Title
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Authors
Bass, Phoebe
Choy, Min

Publication Date
2004-05-11

CHANNEL INCISION IN RODEO CREEK, MARIN COUNTY

Phoebe Bass and Min Choy
LA 222: Hydrology for Planners
11 May 2004

Abstract
Rodeo Creek drains approximately 1.2 mi^2 in coastal Marin County, California, debouching into the Pacific Ocean at Pt. Bonita in Golden Gate National Recreational Area. We documented the current degree of channel incision. Channel incision can lower adjacent water tables and cause bank collapse, which can increase sediment load resulting in aggradation downstream. Lower water tables can desiccate the native wetland community and allow non-native vegetation to become established. We measured eight cross sections along the length of Rodeo Creek using measuring tape and a stadia rod to measure top of bank, thalweg, high water marks, and inflection points along the banks. We made detailed sketches of channel morphology and vegetation at each cross section. We compared the resulting incision profiles of Rodeo Creek with a stream incision study of Walker Creek in northern Marin County by William Haible (1976). Rodeo Creek is less incised than Walker Creek. The most severe incision in Rodeo Creek was less than 7 ft compared to an average of 18 ft in Walker Creek. The incision in Rodeo Creek is still cutting through the alluvial fill of clays and silts as no evidence of bedrock was seen in any of the cross sections. In contrast, Walker Creek has hit bedrock. Rodeo Creek may still be in the initial stages of incision. This may indicate that more severe incision is to come as incision evolution progresses in Rodeo Creek. Clear management objectives may allow incision to progress at a more natural rate.

Introduction

Stream valleys in the Central California Coast region are typically characterized by valley fills graded to adjacent hillslopes. Many modern streams are now incised into these fills. Stream morphology can be used to decipher the history of the stream and changes to the surrounding watershed (Haible 1976).

The National Park Service is concerned that Rodeo Lagoon is filling with sediments from the watershed. It is uncertain which drainage, Rodeo Valley or Gerbode Valley, is contributing most of the sediments. An examination of the current incision at Rodeo Creek would provide potentially useful information for further studies in the system.

Stream incision is the result of many different influences including geology, geomorphic changes, climate, hydrology, animals and humans (Schumm 1999). Anthropogenic contributions to channel incision can be a great. For example, humans change topography by changing channel shape, increasing sediment storage and gradient by building dams, and increasing landslide potential by decreasing the stability of surrounding hillslopes (Schumm 1999). Alluvial valleys have also been used to graze cattle. Grazing weakens vegetation cover, causes rilling in animal paths, compacts the soil and increases runoff (Schumm 1999). Direct human influences include decreased sediments loads, increased and concentrated discharges (from impervious surfaces), and increased channel gradients (Schumm 1999).

Once stream incision has commenced, it is unlikely to stop naturally until it has run its natural pattern, either reaching a new equilibrium at a lower level or reaching bedrock (Fig. 1) (Schumm 1999). Channels cutting into clays and silts tend to deepen rapidly, and channels cutting into sand tend to deepen less, but widen rapidly (Schumm 1999).

Stream incision can collapse banks, lower adjacent water tables, and establish non-native riparian. We are studying Rodeo Creek to qualitatively document its current channel morphology and from that make some preliminary assessments of stream incision. Results could assist management decisions and lead to preventative measures.

The Watershed Environment Rodeo Creek is located in West Marin County, California, about 10 mi north of San Francisco. Rodeo Creek has a watershed of 1.2 mi^2. The Creek runs approximately 1.8 mi from the confluence of small tributaries at the Baker-Barry tunnel to Rodeo Lagoon near Fort Barry (NPS 2002). Rodeo Valley is located in the Golden Gate National Recreation Area (GGNRA) and is managed by the National Park Service (NPS).

Rodeo Valley is underlain by the Franciscan Formation, which consists of a repeating sequence of cherts, altered basalts (greenstone) and sandstone (greywacke). These layers are wedges of sediments that accumulated at a subducting plate margin. The area is mantled by hillslope colluvium and valley bottom alluvium, making bedrock outcrops rare (Oerter 2003).

The coastal vegetation is adapted to seasonal rainfall and a narrow temperature range characteristic of the coast. Riparian vegetation consisting of predominantly willows, elderberry, dogwoods, rushes, stinging nettles, sedges, horsetails and ferns. Adjacent hillslopes are covered with grasses, lupines, poison oak and scrub brushes. Vegetation is important in binding and holding soils on slopes and on stream banks. When vegetation is reduced from grazing or clearing (for the construction of roads or other features) sediment is lost easily to surface wash and gullying (Haible 1976).

Since the arrival of European settlers in the 19th century, the valley has been used for agriculture and the military (NPS 2002). Regions of the valley floor were partially drained with ditches in order to grow grain to feed dairy cattle (NPS 2002). Ditches caused water tables to drop, thereby decreasing saturated soils and allowing the encroachment of non-native species (NPS 2002). Following agricultural use, the valley came under the ownership of the U.S. Army. Roads were installed and barracks and riffle ranges built. Fill material was placed in the floodplain towards the bottom of the watershed and near the top by the tunnel (NPS 2002).

Currently the Valley is used for recreation as part of the GGNRA. Former army barracks are located adjacent to Rodeo Creek near the top of the Valley.

In this study, we compared the channel morphology of Rodeo Creek to a Master's Thesis study by William Haible in 1976 in Walker Creek. Walker Creek is located north of Rodeo Creek near Pt. Reyes, but it has similar geologic and climatic conditions. The drainage area of Walker Creek at 69 mi^2 is greater than that of Rodeo Creek (1.2 mi^2). Walker Creek flows into Tomales Bay in Marin County. According to Haible (1976), Walker Creek had been degrading upstream and aggrading downstream for 60 years.

Walker Creek The upstream reach of Walker Creek was an arroyo-like channel cut down to bedrock in the alluvial valley (Haible 1976). The flat of the valley stood as a terrace (the high terrace) from 15 to 25 ft above the streambed (Fig. 2). The high terrace usually has a steep face where the stream has eroded into it, or where bank failure has occurred (Haible 1976). Closer to the streambed lies the inner terrace (Fig. 2). It was the flood plain 60 years prior, but at that point stood eight feet above the streambed. It is a cut terrace and existed in remnant patches along the channel (Haible 1976).

Downstream in Walker Creek the channel was not obviously incised (Fig. 3). The flood plain had been aggraded about four feet in the last 60 years and natural levees were commonly seen (Haible 1976). Presence of two terraces in the downstream channel was uncertain, but it was thought that the flood plain had aggraded on the high terrace. Much of the stratigraphy of the fill downstream was obscured by modern deposits, which made hypotheses about terraces unjustified (Haible 1976).

Our objective was to compare the patterns of channel morphology in Rodeo Creek to those studied by Haible (1976) in Walker Creek to infer incision processes and sequences.

Methods

After an initial reconnaissance on March 11th, we conducted fieldwork on March 27 and March 31, 2004. No rainfall occurred between the two dates. Our original intent was to survey cross sections of the creek and provide a quantitative description of the existing incision pattern. However, surveying proved impractical because dense stands of willows obscured the stadia rod throughout most of the channel even when the rod was fully extended. The method we then developed was to draw detailed cross sectional sketches of channel morphology and vegetation to document the existing pattern on Rodeo Creek.

We documented a total of eight cross sectional sketches along Rodeo Creek, from near the confluence with Gerbode Creek upstream to the top of Rodeo Valley, to capture different incision patterns along the creek. The eight cross sections are numbered 1 to 8 going upstream.

At each site, we performed a detailed cross-sectional sketch by first stretching a tape or a stadia rod across the channel, depending on the width of the channel, from one side of the floodplain to the other side. One person held a stadia rod and read the depth at the thalweg, left and right edge of water (LEW, REW), and inflection points of the banks. Features such as depositional bars and High Water Marks (HWM) were captured as well. In addition, we noted and sketched the types of vegetation present, and looked closely at root mats and other vegetative features that appear to be erosion-control features.

A plan view of each site was sketched to note adjacent stream meanders and channel form. Photographs were also taken of the channel at each cross section site, looking downstream and upstream of each site, and of incision features. Photographs assisted in estimating Manning's n values as well. We marked the approximate location of the eight cross sections on 1:24,000 US Geological Survey topographic maps. Rodeo Valley is contained within the Point Bonita and San Francisco North quads (Figure 5).

We used Manning's equation to calculate the most recent peak flows in Rodeo Creek by the location of HWMs. We were able to locate HWMs on Cross Sections 1 through 4. The Manning's equation is: $V= C(S^{0.5} R^{0.67}) / n$. C is a constant equal to 1.49 for English units. The slope (S) was estimated from contour interval change over the four cross sections divided by the longitudinal distance from USGS 1:24,000 topographic maps (Pt. Bonita and San Francisco North). R is area divided by the wetted perimeter. Area was estimated by counting squares on grid paper, while the wetted perimeter was approximated as being roughly rectangular and calculated using $P_w=2H+W$. Values for Manning's N (roughness coefficient) were chosen with the Chow method.

Results

Cross Section 1

Cross section 1 is located in a riffle at the lower end of Rodeo Valley (Fig. 5). Channel width is 28 ft (the widest of all measured cross sections) and maximum depth from the top of bank to the thalweg is 5.9 ft (Table 1). There is a gravel bar on the left bank and a mud bank on the right (Fig. 6). The left bank rises to a bench, while the right bank rises to a floodplain. Banks are not steep and do not appear to be recently incised (Fig. 7). Vegetation surrounding the channel is willow brush, which downstream has deposited wood debris across the channel.

Cross Section 2

The channel at Cross section 2 is located in a riffle with a 2-3 foot head cut drop about 10 feet upstream (Fig. 6). The channel is 10 ft wide from top of LB to RB with a maximum depth of 2.8 ft. No depositional features are present. Banks are clay and soil with moss and roots extending out (Fig. 8). Woody debris from willows hangs down into the channel. Willows, ferns, and horsetails are found next to the channel.

Cross Section 3

Rodeo Creek is 5 ft wide at Cross section 3 and is incised about 3.4 ft. The XS is in a riffle. The banks are very angular suggesting active incision. The bed and banks are comprised of sediment and clay held together by fine root mats and moss. The top of the left bank is lower than the right. A large willow in the channel stabilizes the right bank, creating a bench (Fig. 9). There are no deposition features evident. Trees surround the channel and there are shrubs further away from the channel.

Table 1. Channel width and height at Cross Sections 1-8.

Cross Section #	width (ft)	height (ft)
1	28	5.9
2	10	2.8
3	5	3.4
4	8	4.1
5	5.5	4.3
6	3	1.55
7	17	6.95
8	8	5.7

Cross Section 4

Cross section 4 is has a channel width of 8 ft and a depth of 4.1 ft. Banks are incised and there is a missing section out of the right bank from bank failure (Fig. 6). The right bank shows a small bench. Ferns and rushes cover the right bank while an elderberry stabilizes the left bank. Undercut and exposed roots from the elderberry extend into the channel.

Cross Section 5

Cross section 5 was taken at a riffle with a channel width of 5.5 ft wide and a depth of 4.3 ft. There are no obvious benches, but the left bank is overhanging and held in place by a fern. Banks are beginning to collapse (Fig. 11, Fig. 6). An island of sedges occurs in the middle of the channel. There are rushes and sedges on both banks and the ground is wet, indicating a very high water table.

Cross Section 6

The channel is barely incised at cross section 6 at 3 ft wide and 1.55 ft deep. Here, Rodeo Creek is a small channel running through a wide flat marsh (Fig. 12). Sedges and grasses grow in the meadow as well as in the channel. There are no pools in this reach.

Cross Section 7

Cross section 7 is located next to former army barracks (Fig. 5). It is the most deeply incised of all cross sections at 10 ft wide and 6.95 ft deep (Fig. 13). The soil and clay banks are deeply incised and continuing to collapse. Sedges are creating a deposition bank in the channel towards the left bank (Fig. 13). There appears to be a bench on each bank. Willows, vetch, sedge and horsetail are the dominant riparian vegetation. Dead willows have fallen into the stream and created large woody debris in the channel downstream. There is a 3 ft headcut about 13 ft upstream of the cross section (Fig. 6). The cross section is located in a riffle.

Cross Section 8

The channel is 6 ft wide and 5.7 ft deep at Cross Section 8. There are benches on the right bank and the left bank is overhanging with exposed roots (Fig. 14). Vegetation surrounding the channel include ferns, rushes and sedges. A large fern appears to help stabilize the overhanging left bank. There is some woody debris in the stream from small trees that appear to be cut down recently. There are young horsetails in the channel, suggesting that this reach of the stream may not have received scouring flows this year. To the left of the channel is a steep slope created by a large mound of fill deposited by the army.

Overall the channel shows increasing incision going upstream. The majority of the banks are clay and soil with no rock. The banks are being stabilized primarily by vegetation.

The channel shows many of the characteristics of an incising channel such as steep scoured banks, collapsing banks and benches in the banks.

For results from the Manning equation of flows at high water marks (HWMs) on Cross Sections 1 through 4, see Table 2.

Table 2. Estimates of 2004 peak flow from HWMs and Manning's Equation.

Cross Sec.	width (ft)	depth (ft)	R	S	n	Velocity (ft/s)	Discharge (cfs)
1	12	1.25	0.617	0.023	0.08	2.04	37.7
2	7	1.5	0.524	0.023	0.095	1.54	16.9
3	4.5	1.75	0.508	0.023	0.075	1.91	15.3
4	4.5	2.75	0.485	0.023	0.08	1.74	20.9

Discussion:

Rodeo Creek appears to be in its early stages of incision; the most severe incision we observed was 7 ft compared to Walker Creek's average incision of 18 ft. It should be noted, however, that Walker Creek has a much greater drainage area. Incision rates and patterns are important because incision lowers the adjacent water table, draining water that supports a healthy wetland community.

Cross Section 1

Cross section 1 resembles the downstream terrace morphology of Haible's study. This is expected because downstream reaches typically have a lower gradient and fill with alluvium from direct channel erosion upstream and from the watershed. Banks at Cross Section 1 were not steep and did not appear incised. There was a gravel bar in the meander, showing that deposition has recently occurred or is occuring. We observed a notch in the left bank, but it does not appear to be a high terrace nor a flood plain.

Cross Section 2

Cross Section 2 had a steep right bank and a small step in the left bank. Because the banks were not as gradual compared to Cross Section 1 and showed more scouring, we assumed that incision was greater here. At this cross section we observed exposed roots extending from the left bank, which were likely securing the bank. Because this Cross Section resembles the downstream model of Haible, the step in the left bank is more comparable to an intermediate berm than to a flood plain (Fig. 2 and 3).

Cross Section 3

At Cross Section 3, the channel was narrower than the downstream cross sections. More incision has occurred at this location as evident from the deeper and narrower channel. The banks are at two different levels. The left bank is the current floodplain, while the right bank is a terrace, most likely a high terrace. The stream bed is covered by a cushion of moss and vegetation roots, which could be a stabilizing feature in the channel. A willow tree is stabilizing the right bank.

Cross Section 4

At Cross Section 4 we see a narrow and steep sided channel which is more deeply incised than the downstream cross sections. Both banks are exposed and actively eroding, as evident from undercut banks with exposed roots. No steps or benches were obvious in channel morphology at this cross section.

Cross Section 5

At Cross Section 5 we see evidence of active bank erosion which included an overhanging bank and a collapsed bank directly upstream. Prior to this cross section, riparian trees surrounded the stream, with scrub in the adjacent floodplain. But at this location, the stream was bordered by wetland vegetation including rushes, sedges, and horsetail that extended about 150 feet to either side. We observed a vegetation island in the channel suggesting that sediment deposition had occurred during a time of low flow. Incision is increasing as we move upstream, with Cross Section 5 being the most incised so far.

Cross Section 6

Cross Section 6 was in a narrow shallow channel in a wetland meadow. The channel showed little to no incision with stable vegetated banks. Perhaps this section of the stream has a lower gradient with less erosive power.

Cross Section 7

Cross Section 7 was the most severely incised with a incision depth of almost 7 ft. This cross section is located behind a small housing development of former army barracks. The channel is wider than previous cross sections, suggesting that lateral incision was occurring as well. Both banks are bare and actively eroding. Small steps in the right and left banks result from the accumulation of sloughed bank materials. There is a culvert discharging into the channel downstream of this point, between Cross Section 6 and 7. A head cut could have propagated upstream to cause this lateral and vertical incision. We observed steps in the channel profile, with a 2 ft drop directly downstream of our cross section, and a 3 ft step directly upstream. Channel gradient could be higher as well.

Cross Section 8

Cross Section 8 was located farthest upstream. Its channel morphology is similar to Cross Section 5, with overhanging banks partly stabilized by vegetation. There was a 3 ft step in the channel profile directly upstream of the cross section. There appears to be little incision in the stream channel upstream of the step.

Channel morphology clearly changed as we progressed up Rodeo Creek (Figure 16). The channel is shallower and wider downstream, and gradually becomes deeper and narrower. Cross section 7 did not fit the pattern because its channel is wider than expected. We do not know what processes are occurring to cause this, but we believe that the housing development and the associated culvert are likely causes.

From what we observed, the incision has not yet incised into bedrock. Banks and streambed consist of a clay and silt alluvium. Our cross sections showed that very little gravel and sand is present within the channel. We therefore believe that Rodeo Creek has not incised to bedrock, and is at an earlier stage in its incision evolution than Walker Creek. At various cross sections, we observed steps in the banks, but they did not seem comparable to Haible's descriptions of an inner terrace or floodplain. On average, the terraces we observed were much lower than described in Haible's work. Our highest terrace was in many places the current floodplain. This supports our hypothesis that Rodeo Creek is in the initial stages of incision, compared to the much more severely incised coastal streams in Marin.

There could be many reasons why Rodeo Creek is less incised. Localized controls could include landslides, roads and other human disturbances, and vegetation. Several landslides are depicted on geologic maps for this area (Fig. 15). Landslides would deposit huge amounts of sediment onto floodplains, lowering the gradient and creating a thicker layer of material for the stream to cut through. One hypothesis is that a landslide occurring in the lower reach of the stream could create a nick-point in the stream profile and effectively lower the gradient of the whole channel, thereby decreasing incision, however, there is currently no supporting evidence for this theory in Rodeo Creek.

We did not find any correlation between incision rates and Manning's velocity in the first four cross sections (which were the only cross sections where HWMs were observed). Manning's n values were very similar across cross sections as all were thickly vegetated. In addition, Manning's n values are subjective due to choosing categories of the channel morphology in the Chow table without extensive experience of comparing streams.

Conclusion

This is a preliminary study serving only to document existing conditions on Rodeo Creek. We looked only at channel cutting into the floodplain. Due to the difference in scale between Rodeo Creek and Walker Creek, incision depth cannot be directly compared. However, our observations and qualitative cross sections indicate that Rodeo Creek is not incised very much, and that its incision pattern is not comparable to what Haible observed in Walker Creek. The channel morphology of Walker Creek with its two terraces indicate that it is late along the evolution of stream incision. Rodeo Creek does not have those features. In addition, Walker Creek has hit bedrock while Rodeo Creek is still cutting through silt and clay.

It should also be noted that incision is not merely defined by depth of channel, but by lateral cutting as well. A more comprehensive study for the future would be to examine the width to depth ratio of the channel.

For all the reasons given above, we believe that Rodeo Creek is not very incised compared to Walker Creek. This study provides preliminary documentation of the current state of incision in Rodeo Creek which we hope will aid in directing future studies of incision in this system.

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