Introduction

During the months of March and April 2004, I spent a total of four days working in a small reach of Redwood Creek located on the southern slope of Mt. Tamalpais in Marin County. The reach of the creek where I performed this study is directly adjacent to southern boundary of Muir Woods in the Golden Gate National Recreation Area. Redwood Creek reaches the Pacific Ocean at Muir Beach, less than two miles downstream from where I was working. The type of study that I set out to conduct is mainly based on flow measurements taken in the field. Inspired by the chapter on *Water and Sediment in Channels* in Fluvial Processes in Geomorphology by Leopold et al., I set out to study the geomorphic effects of flow in a channel. Keeping in mind the equipment, manpower, and amount of time I had to conduct the study I decided that the most effective way to observe geomorphic effects of flow in a channel was to do so on a very small scale. Ultimately I chose a two hundred foot reach of Redwood Creek below a concrete overpass as my study area. After considering a number of different localities in the creek, I settled on this one because flow in the channel exhibited a relatively high amount of complexity in a very short reach of the creek. This location proved to be ideal for making detailed observations about the nature of flow on a small scale and relating those observations to erosion in the channel. Another factor that influenced my choosing this reach of the creek was my interest in examining the effects of the concrete bridge, the foundation of which is in the channel, on flow.

Goals of the Study

Officially stated, the goals of this study are:

1. To determine direction, magnitude, and nature of flow in different parts of the channel and use that data to explain current geomorphic features and to predict future erosion in the channel.
2. To determine the interaction between the bridge and flow in the channel.

In attempting to achieve these goals, one of the main focuses of the study became the construction of a flow diagram that maps flow direction and magnitude (fig 1).

Methods

The first step in collecting data for this project was to tie off a measuring tape and decide on intervals for flow data collection. The measuring tape was tied off at a log that had fallen across the width of the channel. This log, located about 100 feet upstream from the center of the bridge, became station 0. It was decided that the study area would encompass the 100 feet from the log to the bridge and then continue another 100 feet past the center of the bridge as this constitutes a reasonable reach of stream that contains a fair amount of flow complexity. Initially, to assess the nature of flow, I decided to take measurements with a current meter at five foot intervals along the 200 foot reach. These measurements were taken from the thalveg at each interval. At intervals where flow appeared to differ in velocity significantly across the width of the channel, a second flow measurement was taken from a point outside of the thalveg. At each interval, after flow measurements were taken, I spent an average of 10-15 minutes standing in the channel and walking back and forth across the width of the channel making observations about flow. Rather than using a single set method for observing flow across the width of the channel, I adapted my methods here to whatever seemed necessary to make an assessment of flow that was detailed enough and accurate enough to have geomorphic implications. For example, at station five, flow appeared to be concentrated mainly to the right side of the channel. Things such as ripples on the water's surface and debris in the channel appeared to be moving fastest on the right side of the channel. So I took a depth reading with the current meter in the middle of the right part of the channel. I moved the current receiver (the small fan on the base of the rod to the current meter) around a little bit to find the part of the channel and the direction that appeared to cause the current receiver to move steadily at the fastest rate possible. Once I determined the thalveg, I took a flow reading. In this case the current receiver exhibited the highest reading when faced not directly upstream, but at about a 30 degree angle towards the right bank. Then, walking across the width of the channel, I would place the current receiver in the creek at other points confirming the apparent direction and magnitude of flow relative to the numerical measurement taken at the thalveg. If I was satisfied with my interpretation of flow at this interval, I would draw a series of four or five arrows across the channel on a rough flow diagram. The first arrow, towards the right bank, would represent the measured velocity of .55ft/sec and would point approximately 30 degrees toward the left bank. Since the current receiver gradually exhibited less motion and smaller angles as it was placed closer to the left bank, arrows would be drawn accordingly on the flow diagram relative to the more official "thalveg" arrow.

In a situation such as station fifteen, where flow exhibited noticeably different velocity and direction across the width of the channel, two flow readings were taken from different points in the channel and the flow diagram for that interval was made relative to both measurements. Thus, the completed flow diagram (fig 1) is meant to be looked at as a relative and non-scalar overview of the direction and magnitude of flow in the channel and is not sufficient for picking out a certain arrow and trusting it's implied angle and velocity as verified scientific data.

Many pages of notes were taken in the field pertaining to erosion in the channel, vegetation, bank material, bed material, interaction between the channel and the bridge, and so on. These notes are not included in this report as data but are the basis for the interpretation of flow and erosion in the channel.

Data

Table 1 contains depth and flow measurements from each interval within the channel. If the thalveg was more or less in the middle of the channel the position of the measurement is not noted. If the thalveg was not in the middle of the channel or a measurement was taken from outside the thalveg, the position in the channel that the measurement was taken from is noted in the description column. The description column also notes the locations of bars, pools, and other channel characteristics.

General Characteristics of the Channel

In the reach of Redwood Creek that was studied, the width of the channel varied between about 12 and 20 feet. The wet width of the channel, as recorded in mid-April, varied between about 4 and 15 feet. The depth of the creek in this reach was found to vary anywhere between 0.2 feet and 1.3 feet. The banks are steep and are composed of fairly uniformed mud that is very compacted. In sections of the reach, the banks are covered by a dense layer of cobbles. These cobbles, which range in diameter from about 3-10 inches, are very common throughout the channel. Bars in the channel are composed almost completely of cobbles and mud. Foliage on and directly above the banks is mainly ferns and ivy (photo 6). There is generally 1-2 feet of muddy or cobbly bank between the surface of the water and the base of vegetation in the channel. The bed material in the channel ranges between pebbles and cobbles. Although silt and sand can be found below the pebbles and cobbles, the coarser grained material is so dense on the stream bed that it clearly is the dominant type of sediment that interacts with the stream.

Analysis of Flow

Flow exhibits rapidly changing velocity, direction, and dispersion as a result of one or more of the following characteristics observed in the channel.

1. Microtopography of the stream bed: Where the streambed is level, flow is dispersed evenly across the channel. In many places, the streambed slopes towards one bank or the other. Here, flow moves faster towards a bank and either pools up or concentrates into a narrow sub-channel depending on the slope downstream.
2. Obstructions in the Channel: Obstructions such as cobble and mud bars, logs, and concrete, cause flow to change direction, pool up, or concentrate into sub-channels.
3. Changes in Width of the Channel: As the channel becomes narrower, flow responds by concentrating into a narrower, deeper channel where velocity is increased. Where the channel becomes wider, flow is more dispersed and often displays more diversity across the width of the channel.

As opposed to describing the facets of flow for the entire length of the channel, it seemed more relevant to choose certain sections of the reach that exhibit a high complexity of flow and give a detailed analysis of them. When station numbers (distance from the first fallen log) are given, it is best to refer to the flow diagram and photographs listed to get a picture of what the channel looks like at a certain location.

From station 0, flow is beginning to tend from the right bank towards the left bank. Initially the strongest flow is in the right side of the channel, flowing away from the right bank . Approaching station 10, the stream has become shallower and flow is more evenly distributed. All flow is tending towards the left bank except for the portion of the stream directly adjacent to the right bank which appears to be flowing along the right bank and beginning to pool up there. By station 15, a sub-channel has developed along the left bank. This sub-channel is a 2-3 feet wide and about 0.3 feet deeper than the rest of the channel. Flow within the sub-channel is much stronger (1.67 ft/sec as opposed to 0.92 ft/sec) than flow in the rest of the channel.

This is a good point to step back and ask a few questions about what has been observed so far. First off, what is causing flow to move from right to left? Also, what is causing flow to pool up along the right bank? The obvious reason for flow tending towards the left bank is a drop in elevation of the stream bed. Depth measurements show that the channel becomes deeper towards the left bank. But does the fact that the channel is deeper on one side than the other necessarily mean that flow will tend towards that side of the channel? One hypothesis that helps to explain the dispersion of flow here involves the large bar of cobbles along the right bank that begins around station 35 (In Photo 1, it’s the first major bar along the right bank). The end of the bar closest to the top of the diagram forms a stretched out U. The proposed hypothesis is that the left point of the U, the one furthest into the channel, extends upstream as a small arc in the microtopography of the streambed. The fact that the bar of cobbles has formed with a point in the middle of the channel supports the idea that it is the top of an arc which extends upstream and diverts flow away from that point. A slight arc upstream would help to divert flow towards the left bank and also explain why the flow to the right of the arc remains along the right bank and forms a pool there. Unfortunately, this hypothesis was conceived after data collection was completed and the necessary topographic data was not collected in the field to prove it.

The nature of flow from stations 0-15 has clear geomorphic implications. The flow diverted towards the right bank from the hypothetical arc extending from the left point of the cobble bar loses velocity abruptly as it is dammed by the bar ahead. This would cause any sediment being transported in this section of the stream to settle. Theoretically, the long term effect of this settling would be: 1. An accretion of sediment on the arc, causing it to become more pronounced. 2. An accretion of sediment in the pool and on the lip of the bar. Flow that is diverted to the left bank develops into a strong-flowing sub-channel. As depicted in the flow diagram, flow in this sub-channel comes into the bank at an angle as opposed to flowing directly downstream. As a result of strong flow into the left bank, significant undercutting of the bank has occurred. Seen in photo 2, undercutting of the muddy bank along the sub-channel has exposed the roots of vegetation higher up on the bank. The data collected suggests that undercutting of the bank is continuous and will lead to an eventual widening of the channel in this section of the stream.

The sub-channel along the left bank continues from stations 15-25. By station 30 flow is distributed fairly evenly across the channel. By station 40 flow across the channel is clearly tending towards the right bank. With the exception of flow diverted around the log at station 55, all flow from stations 40-75 is moving steadily towards the right bank. Beginning at station 55 and extending to the bridge, there is a step on the stream bed that drops off 1-2 feet towards the right bank. This step is represented on the flow diagram by the solid line in the channel that is parallel to the right bank. From stations 60-85, flow strongly spills over this step into a sub-channel along the right bank (photo 3). In the part of the sub-channel furthest upstream, flow entering the sub-channel pools up against the right bank and the cobble bar (far left in photo 3). By station 75, flow accumulated in the sub-channel is rushing downstream in a strong, concentrated flow. At station 85 (part of sub-channel where the muddy bank meets the concrete in photo 3), flow within the sub-channel is rushing downstream at rate of 3.17 ft/sec. By station 95, water has pooled up against the foundation of the bridge. This deep, slowly flowing pool continues for the length of the bridge.

In the section of stream described above, there are three obvious factors that could play a role in diverting flow from the left side of the channel towards the right.

1. A drop in elevation of the stream bed definitely occurs from left to right. The dry part of the channel near the left bank is at least 3-4 feet higher in elevation than the bed at the bottom of the sub-channel (photo 4, left bank= cobbly bar along right side of photo, sub-channel= part of stream against the foundation of the bridge on left of photo).
2. The dense bar of cobbles (same as mentioned above) along the left bank rises 1-2 feet above the water's surface. The densely packed cobbles allow very little penetration for water. As a result the water is reflected away from the bar towards the right bank.

3. As seen in the flow diagram and in the very bottom of photo 1, the section of the main channel directly upstream from the bridge is almost completely filled in by cobbles. The end of this cobble bar towards the left bank is at about station 75. The end of the bar towards the right bank is at about station 85. The diagonal position of the bar relative to flow, allows water in the channel flowing towards the bar no alternative to being funneled over the step into the sub-channel.

The presence of an easily defined sub-channel so close to a to the man-made bridge leads one to wonder if the sub-channel was developed on purpose by the builders of the bridge. It is possible that the channel previously produced strong flow along the left bank that potentially could have caused erosion damage to the foundation of the bridge. If this is the case, did the builders attempt to divert flow by putting a bar of cobbles across the channel? Whether or not the sub-channel was man-made in response to the construction of the bridge, it certainly has an affect on the bridge now. As seen in photo 5, the heavy, concentrated flow of the sub-channel along the bridge foundation has eroded away the bank material that the foundation was built upon. The corner of the bridge foundation pictured is left hovering at the water's surface.

The strong flow within the sub-channel along the right bank is likely to perpetuate it's own existence. The bank material is mud that is not protected by cobbles. The bed material is fine compared to that of the rest of the channel. The flow in the sub-channel is likely to make the sub-channel deeper, increasing the drop into the sub-channel, which increases the rate of flow into the sub-channel, which increases erosion in the sub-channel. As the bank material along the sub-channel is eroded and the sub-channel is widened, the potential for erosion further beneath the foundation of the bridge is increased. In the future, further erosion of bank material below the foundation of the bridge could seriously jeopardize the stability of the bridge.

Effects of the Bridge on Flow

As mentioned above, the bank material below the foundation of the bridge along the right bank has undergone a fair amount of erosion. A man-made bar of cement and cobbles (photo 7) has been built in front of the foundation of the bridge along the left bank to prevent such erosion. As seen in photo 7, this man-made bar connects to the top of the bridge foundation and slopes down into the stream from there. The bar extends nearly halfway across the width of the channel. As a result, the width of the wet channel is decreased by about 40%. The main consequence of this decrease in width of the channel is an increased concentration of flow, causing the channel to become deeper and produce higher rates of flow downstream.

Conclusions

An overview of the observations made during this study show this particular reach of Redwood Creek as being characterized by the following:

1. Diverse microtopography.
2. A series of bars of mud and cobbles extending from either bank into the channel.
3. Fluctuation between flow dispersed over the width of the channel, and flow concentrated into narrow sub-channels.
4. Pools along the banks of the stream often caused by bars acting as dams.

The nature of flow in this reach of stream appears to have significant erosive potential, even under relatively mild seasonal conditions. The common concentration of flow along the muddy banks, causing the outward erosion of these banks, accounts for the high width to depth ratio of the channel. As flow continues to be concentrated into sub-channels along the edges of the stream, outward erosion will continue, and the channel will gradually widen. A look at photo 8 provides a glimpse into the future of the channel. Heavy, channelized flow has eroded bank material, leaving a tree on an unstable ledge above the channel. As erosion pushes the bank further back, the tree will surely fall across the channel and join the two other fallen logs in this reach, which most likely fell due to the same process.