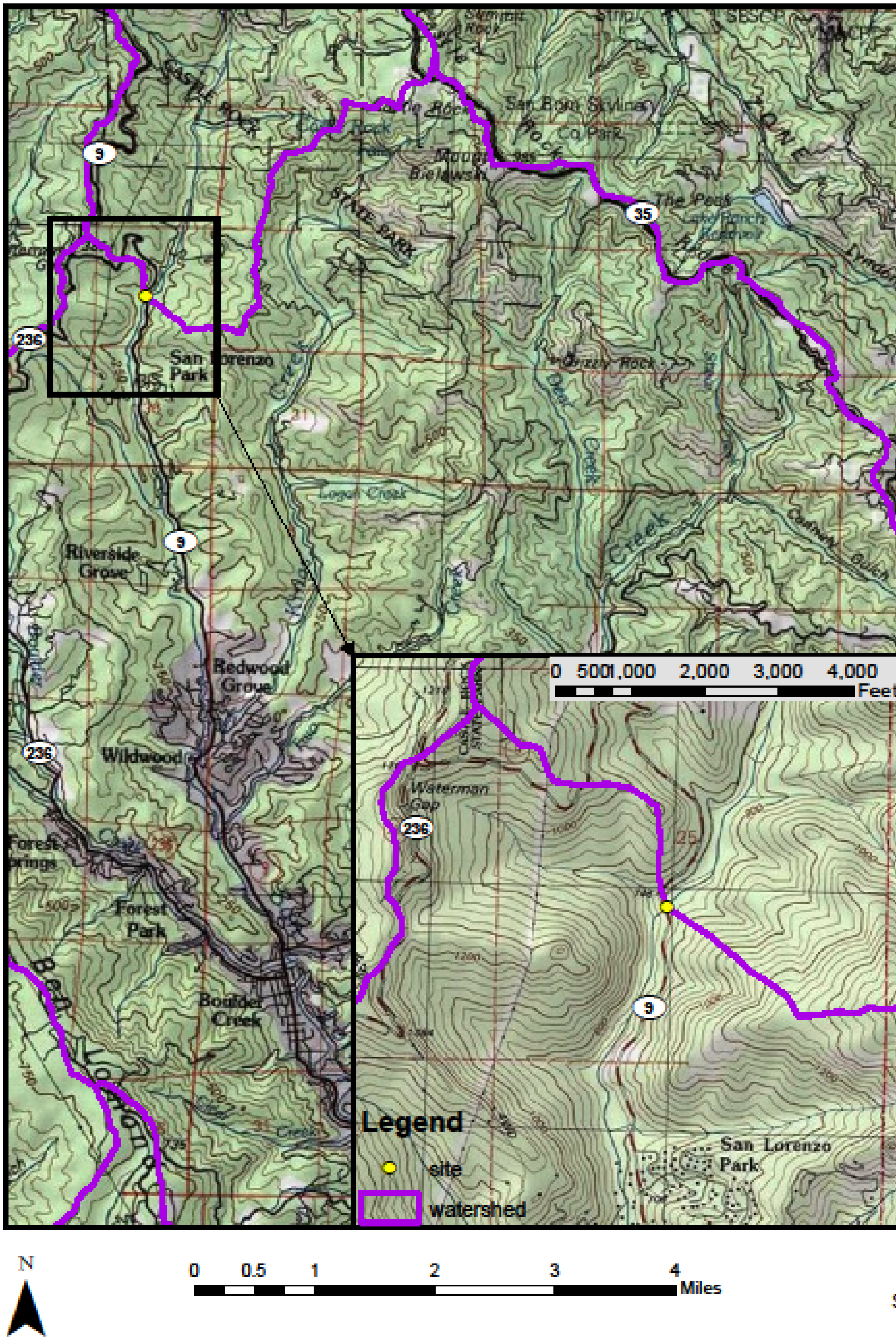
San Lorenzo R NR Boulder C, CA

USGS Gaging Station 11160020



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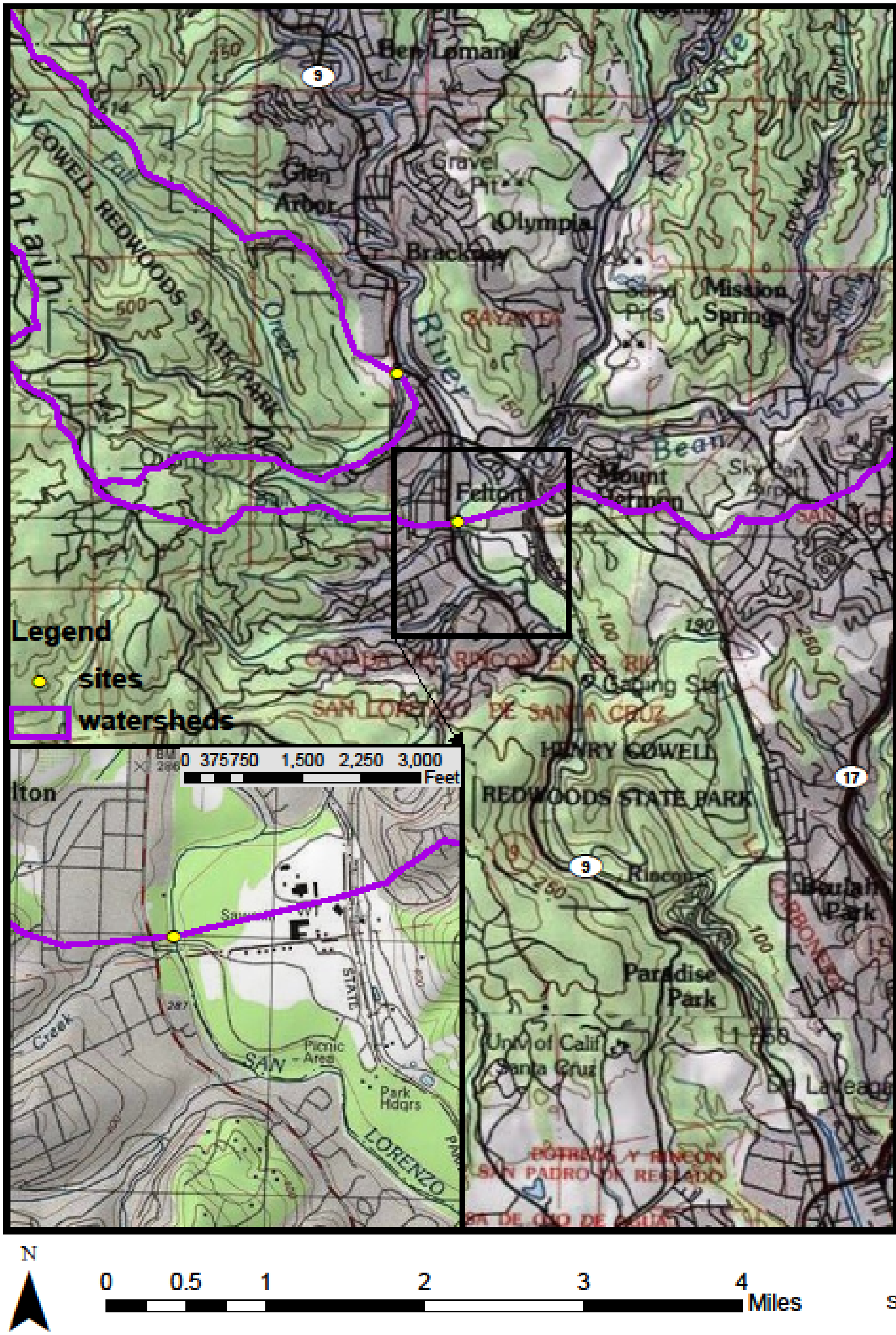
San Lorenzo R A Big Trees, CA
USGS Gaging Station 11160500



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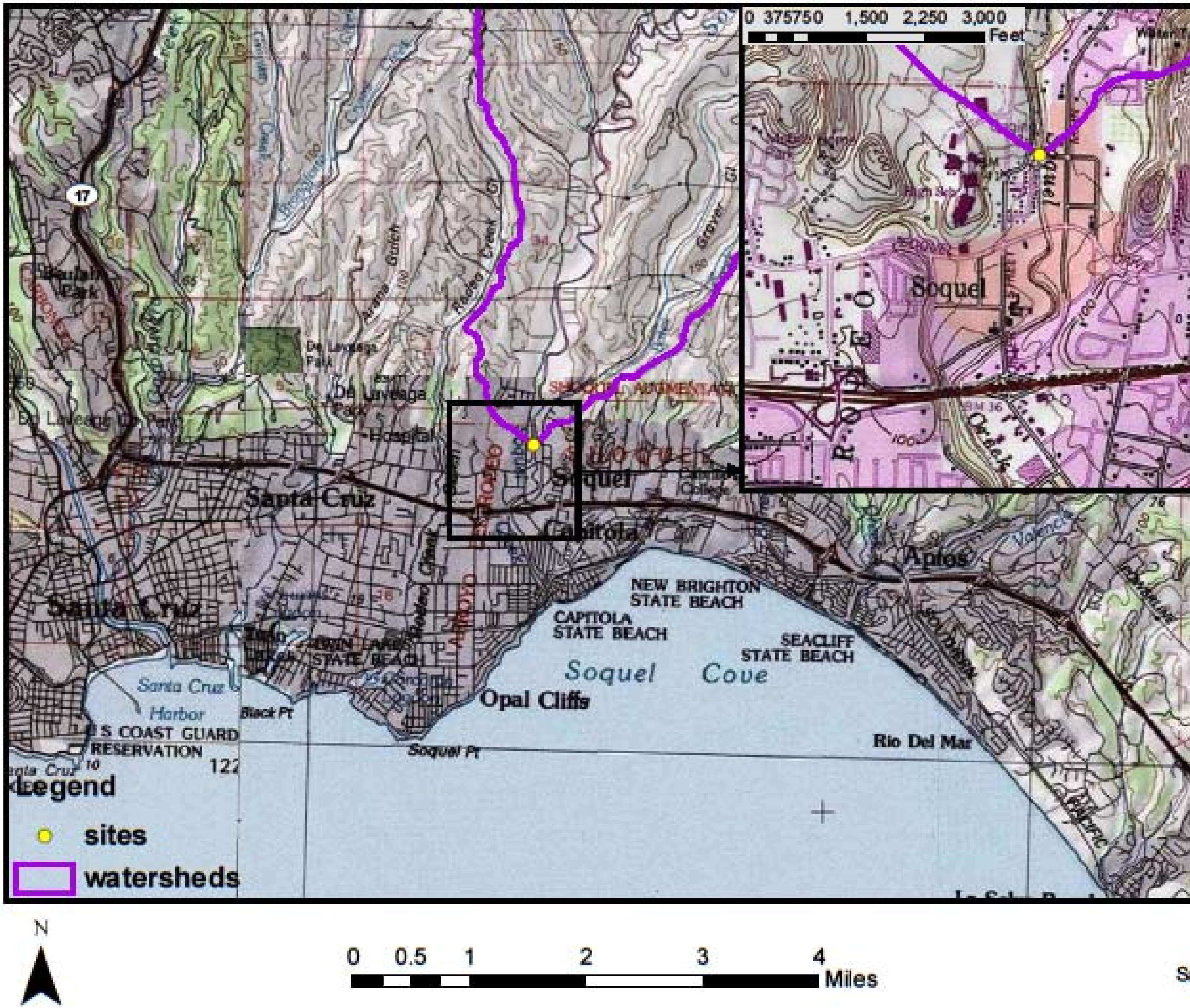
Soquel C A Soquel, CA

USGS Gaging Station 11160000



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3/14/09

Appendix B

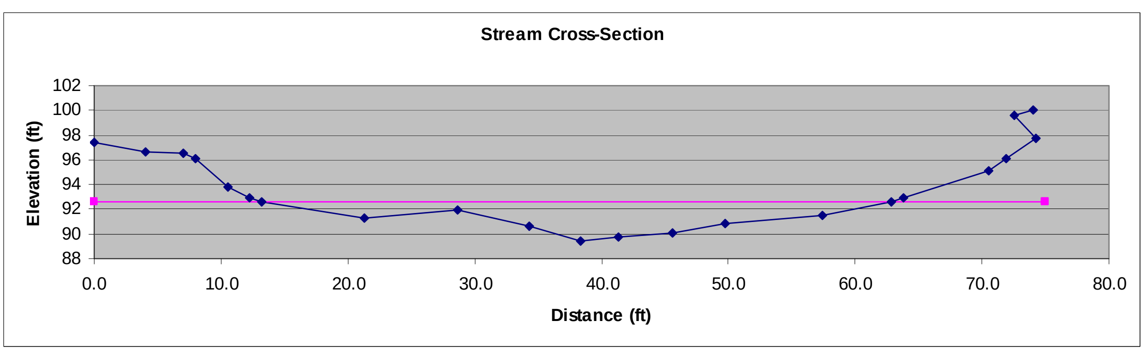
EB Soquel C A SDF, CA

East Branch of Soquel Creek at Long Ridge Road crossing in Soquel Demonstration Forest

Field Cross-Section Data, Site Summary, and Stream Profile

Distance (ft)	Elevation (ft)	Notes	Area (sq ft)	WP (ft)
0.0	97.38	RB pin		
4.0	96.62			
7.0	96.48			
8.0	96.14			
10.5	93.76			
12.3	92.94			
13.2	92.63	BFR		
21.3	91.33		5.27	8.20
28.7	91.91		7.47	7.42
34.3	90.66	WER	7.53	5.74
38.4	89.46		10.54	4.27
41.3	89.7		8.85	2.91
45.6	90.11		11.72	4.32
49.7	90.85	WEL	8.82	4.17
57.4	91.55		11.01	7.73
62.8	92.63	BFL	2.92	5.51
63.8	92.94			
70.5	95.07			
71.9	96.14	Bottom of UC		
74.2	97.69	UC		
72.5	99.56			
74.0	100.03	LB pin		
		Totals =	74.11	50.27

Slope =	1.42%
n =	0.043
WP =	50.27
Cross-sectional area =	74.11
R =	1.47
Bank full width =	49.6
Bank full depth =	1.49
Bank full discharge =	395.57
Watershed area (sq mi) =	10.930



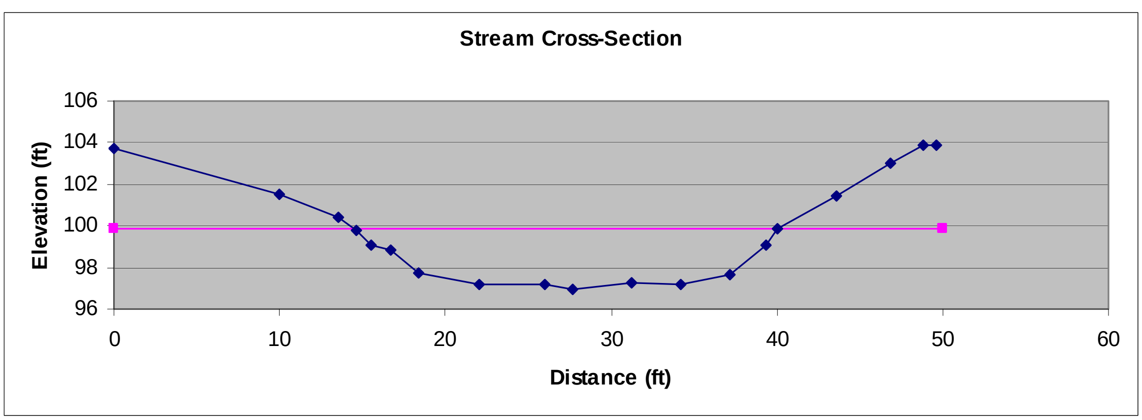
San Vicente A CEMEX

San Vicente Creek on CEMEX property northeast of Davenport, CA

Field Cross-Section Data, Site Summary, and Stream Profile

Distance (ft)	Elevation (ft)	Notes	Area (sq ft)	WP (ft)
0	103.74	LB pin		
10	101.53			
13.5	100.44			
14.6	99.81	BFL		
15.5	99.04		0.36	1.18
16.7	98.8		1.08	1.22
18.4	97.7	WEL	2.67	2.02
22	97.18		8.57	3.64
26	97.18		10.56	4.00
27.7	96.93		4.70	1.72
31.2	97.24		9.57	3.51
34.2	97.19		7.82	3.00
37.2	97.69	WER	7.14	3.04
39.3	99.1		2.99	2.53
40	99.82	BFR	0.25	1.00
43.6	101.4			
46.9	102.97			
48.8	103.9			
49.6	103.84	RB pin		
		Totals =	55.70	26.88

Slope =	1.73%
n =	0.036
WP =	26.88
Cross-sectional area =	55.71
R =	2.07
Bank full width =	25.4
Bank full depth =	2.19
Bank full discharge =	491.62
Watershed area (sq mi) =	10.501

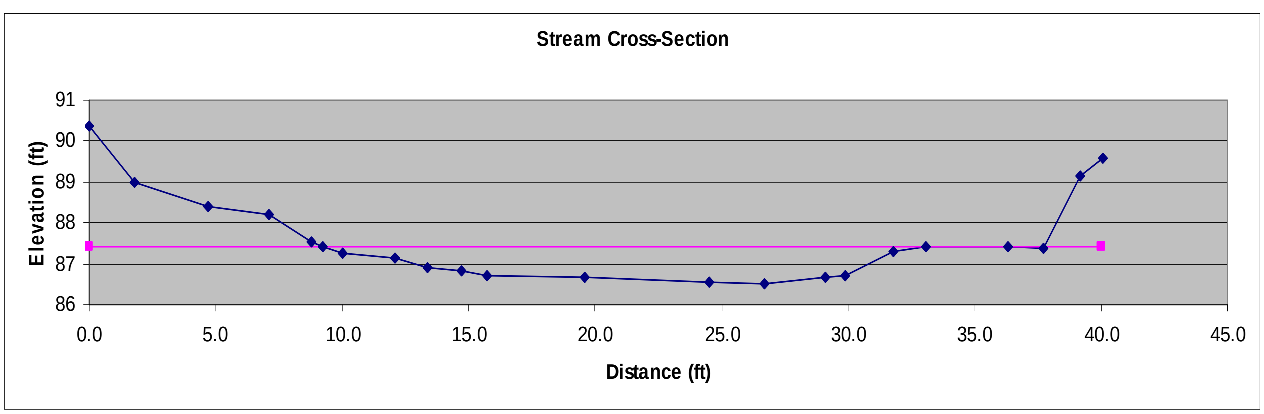


Opal C A Big Basin
Opal Creek at Big Basin State Park northwest of park headquarters

Field Cross-Section Data, Site Summary, and Stream Profile

Distance (ft)	Elevation (ft)	Notes	Area (sq ft)	WP (ft)
0.0	90.36	LB pin		
1.8	89.01			
4.7	88.42			
7.1	88.2			
8.8	87.52			
9.2	87.43	BFL		
10.0	87.27		0.06	0.79
12.1	87.16		0.45	2.10
13.4	86.92		0.51	1.32
14.7	86.83		0.72	1.30
15.7	86.69	WEL	0.67	1.01
19.6	86.68		2.91	3.90
24.5	86.55		3.99	4.90
26.7	86.53		1.96	2.20
29.1	86.65	WER	2.02	2.40
29.9	86.7		0.60	0.80
31.8	87.28		0.84	1.99
33.1	87.4		0.12	1.31
36.3	87.43	Top of bar, BFR	0.05	3.20
37.7	87.37			
39.2	89.16			
40.1	89.6	RB pin		
		Totals =	14.89	27.22

Slope =	0.75%
n =	0.027
WP =	27.22
Cross-sectional area =	14.89
R =	0.55
Bank full width =	27.1
Bank full depth =	0.55
Bank full discharge =	47.47
Watershed area (sq mi) =	3.38



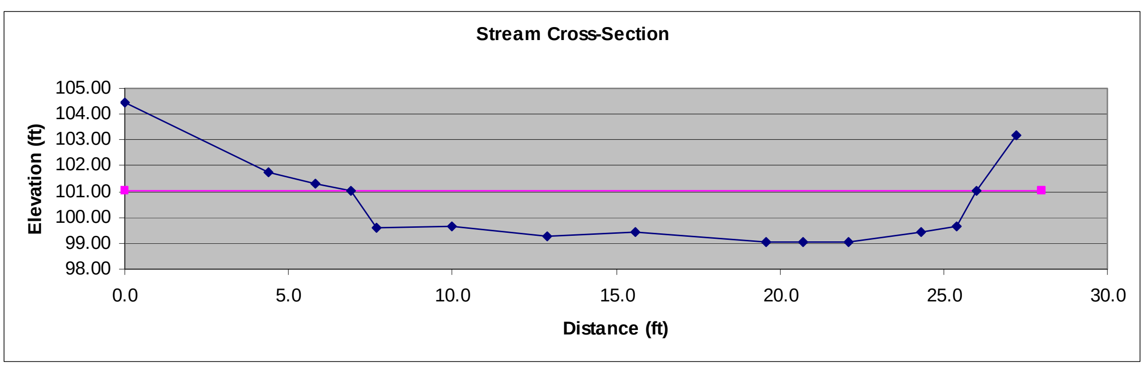
Fall C A Felton, CA

Fall Creek at Felton near Fall Creek Drive

Field Cross-Section Data, Site Summary, and Stream Profile

Distance (ft)	Elevation (ft)	Notes	Area (sq ft)	WP (ft)
0.0	104.47	LB pin		
4.4	101.77			
5.8	101.28			
6.9	101.02	BFL		
7.7	99.60	WEL	0.57	1.63
10.0	99.67		3.19	2.30
12.9	99.28		4.48	2.93
15.6	99.41		4.52	2.70
19.6	99.07		7.12	4.01
20.7	99.02		2.17	1.10
22.1	99.02		2.80	1.40
24.3	99.45	WER	3.93	2.24
25.4	99.65		1.62	1.12
26.0	101.02	BFR	0.41	1.50
27.2	103.20	RB pin		
		Totals =	30.80	20.93

Slope =	2.37%
n =	0.043
WP =	20.93
Cross-sectional area =	30.80
R =	1.47
Bank full width =	19.1
Bank full depth =	1.61
Bank full discharge =	212.15
Watershed area (sq mi) =	4.97



Appendix C

1. Photos of Cross-Section at EB Soquel C A SDF

Looking upstream

Looking downstream


From right bank

Temporary bench mark

2. Photos of Cross-Section at San Vicente A CEMEX

Looking upstream

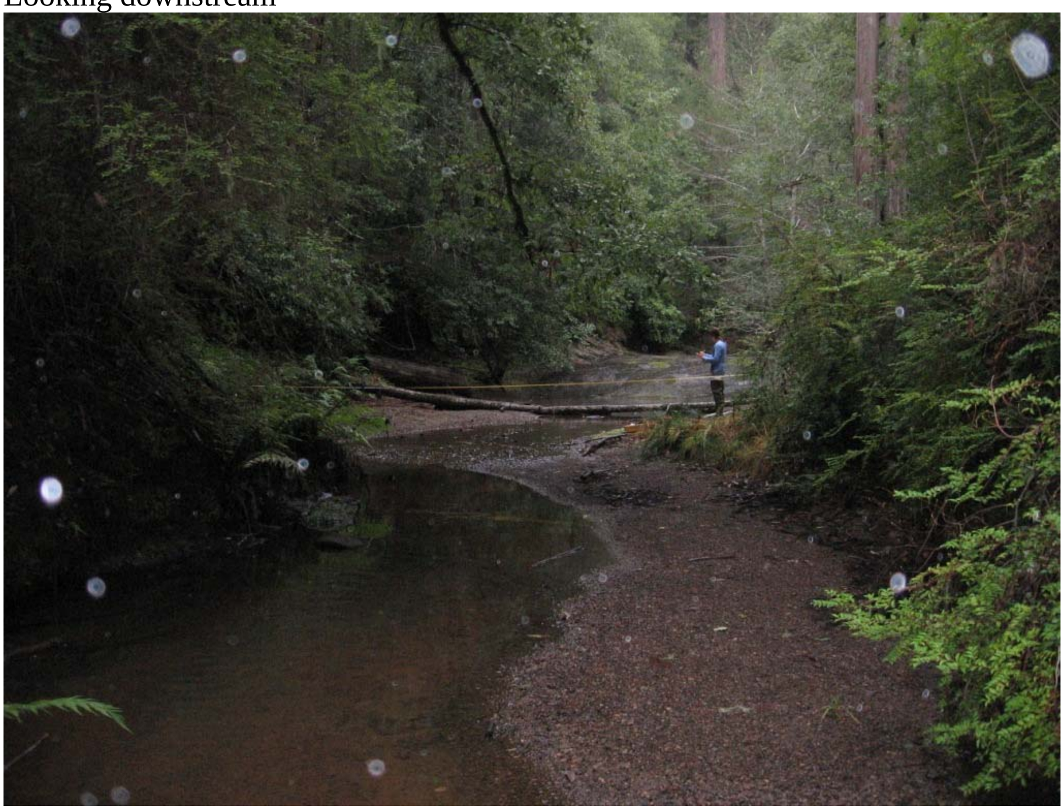
Looking downstream


From right bank

From left bank

3. Photos of Cross-Section at Opal C A Big Basin

Looking downstream



Looking upstream


From right bank

From left bank

Temporary bench mark

Path to Opal Creek

Path to bridge

4. Photos of Cross-Section at Fall C A Felton, CA

Looking upstream

Looking downstream and shot to temporary benchmark

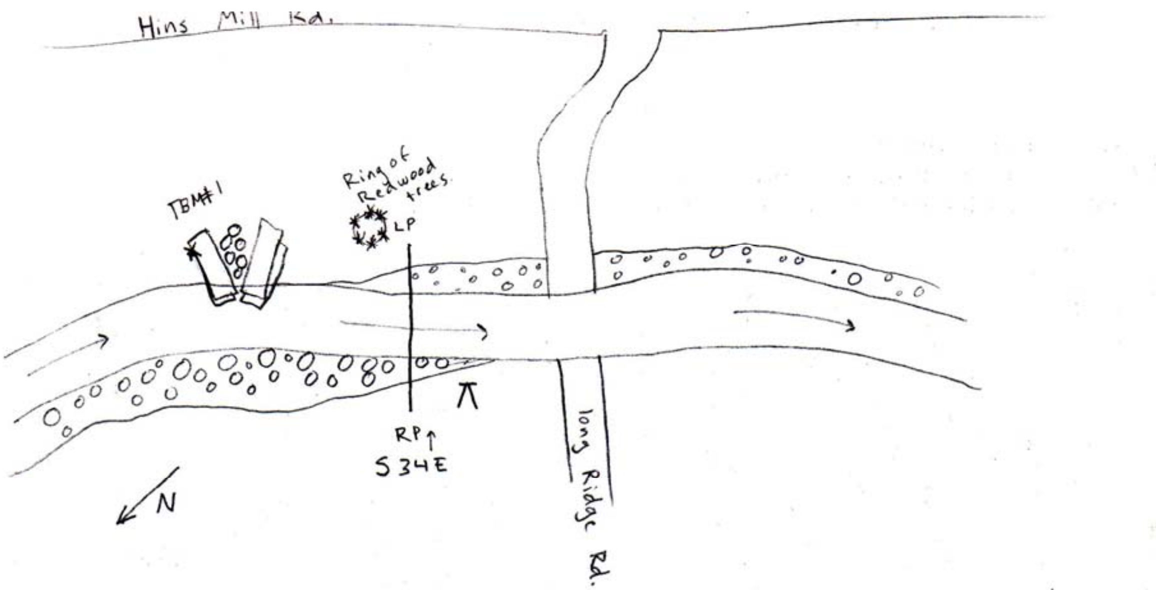

From left bank

From right bank


Temporary bench mark

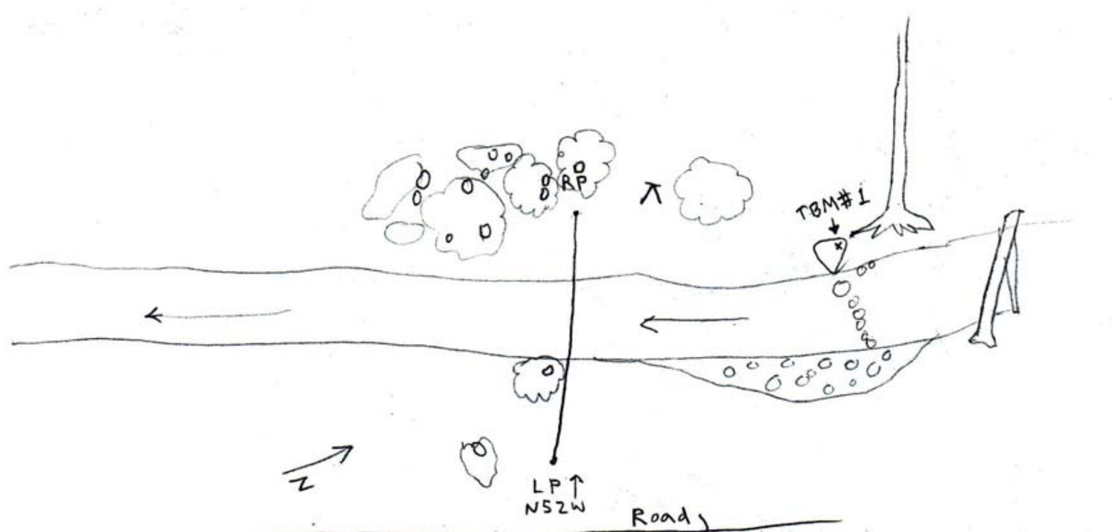
Appendix D

1. Detailed Hand Drawn Map of EB Soquel C A SDF, CA



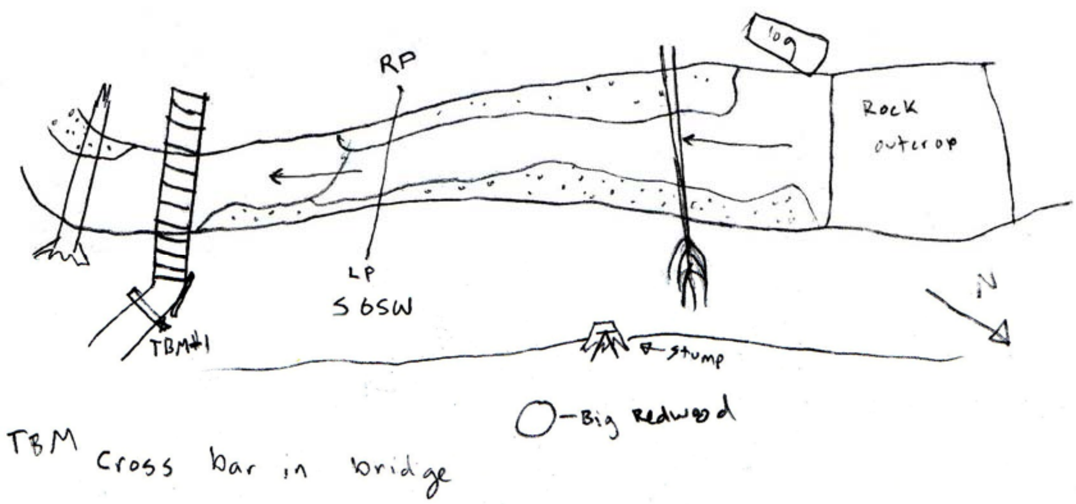
TBM#1 Large Redwood log in bunch of four. Upstream top log at branch node on upper, upstream end.

2. Detailed Hand Drawn Map of San Vicente A CEMEX



TBM#1 Largest rock immediately downstream of alder root wad. Highest point. Bright green moss covering rock.

3. Detailed Hand Drawn Map of Opal C A Big Basin



4. Detailed Hand Drawn Map of Fall C A Felton, CA