JERRY R. JONES & ASSOCIATES, INC.
ENGINEERS • PLANNERS • SURVEYORS

GEOMORPHOLOGY STUDY OF THE SANTA CRUZ RIVER FROM NOGALES TO CANOA ROAD FOR THE SOUTHERN PACIFIC TRANSPORTATION RAILROAD

PREPARED FOR
THE SOUTHERN PACIFIC TRANSPORTATION COMPANY

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DECEMBER 20, 1985

DJA JOB NO. 85-196

(RPT.41)

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EXECUTIVE SUMMARY

A geomorphic analysis of the Santa Cruz River was performed in order to propose bank protection alignments along the Nogales Branch of the Southern Pacific Railroad. The study reach extended from the confluence of Nogales Wash and the Santa Cruz River (Milepost 1041) to the Canoa Road bridge (Milepost 1018). The section of tracks between the Nogales Wash and Santa Cruz River confluence (Milepost 1041) to Nogales (Milepost 1047) will be analyzed during the design phase of the project. The total length of the river covered in the geomorphic analysis is approximately 23 miles.

Discharge values for various return periods were provided by the Flood Insurance Study for Santa Cruz County and adjusted by a recent Pima County study. The study reach is hydrologically a single reach.

The thalweg and valley line were drawn on aerial photos and geomorphic analysis was used to plot 2-, 10-, and 100-year meander envelopes. These help predict the extent of river bend migration and identify the vulnerable sections of track.

Ten locations were identified as being vulnerable to damage in the next flood. Horizontal alignments of bank protection are proposed and alternatives provided. The total length of bank protection with the preferred alignments are 30,100 feet, while the total length under the alternate alignments is 25,600 feet. A higher degree of protection is provided by the preferred alignments. The lengths and alignments will no doubt be modified as the design and cost analysis proceed in the second phase of the project.

I. INTRODUCTION

1.1 Authorization

This project is authorized and funded by the Southern Pacific Transportation Company. This report was done under the scope of services for the Southern Pacific Transportation Company dated October 15, 1985, Southern Pacific Transportation Company Job Number E911/345-11.

1.2 Location

This project is located in Santa Cruz County, Arizona (see Figure 1). The study area of the Santa Cruz River starts downstream from the railroad Milepost 1018 (Canoa Road) to the confluence of the Nogales Wash, then extended upstream to the railroad Milepost 1047 (Baffert Dr.).

1.3 Site Description

The Santa Cruz River, with headwaters in Southern Arizona and New Mexico, flows northwesterly along the west side of the Southern Pacific Railroad Nogales Branch. The climate of lower elevations of Santa Cruz River is characterized by dry winters and hot summers. Afternoon temperatures in the summer are near 100 degrees Farenheit and average winter temperatures are above 32 degrees Farenheit. Temperatures are generally lower at the higher elevations. The annual precipitation ranges from slightly more than 10 inches in the valley to approximately 25 inches in the mountains. Approximately one-half of the annual

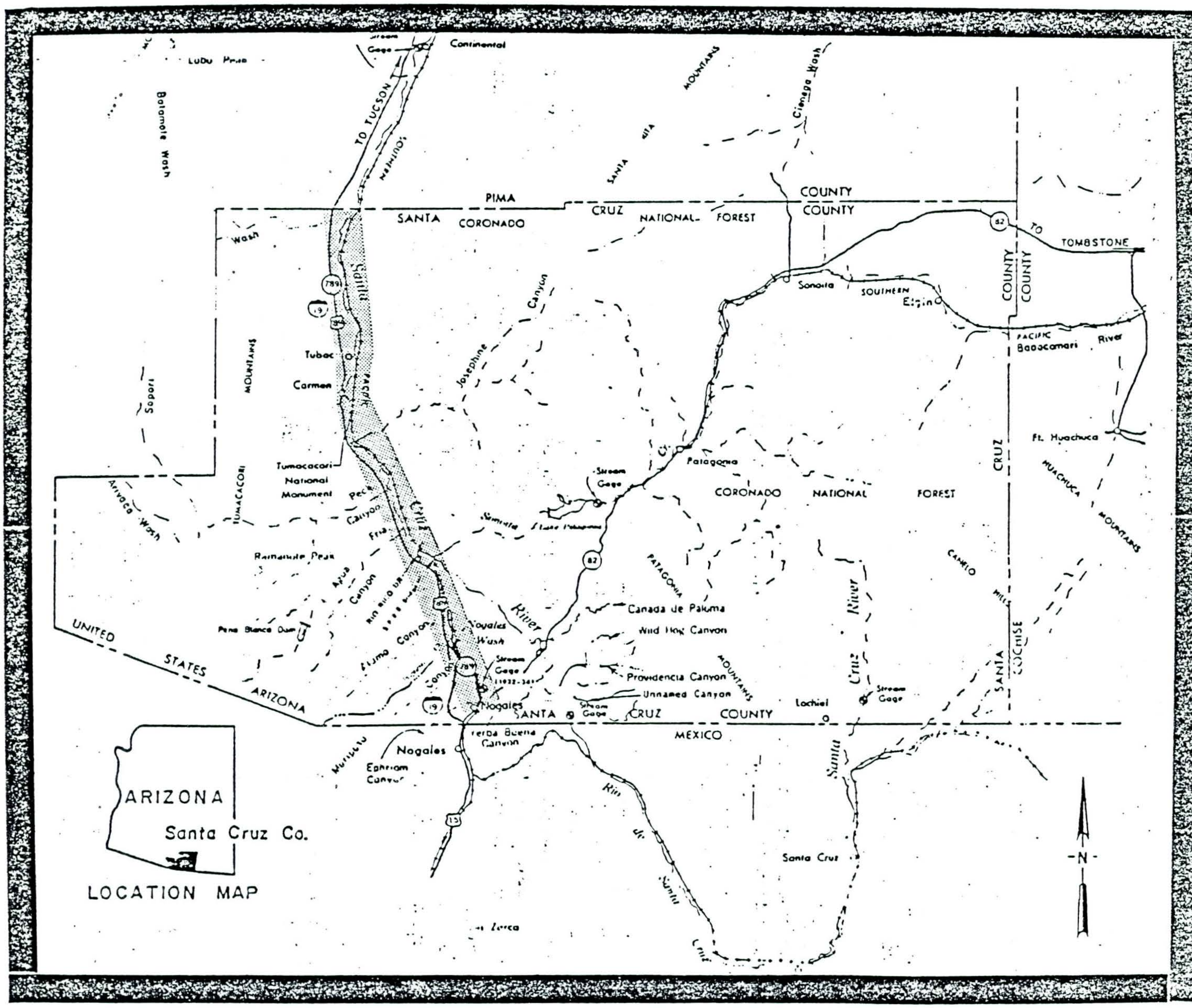


FIGURE 1
LOCATION MAP

precipitation falls during the summer thunder-storms originating in moist air that flows into Arizona from the Gulf of Mexico. Rainfall is normally most intense in the late afternoon or early evening. Some storms, especially those affecting a large area, are associated with weak tropical disturbances moving northward from the Pacific Ocean and the Gulf of California. Most of the remaining precipitation occurs during the winter and is caused by Pacific storms that move through Arizona. The precipitation associated with these disturbances usually falls in gentle, widespread rain showers which may continue intermittently for several days.

Vegetation in the lower valley is mainly cactus, desert brush, mesquite, and creosotebush. The foothills consist of mostly cactus and palo verde trees. In the mountains, desert vegetation is replaced by chaparrel. Above an elevation of approximately 7000 feet, the mountain vegetation is composed of pine forests.

1.4 Project Background

The Southern Pacific's Nogales Branch is a rail line that connects the east-west transcontinental main line at Tucson with Nogales, Arizona. The line is approximately 61 miles long, and runs in a north-south direction, and is parallel to the east side of the Santa Cruz River valley. The line was originally constructed between 1875 and 1880. The location of the route and the railroad Mileposts are shown on the maps in the Appendix.

Approximately 35 miles of this route, from Milepost 1012 to Milepost 1047, is located within either the main or overflow channel of the Santa Cruz River. Within this 35-mile distance, the track is exposed to the hazards of bank erosion when flooding occurs on the Santa Cruz River. The track embankment and the river banks are composed of very erodible materials, with the result that seasonal flooding has produced significant erosion of the bank and damage to the rail line approximately every three to five years since the line was originally constructed. Most of the damage occurs at the outer bend of the river meanders.

A recent history of rail service interruptions due to the flood damage is as follows:

October 10 to November 20, 1977

December 20 to December 30, 1978

October 3 to November 15, 1983

December 27, 1984 to January 12, 1985

It should be pointed out that not all of the flood damage on the Nogales Branch is a result of bank erosion from the parallel location of the Santa Cruz River. A lesser amount of flood damage occurs at cross-channel bridges and culverts and at the only Nogales Branch crossing of the Santa Cruz River, a 280-foot, steel, open deck bridge located at Milepost 1040.18. Cross-channel damage also occurs at Milepost 1041.86 where the Nogales Branch corsses Potrero Creek.

Historically, repair of flood damaged rail facilities on the Nogales Branch has been the quickest and most expedient means available, as the primary objective of the repair efforts is to restore rail service as soon as possible. Washed out embankments are rebuilt to the same span and channel opening or replaced with culverts. Engineering and design of bank protection and channel opening are performed where possible, but is usually subordinate to the efforts to resume rail service.

After rail service is restored, attempts have been made to provide permanent protection. Prior to the fall of 1983, the most common method of bank protection has been rock, side-dumped from rail cars on the embankment requiring protection. In most cases the rock was not keyed and a toe was not provided below scour level. Also, the rock was not placed to a specified slope. Another method of protection was to widen the embankment with local borrow. Both of these methods were used only where it was apparent that erosion damage would certainly occur with the next storm.

Other pre-1983 protective measures have included the installation of retards and jetties. The purpose of these devices was to reduce the velocity of the current and induce silting behind the device or to deflect the river away from the bank. These protective devices consisted of single and double lines of rail, sometimes backfilled with rock or faced with car doors.

After the fall 1983 storms, the embankment was restored and tracks and bridges rebuilt. After rail service was restored, permanent protection was installed over the next three or four months. Permanent protection consisted of dumped rock and rock-and-wire matresses, more commonly known as gabions, and dumped rock installations.

During the most recent 1984/1985 winter floods, some of the recently constructed gabion installations were significantly damaged. In every instance, the gabions succeeded in protecting the track embankment. It appears that the gabions failed or slipped down the embankment for two principle reasons. The first reason is that an apron was not provided at the toe to prevent scour and undercutting. The second reason appears to be that too much fines and undersized rock were used to fill the gabions, and some of this material was "sucked out" by the rapid current of the river.

Repair efforts for the 1984/1985 flood damage consisted of rebuilding the embankment railroad track, and bridges. After rail service was restored in mid-January of this year, thirty thousand cubic yards of rock (nominal size 3-inch to 1-1/2 foot) was side-dumped to protect the most vulnerable embankments. This work was performed in February and March of 1985. No other work has been performed since that time.

In summary, the Nogales Branch was originally located within the Santa Cruz floodplain and has suffered the consequences of bank erosion ever since. The line is also vulnerable to erosion from Milepost 1012 to Milepost 1047 and at the Santa Cruz River Bridge, Milepost 1040.18 and at the Potrero Creek Bridge, Milepost 1041.86. This long length of exposure to the meandering river has prohibited continuous protection. Therefore, protection has been provided at the points of greatest hazard and protection at other locations has been deferred until the bank erosion advanced to the track. Dumped rock, widened earth fills, gabions, and jetties have all been used to protect the track embankment with a varying, if not disappointing, degree of success.

1.5 Objectives

The purpose of this report is to study the geomorphic changes of the Santa Cruz River in order that a bank protection program can be developed for the Southern Pacific Transportation Comany with confidence that the integrity of the Nogales Branch can be maintained during and after times of flooding.

II. METHODOLOGY AND PROCEDURES

2.1 Geomorphic Analysis

The reach of the Santa Cruz River which was examined extends from the Canoa Road Bridge to the confluence of Nogales Wash. Using aerial photographs, onsite investigation, and geomorphic research, an analysis of the Santa Cruz River geomorphic change can be completed by utilizing quantitative results for qualitative indications of trends.

Rivers can be classified broadly in terms of channel pattern, that is, the configuration of the river as viewed on a map or from the air. Patterns include straight, meandering, braided, or some combination of these. A straight channel can be defined as one that does not follow a sinuous course. Truly straight channels are rare in nature but can be created by natural or man-made cutoff or meander loops where long reaches of sinuous meandering channels with relatively flat slopes are converted to shorter reaches with much steeper slopes. Straight reaches can also be man-induced by placing of contraction works such as dikes and revetments to reduce or control sinuosity. A braided river is generally wide with poorly defined and unstable banks and is characterized by a steep, shallow course with multiple channel divisions around alluvial islands. A meandering channel is one that consists of alternating bends, giving an S-shape appearence to the plan view of the river. The typical S-curve of a single meander loop is formed as the thalweg flows from a pool through a crossing to the next pool. Alluvial channels of all types deviate from a straight alignment. The thalweg oscillates transversely and intitates the formation of bends. When the current is directed toward a bank, the bank is eroded in the area of impingement and the current is deflected away and may impinge upon the opposite bank further downstream. The angle of deflection of the thalweg is affectedby the curvature formed in the eroding bank and the lateral depth of erosion. In general, bends are formed by the process of erosion and deposition. Erosion without deposition to assist in bend formation would result only in escalloped banks. Under these conditions the channel would simply widen until it becomes so large that the erosion would terminate. As a meandering river system moves laterally and longitudinally, the meander loops move at an unequal rate because of the unequal erodibility of the banks. This causes a tip or bulb to form and ultimately this tip or bulb is cut off. After the cutoff has been formed, a new bend may slowly develop.

The Santa Cruz banks are mainly vertical in the reach being studied. From soils reports and field investigation of Midvale Park near the river, the soil is probably a silty clay with river sand and cobbles in the bed. This type of soil is highly erodible. Low flows of the river undermine the vertical banks slowly causing large sections of the banks to cave in during a large flow. This undermining usually occurs on the outside of the bends where velocities are higher and the flow is directed toward the banks. On the inside of the bends, the banks tend to be less eroded and more stable due to low velocities and sediment buildup. Since the Santa Cruz is an ephemeral stream, the banks are also subject to erosion by wind and rain.

2.2 Hydrology

The pertinent hydrologic studies for the Upper Santa Cruz River are: 1) Flood Insurance Study for Santa Cruz County, Arizona performed for the Federal Emergency Management Agency (FEMA) in February, 1980 (Reference 4); 2) Hydrologic Evaluation of the Santa Cruz River Basin, Arizona by the Pima County Department of Transportation and Flood Control District (PCDOT & FCD) in October, 1974 (Reference 9). The FEMA study is based on statistical analysis of recorded streamflow data, while the PCDOT & FCD study uses rainfall-runoff computer simulations.

The results of these two studies varied significantly, with the PCDOT & FCD discharges being approximately 50% higher than the FEMA values. The relationship between the PCDOT & FCD 100-year discharge and the FEMA 100-year discharge is used to adjust the 2-, 10-, 25-, 50-, and 500-year FEMA discharges upward. The adjustment is based on two assumptions: 1) the PCDOT & FCD has a realistic 100-year peak, since it is calibrated by the flood of October 2, 1983; (2) the slope of the FEMA frequency-discharge curve (on log-probability paper) is correct. Table 1 shows the unadjusted FEMA discharges and Table 2 shows the adjusted and unadjusted 100-year discharges. Table 3 summarizes all of the adjusted discharges along the upper Santa Cruz River.

Generally, discharges increase in a downstream direction along a river. Table 3 shows that the discharges along the Santa Cruz River remain relatively constant. This is due to the timing of the incoming tributary flows and the losses due to infiltration and evaporation. For the pruposes of this geomorphic analysis, the study reach can be considered a single hydrologic reach. Table 4 shows the 2-, 10-, 25-, 50-, 100-, and 500-year discharges that are representative of this reach of the Santa Cruz River.

Table 1. Summary of FEMA Discharges

Flooding Source and Location	Drainage Area (Square Miles)	Peak Discharges (Cubic Feet per Second) 10-Year	50-Year	100-Year	500-Year
Santa Cruz River					
At Continental Road	1,662	11,000	22,000	30.000	72,000
At Pima-Santa Cruz County Limits	1,448	19,559	21,600	30,000	72,000
At Amado Road	1,279	10,680	21,960	30,500	73,200
At River Avenue	1,209	10,850	22,320	31,000	74,400
Downstream from Confluence with Jospehine Canyon (Cross-Section AK)	1,163	10,710	22,030	30,600	73,440
Downstream from Confluence with Peck Canyon (Cross-Section BG)	1,097	10,500	21,600	30,000	72,000
Downstream from Confluence with Agua Fria Canyon (Cross-Section BV)	1,045	10,330	21,240	29,500	70,800
At Rio Rico Drive	1,000	10,150	20,880	29,000	69,600
At Southern Pacific Railroad	722	9,100	18,720	26,000	62,400

Table 2. Adjusted 100-Year Discharges
Santa Cruz River

Location	Unadujsted Q100 cfs	Adjusted Q100 cfs
Above confluence with Rillito Creek	30,000	45,000
At Continental Road	30,000	45,000
At Pima-Santa Cruz County Limits	30,000	45,000
At Amado Road	31,000	46,500
Downstream of Confluence with Josephine Canyon (Cross-Section AK)	30,600	45,900
Downstream of Confluence with Peck Canyon (Cross-Section BG)	30,000	45,000
Downstream of Confluence with Agua Fria Canyon (Cross-Section BV)	29,500	44,250
At Rio Rico Drive	29,000	43,500
At Southern Pacific Railroad	26,000	39,000

Table 3. Summary of Adjusted Discharges

Flooding Source and Location	Drainage Area (Square Miles)	Peak Discharges (Cubic Feet per Second) 2-Year	10-Year	50-Year	100-Year
Santa Cruz River					
At Continental Road	1,662	5,300	17,000	35,000	45,000
At Pima-Santa Cruz County Limits	1,448	4,600	16,000	34,000	45,000
At Amado Road	1,279	4,500	16,000	35,000	45,750
At River Avenue	1,209	4,450	16,000	35,000	46,500
Downstream from Confluence with Jospehine Canyon (Cross-Section AK)	1,163	4,400	16,000	35,000	45,900
Downstream from Confluence with Peck Canyon (Cross-Section BG)	1,097	44,000	16,000	35,000	45,000
Downstream from Confluence with Agua Fria Canyon (Cross-Section BV)	1,045	4,350	15,500	34,000	44,250
At Rio Rico Drive	1,000	4,250	15,500	33,500	43,500
At Southern Pacific Railroad	722	3,900	14,000	30,000	39,000

Table 4. Discharges Used in the Geomorphic Study

Return Peiod Years	Discharge cfs
2	4,400
10	15,800
25	25,000
50	34,200
100	45,000
500	108,000

2.2. Dominant Discharge

Channel formation is accomplished either by bank erosion or berm buildup. The channel will be enlarged until a stable condition is reached, in which the discharge just filling the channel has these properties: (1) it can maintain the channel at its present cross-section without scour or deposition; (2) it is not exceeded frequently enough for berm buildup to be appreciable. This discharge can, therefore, be conveniently adopted as the dominant discharge. It is clear from this discussion that the notion of frequency will play an important part in defining the dominant discharge. That is the natural river has formed a stable single channel with stable berms of floodplains, the discharge which just fills the channel is the dominant discharge. Some higher frequency floods may overtop the berms or cause some bank erosion. The dominant discharge has a tendency to fill up the collapsed bank, to maintain its own water course, channel cross-section, channel bed grain size and channel slope. Wolman and Leopold's experiement in the United States (Ref. 10) showed that:

$$Q_D = Q_{1.4} \sim Q_2$$

Where: Q_D = dominant discharge

$Q_{1.4}$ = 1.4 year frequency flood

<u>Stable Channel Hydraulic Character Analyses:</u>

Governing Equations (Ref. 6)

$$P = B = \frac{127\ Q^{5/6}\ S^2}{d^{5/3}} \qquad (1)$$

$$\text{and} \quad S = \frac{(8\sqrt{12d}\,)^{5/3}}{1750\ Q^{1/6}} \qquad (2)$$

$$8\sqrt{12d} = 193\ R^{1/3}\ S^{2/3} \qquad (3)$$

$$Q = \frac{1.49}{n}\ A\ R^{2/3}\ S^{1/2} \qquad (4)$$

must be satisfied. (If river bed is sand or silt of grain size less than 1/4 in.)

Where:

S = Channel slope (ft/ft)

Q = Discharge (cfs)

P = Wetted Perimeter (ft)

B = Top width (ft)

d = Grain size (ft)

R = Hydraulic radius (ft)

n = Mannings coefficient

A = Channel cross-section area (ft^2)

1. Dominant Stable Condition:

from equation (1), (2), (3), (4)

$d = 827582023 \times n^{7.2} \times Q^{0.2}$

now, $Q = 4,400$ cfs and assume $n = 0.03$

$d = 0.04806$ ft.

Consequently:

$S = 0.00286$ ft./ft. from (2)

$P = B = 177$ ft. from (1)

$A = 479\ ft^2$ from (3)

$R = Y = 3.81$ ft.

$V = 6.52$ ft/sec

Check from equation (4)

$Q = 4,373$ cfs

In summary, this says that a river reach with a dominant discharge of 4,400 cfs will achieve a channel bed slope of 0.00286 ft./ft., top width of 177 ft., and a bed grain size of 0.04806 ft. at final stable stage.

2. Present Condition:

$S = 0.004$ ft./ft.

$d = .00118$ ft.

$Q = 4,400$ cfs

A. $S = 0.004$ maintains constant

then $d = 0.072$ ft.

$P = B = 177$ ft.

$R = Y = 3.58$ ft.

$A = 633\ ft^2$

$v = 6.95$ ft/sec.

adjust n value.

$$n_1 = n_o \left(\frac{d_1}{d_o} \right)^{1/6}$$ (Strickler's Formula)

$n_o = 0.03$ $d_o = 0.04806$

so $n_1 = 0.0321$

check from equation (4)

$Q = 4,349$ cfs

That is, through this river reach if the slope of 0.004 ft./ft. maintains constant with $Q_D = 4,400$ cfs, the river will try to achieve a top width of 177 ft. with 6.95 ft/sec. velocity which will scour the grain size to less than 0.072 ft. from this reach and leave every sediment load with grain size greater or equal to 0.072 ft. through this reach.

B. $d = 0.00118$ ft. maintains constant.

then $S = 0.00013$ ft./ft.

$P = B = 177$ ft

$R = Y = 7.1$ ft

$A = 1256$ ft^2

$v = 3.50$ ft./sec.

adjust n value : $n_o = 0.031\ d_o^{1/6}$

$n_1 = 0.034\ d_1^{1/6}$ $(d_o > 2d_1)$

then: $n_1 = \frac{0.034}{0.031} \times \left(\frac{d_1}{d_o}\right)^{1/6} \times n_o$

therefore: $n_1 = 0.018$

check from Equation (4);

$Q = 4,379$ cfs

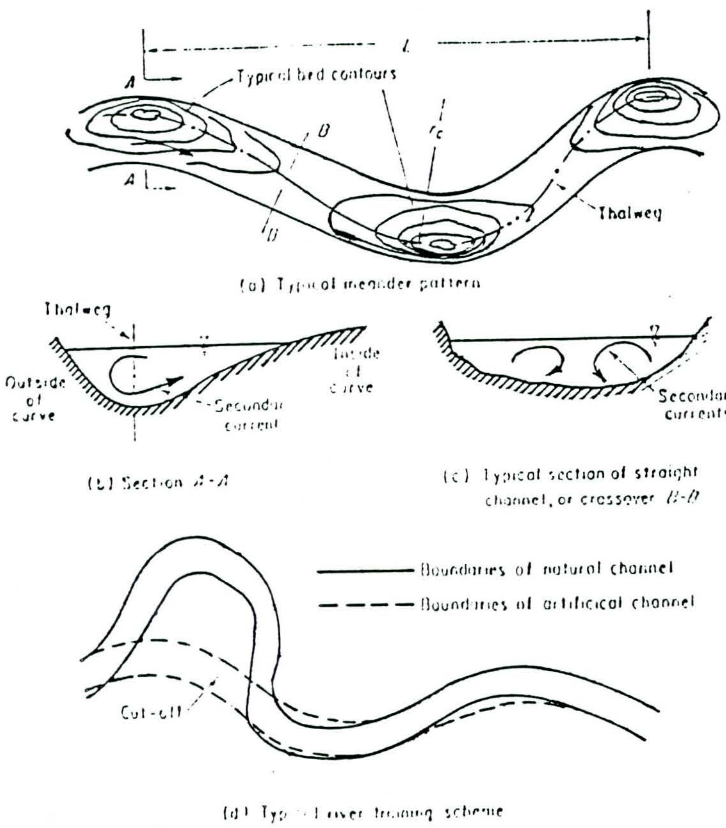
That is if the grain size throughout the river is the same (0.00118 ft) the river will try to achieve a top width of 177 ft, a slope equal to 0.00013 ft./ft. with the velocity equal to 3.50 ft/sec which will only scour a grain size less than 0.00118 ft. and deposits sediment with a grain size greater or equal to 0.00118 ft. through this reach.

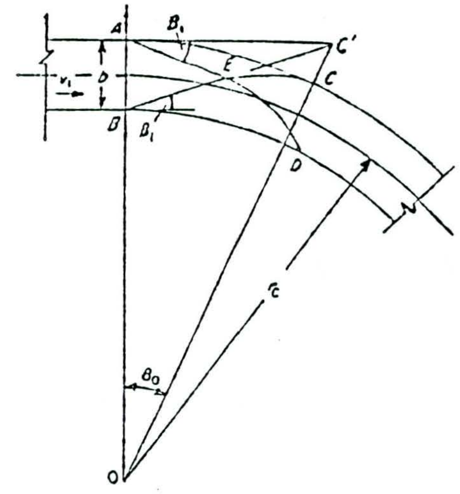
Conclusion of 1, 2-A, 2-B: with the dominant discharge of 4,400 cfs through this reach of the Santa Cruz River, the river will try to achieve a unique character with a top width equal to 177 ft.

2.4 Meandering Radius (r_c) and Wave Length (L) Computation:

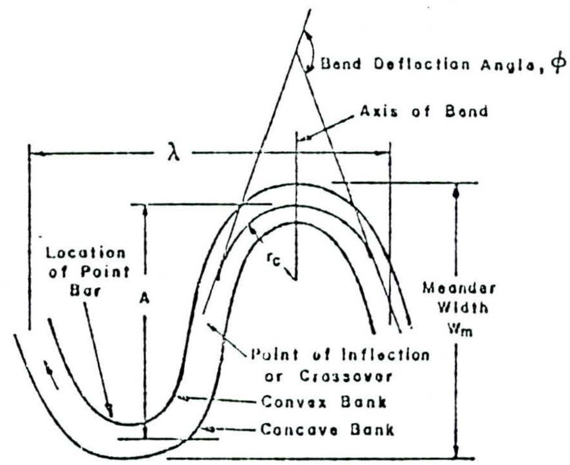
The relationship between r_c and L of ideal mature stable meander loops has been verified as $L = 2\sqrt{3}r_c$ to $4r_c$ ______________ (5)

which is a function of the central angle θ_o (see Figure 2) of a bend. The central angle θ_o has been derived as:

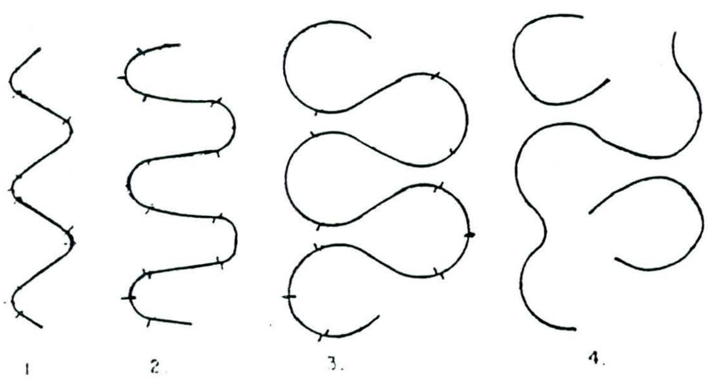




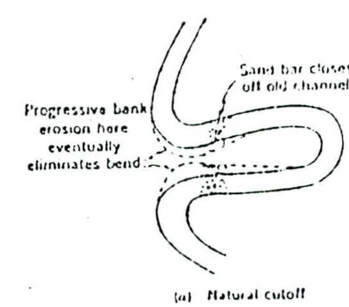
Schematic Wave Pattern at a Circular Curve



Definition sketch for meanders.



Development of natural cutoffs (after NEDECO, 1959).



Formation of cutoffs.

FIGURE 2

DEVELOPEMENT OF MEANDERING CUTOFFS

$$\tan\theta_o = \frac{b}{(rc + b/2)\tan B_1} \quad ; \quad \sin B_1 = \frac{1}{Fr}\sqrt{\frac{\tanh(2\pi y/b\cos B)}{2\pi y/b\cos B_1}}$$

(Ref. 2, 3)

By treating waves as surges the equation is applicable only to supercritical flow. Wave formation is by no means negligible in subcritical flow, particularly near the critical condition. Nevertheless, the relationship is good enough to serve as a maximum limitation for subcritical flow. Measurements of the horizontal dimensions of meander patterns show relations between certain of the parameters which stay remarkably consistent through a large range of stream sizes from laboratory streams a foot wide to the Mississippi River nearly a mile wide. Many observers have noted such relations and their work is summarized by Leopold and Wolman (Ref. 7). The wavelength (L) and loop radius (rc) are related to the width (B) by these equations:

$$\frac{L}{B} = 7 \text{ to } 11 \qquad (6)$$

$$\frac{r_c}{B} = 2 \text{ to } 3 \qquad (7)$$

$$\text{then } L = 3.5\, r_c \text{ to } 3.7\, r_c \qquad (8)$$

The numbers in equation (7) occur in the median range. Some streams might deviate slightly. The similarity between equation (5) and (8) confirms the reliability of using equation (6) and (7).

From stable channel analyses B = 177 ft. for the reach under study, so

$L = 1239$ to 1947 feet

$r_c = 354$ to 531 feet

From Leopold's meandering amplitude equation

$A_m = 2.7\ B^{1.10}$ ________________ (12) (Reference 13)

Meander Width:

$W_m = A_m + B = 979$ feet

Meander Radius:

$r_c = W_m 1/2 = 490$ feet

Verification

The Santa Cruz River is geologically young and therefore has few mature S-loops. The following three locations exhibit bends that are approaching maturity. The first two are active, while the third is abandoned. The measured radii, meander widths, and meander lengths verify the results of the equations.

The three locations are:

1. Milepost 1037.0 to 1036.5

   rc = 600 feet Wm = 1030 feet L = 1260 feet

2. Milepost 1033.2 to 1032.8

   rc = 510 feet Wm = 820 feet L = 1210 feet

3. Milepost 1022.0 to 1021.5

rc = 600 feet   Wm = 1200 feet   L = 1250 feet

2.5 Meander Envelopes

From the concepts of meander loop formation, the original thalweg line is the valley line and the original thalweg line crosses the S-loop around the mid-point. Once the S-loop is mature, the configuration of the loops cannot be more pronounced. The potential for downstream propagation of these loops is negligible, probable loop cutoff would occur if the balance of the stable loop is disturbed.

The development of a natural bend cutoff will start at a point downstream from the apex along the outer curve of a loop and join with a tip outback upstream of the apex of the bend following this loop (see Figure 2). The flow from a new cutoff wall have the same wave deflection angle and the same zig-zag thalweg pattern as before the cutoff. If the wave contact point is different than before the cutoff, the river will start to try to achieve a stable channel from the end of the cutoff by the erosion/sedimentation process. This process would either make the existing loop propogate downstream or create a new loop.

By comparison of the 1967, 1977, 1980, 1983 and 1985 aerial photos, the original thalweg line can be reconstructed. The apex boundary lines can be drawn with a 490 foot setback from each side of the original thalweg line, forming an envelope of potential meandering boundaries.

Since Q is constant (dominant discharge), B, Rc, L are fixed, B_1, O_o are correlated with Q_1. Maximum sinuosity and thalweg pattern are fixed. Propagation patterns and cutoffs of meander loops are determined. The potential meandering boundary of the study area as shown on the maps in the Appendix is well defined.

2.6 Potential Channel Propagation

The procedures of Section 2.3.1 are repeated for the various frequencies and discharges. Assuming that the flow durations are long enough for channel formation, the geomorphic parameters can be calculated. The results are summarized in Table 5.

Table 5. Dominant Geomorphic Parameters for Various Discharges

Return Period Years	Design Discharge cfs	Top Width ft.	Amplitude ft.	Meander Width ft.	Radius ft.	Maximum Wave Length ft.	Minimum Wave Length ft.
2	4400	177	802	979	490	1239	1974
10	15,800	336	1623	1959	980	2352	3696
25	25,000	422	2085	2507	1254	2954	4642
50	34,200	494	2480	2974	1487	3458	5434
100	45,000	566	2880	3446	1723	3962	6226

The dominant channel is comparably small for any flood that has a longer return period. The channel propogation from the dominant loop is forseeable. However, due to the following reasons, the formation of geomorphic the characteristics of Table 5 for longer return period flood are not likely to happen:

(1) The duration of a longer return period flood is comparably short and does not dominate channel formation.

(2) The larger the flood, the longer the return period.

(3) Dominant flow occurs frequently and reshapes the channel after any longer return period flood.

Since the dominant envelope follows the projected apex points of the mature dominant S-loop, the river will tend to follow this track, unless some geological change, climatical change or man-made change interferes.

The bank retreat due to any single flood event from the dominant envelope boundary can be estimated from the following equation and the results are summarized in Table 6:

$$Ws = \frac{0.088Q \cdot (\sin^2 \frac{\alpha}{2} / \cos \alpha)^{0.25}}{Ym^{1.5} \cdot Sc^{0.38}} - B$$

Table 6.

Return Period Yr.	Discharge cfs	Depth ft.	Ws ft.
10	15,800	7.5	287
25	25,000	9.8	315
50	34,200	11.8	332
100	45,000	14.0	341

The bank propogation limits for a particular frequency can be constructed by offsetting the bank retreat from the dominant envelope. The 2-year dominant envelope results from repeated 2-year floods. The 10-and 100-year meander envelopes result show the predicted bank retreat in a single flood. The 10-and 100-year envelopes are closer together than the 2-and 10-year envelopes because as a flood becomes larger, bends tend to cut more in a downstream direction than in a sideways direction. The 2-year dominant envelope is plotted on the maps in the Appendix, as are the 10-and 100-year meander envelopes.

2.7 Sensitivity Analysis

Several factors combine to reduce the accuracy of the geomorphic analysis. First, the equations (1-4) used to calculate the dominant top width require lengthy calibration with measured sediment sizes. Due to scheduling and budget constraints this calibration was not performed.

Second, the thalweg and valley line were drawn without the aid of contour lines. The aerial photographs, when viewed under a stereoscope, help delineate the thalweg and valley line. This is not as accurate as using a topographic map, but budget constraints precluded establishing contours for the entire 35 mile study reach.

III. DISCUSSION AND RESULTS

3.1 Hydraulically Similar Reaches

The geomorphic analysis is only applicable to river reaches that have not been greatly encroached by man. Encroachments such as levees, dikes and bank protection limit the natural meandering of a river when present over long reaches. For this reason, the section of tracks along Nogales Wash is not included as part of this report. Much of the wash is bordered by subdivisions and light industrial development from Milepost 1041.0 to Milepost 1047.0. Any necessary bank protection will be designed as part of the next phase of the project.

The study reach of the Santa Cruz River can be divided into two hydraulically similar sub-reaches. This division is based on a review of the historical aerial photos (Reference 1) that show a drastic change in the character of the downstream portion of the study reach since the 1960's.

The first sub-reach extends from Milepost 1041.5 to Milepost 1022.4, or from the confluence of the Santa Cruz River with Nogales Wash to approximately 1.2 miles upstream of the Amado Bridge. This reach is characterized by a single channel with a few short braided sections. Overbank flow occurs at some locations and the overbank areas are either active or abandoned fields. Some locations exhibit dense stands of vegetation along the banks. This sub-reach is essentially a meandering river.

The geomorphic methods described in the previous section are applicable to the first sub-reach and yield accurate results. The maps in the Appendix show the low flow thalweg, the valley line, and the 2-year, 10-year, and 100-year meander envelopes. These are used to predict the direction and extent to which the river will meander. They also indicate the degree of risk in various magnitude floods at any location.

The second sub-reach extends from Milepost 1022.4 to Milepost 1018.0, or from upstream of the Amado Bridge to the Canoa Road Bridge. The river changes character here and is essentially braided. The channel is typically wide with the low flow channel frequently changing location. Floodwaters often split, recombine, and change course. The flow direction is unpredictable by standard geomorphic equations and techniques. For this reason, the valley line and meander envelopes are not shown for this sub-reach. The low flow thalweg is plotted, however.

A review of the aerial photographs from 1967, 1977, 1980, and 1983 dramatically show the changes in this sub-reach. In 1965, the river was a single, narrow channel (top width of approximately 175 feet) with vegetated banks. It was located at least 1000 feet from the tracks in most locations. The overbanks were all being actively farmed, although they were bare at the time of the December, 1967 flood. The floodwaters overflowed the narrow channel and easily flowed along the furrows of the bare irrigated fields. Large headcuts occurred where the overbank flow dropped back into the channel. The bare fields supplied a ready source of sediment which entered the channel. In some locations, the channel began to widen because of the inability to carry the heavy sediment load. The photographs of 1977 and 1980 show these trends continuing.

The October 1983 flood was the largest in many years and was assigned a 100-year return period. This flood was able to drastically change the course of the river because of the trends induced from 1967 to 1983. The channel widened in some places to over 1000 feet. Old channel locations were abandoned and new banks were cut. Overbank flow continued to erode banks and cause large headcuts. As a result the river now has a wide channel and is free to move within that bed. The farms have largely been destroyed or abandoned and the fields overgrown with weeds. The long-term stability of this sub-reach is largely dependent on the rate at which the fields revegetate.

3.2 Horizontal Aligment of Bank Protection

One of the goals of this report is to identify the stretches of track that are subject to damage and provide a plan view layout for bank protection. The immediate aim is to protect the track from the next large flood and not necessarily to provide long-term protection. The need for remedial or additional bank protecion can be reassessed after the next large flood.

The following guidelines were used to help establish the horizontal alignment:

1. Keep alignment within 70 feet of the tracks in order to facilitate construction with railroad equipment.

2. Direct flow away from the tracks into the existing flow pattern, wherever possible. Flow is not directed at the opposite bank.
3. Keep construction within the railroad right-of-way, wherever possible.
4. Set bend radii in conjunction with existing bends in the immediate vicinity.
5. Use the valley line to indicate the trend of meander propogation.
6. Use the meander envelopes to help identify reaches that may be subject to damage in the future.

This report intends to only define horizontal alignments and alternatives. Types of bank protection, toedown and other design parameters, and methods of construction are to be detailed in the next stage of the project.

3.3 Results of the Geomorphic Analysis

This section follows the river from upstream to downstream on a mile by mile basis. It discusses the rational for the alignments and alternatives shown on the maps in the Appendix.

1. Milepost 1040.2 to Milepost 1039.0

   - This is the only railroad crossing of the Santa Cruz River.
   - The outer east bank is actively eroding and threatens the north abuttment of the bridge.
   - Flow can "bounce" off the east bank and damage the south abuttment.
   - No existing bank protection.
   - Preferred alignment:
     - 2800 feet along east bank all outside of the right-of-way. Radius of 1600 feet.
     - 400 feet of protection provided on west bank near abuttment.
   - Alternative alignment:
     - 400 feet of embankment protection starting at north abuttment and extending north.
     - All within 70 feet of the tracks and the right-of-way.
     - 400 feet of protection for south abuttment (same as in preferred alignment)

2. Milepost 1039.9 to Milepost 1039.5

   - Channel bank is 700 feet from tracks.
   - 100-year meander envelope is 400 feet from tracks.
   - No protection necessary.

3. Milepost 1039.5 to Milepost 1038.4

   - Rio Rico Bridge located at Milepost 1038.8.
   - Channel bank averages 1200 feet from tracks.
   - 100-year meander envelope averages 500 feet from tracks.
   - Existing bank protection on west bank and the bridge tend to fix this bend.
   - No protection necessary.

4. Milepost 1038.4 to Milepost 1037.4

   - Channel bank is within 70 feet of tracks.
   - No existing bank protection.
   - Little or no vegetation along east bank.
   - Preferred alignment:
     - 2800 feet long with a radius of 3600 feet.
     - None is within 70 feet of tracks.
     - Ties into existing rail dike at upsteam end.
     - Tail directs flow away from tracks into existing channel.
     - Construction outside of right-of-way is on Rio Rico property and cooperation is expected.
   - Alternate alignment:
     - 400 feet long, parallel to tracks.
     - All 4000 feet within 70 feet of tracks and right-of-way.
     - Flow direction not directed away from tracks at downstream end, but valley line indicates trend is naturally away from the tracks.

5. Milepost 1037.4 to Milepost 1035.4

- Channel bank is roughly 1500 feet from tracks.
- 100-year meander envelope is 800 feet from tracks.
- No protection necessary.

6. Milepost 1035.4 to Milepost 1035.0

- The upstream west bank is fixed by spur dikes and vegetation.
- Roughly 500 feet of existing riprap.
- Vegetation protects head of bend, but river is cutting behind vegetation.
- Preferred alignment:
  - 2300 feet long with a radius of 2400 feet.
  - 400 feet within 70 feet of tracks.
  - Construction outside of right-of-way is within Rio Rico property and cooperation is expected.
  - This alignment directs the flow away from the tracks and provides protection to approximately Milepost 1034.2.
- Alternate alignment:
  - 1300 feet long with roughly 600 parallel to and within 70 feet of the tracks.
  - 700 feet outside of right-of-way.
  - Flow direction at tail is essential to protect to Milepost 1034.2.
  - Construction outside of right-of-way is within Rio Rico property and cooperation is expected.

7. Milepost 1035.0 to Milepost 1034.2

- Little or no vegetation on east bank.
- 100-year meander envelope is at most 90 feet from tracks.
- Because of the existing flow direction, this stretch of tracks is highly vulnerable to damage.
- Both the preferred and alternate alignments at Milepost 1035.0 direct flow away from the tracks and protect this stretch. That alignment is essential since it is not feasible to bank protect all the way from Milepost 1035.0 to 1034.2.

8. Milepost 1034.2 to Milepost 1033.8

- Upstream west bank is not fixed and incoming flow direction is variable.
- Approximately 550 feet of existing riprap.
- Preferred alignment:
  - 2100 feet long with a radius of 3000 feet.
  - 399 feet within 70 feet of tracks.
  - Tail directs flow into next straight reach.
- Alternate alignment:
  - 1800 feet long, parallel to tracks.
  - All within 70 feet of the tracks.
  - Incoming flow not directed away from the tail, but vegetation helps protect the tracks.

9. Milepost 1033.8 to Milepost 1033.1

- Channel bank is roughly 400 feet from the tracks.
- 100-year meander envelope approaches to within 90 feet of tracks.
- East bank is well vegetated.
- No protection necessary.

10. Milepost 1033.1 to Milepost 1032.7

- Upstream west bank is not fixed and flow direction at head varies from almost perpendicular to parallel to the tracks.
- Roughly 450 feet of existing gabions and riprap.
- Preferred alignment:
    - 1800 feet long.
    - 850 feet within 70 feet of tracks.
    - Requires cooperation of land owner.
    - Tail directs flow away from tracks into existing channel and provides protection to Milepost 1032.4.
- Alternate alignment:
    - 1200 feet long.
    - 850 feet within 70 feet of tracks.
    - Ties into existing bank at downstream end.
    - Requires cooperation of landowner, but to a lesser extent than the preferred alignment.
    - Tail provides no protection to the downstream reach and directs flow to the opposite bank rather than into the existing channel.

11. Milepost 1032.7 to Milepost 1032.4

- Tracks are within 100-year meander envelope.
- No vegetation between river and tracks.
- Damage imminent in next large flood.
- The preferred alignment at Milepost 1032.7 will direct flow away from this stretch and protect the tracks.
- The only other option is to protect another 2000 feet parallel to the tracks.

12. Milepost 1032.4 to Milepost 1031.7

- Channel bank averages 600 feet from tracks.
- 100-year meander envelope averages 100 feet from tracks.
- The trend of the valley line and the river bend is to the west.
- Sparse vegetation along east bank.
- No protection necessary.

13. Milepost 1031.7 to Milepost 1031.0

- Channel bank remains at least 200 feet from tracks.
- Tracks inside 100-year meander envelope.
- East bank is sparcely vegetated.
- No protection necessary, but this should be reassessed after next flood.

14. Milepost 1031.0 th Milepost 1028.8

- Channel bank averages 1400 feet from tracks.
- 100-year meander envelope averages 1000 feet from tracks.

- Abandoned and active fields with some vegetation between tracks and channel.
- No protection necessary.

15. Milepost 1028.8 to Milepost 1027.9
    - Headcut forming between Mileposts 1028.8 and 1028.6.
    - incoming flow direction is approximately 30° to tracks, but overbank flow can approach parallel to tracks.
    - Roughly 1250 feet of track presently protected with riprap.
    - 100-year meander envelope is to the east of the tracks, indicating the river's trend is to continue attacking the tracks.
    - Preferred alignment:
        - 4300 feet long.
        - 3700 feet is within 70 feet of and parallel to the tracks.
        - The remaining 600 feet would require the participation of the landowner.
        - The tail follows the existing bank and directs flow along the existing channel.
    - Alternate alignment:
        - Same as preferred alignment, but tail extends parallel to track rather than following the existing bank.
        - 4700 feet long, all within 70 feet of and parallel to the tracks.

- Protection must extend further downstream than with the preferred alternative, because the direction of flow at the tail is not controlled.

16. Milepost 1027.9 to Milepost 1026.6
    - Channel bank averages 900 feet from tracks.
    - 100-year meander envelope averages 250 feet from tracks.
    - No protection necessary.

17. Milepost 1026.6 to Milepost 1025.9
    - Upstream west bank partially fixed by levee at Milepost 1027.2.
    - Existing bend along tracks has a sharp radius due to an almost direct angle of attack.
    - Roughly 1300 feet of existing gabions and riprap.
    - Tracks moved eastward approximately 170 feet from original alignment due to bank erosion.
    - Preferred alignment:
        - 3200 feet long with a 1600 feet radius.
        - All 3200 feet within the right-of-way and 70 feet of the tracks.
        - No attempt made to direct flow at the tail because of the proximity of the Tubac Country Club on the opposite bank.
    - There is no feasible alternate alignment.

18. Milepost 1025.9 to Milepost 1025.0
    - Channel bank is an average of 120 feet from tracks.

- 100-year meander loop is to the east of the tracks, indicating the river will continue to attack this stretch.
- Direct angle of attack by incoming flow.
- Abandoned fields with sparse vegetation provide little resistance to attack.
- This stretch has a high risk of damage in the next flood.
- Preferred alignment:
  - 1100 feet long, parallel to tracks.
  - All within right-of-way and 70 feet of tracks.
- There is no feasible alternate alignemnt.

19. Milepost 1025.0 to Milepost 1024.0
    - Channel bank averages 900 feet from tracks.
    - 100-year meander envelope averages 100 feet from tracks.
    - Channel is well defined with vegetated banks.
    - No protection necessary.
20. Milepost 1024.0 to Milepost 1023.2
    - Channel bank averages 200 feet from tracks.
    - 100-year meander envelope is to east of tracks.
    - Single, well defined channel.
    - Dense vegetation betewen tracks and channel.
    - No protection necessary because of vegetation, but should be reassessed after next flood.
21. Milepost 1023.2 to Milepost 1022.4
    - Braided channel begins (2nd sub-reach, see Section 3.1).
    - Approximately 500 feet of existing riprap.

- Stretch from Milepost 1022.9 to Milepost 1022.4 has no vegetation, shows signs of heavy overbank flow, and is highly vulnerable to damage.
- Preferred alignment:
  - 1900 feet long with 4000 feet radius.
  - 200 feet within 70 feet of tracks.
  - Cooperation of landowner (may be mine property) required for roughly 1700 feet of construction outside of right-of-way.
  - Tail alignment directs flow away from tracks and protects to Milepost 1022.4.
  - The tail alignment and the alignment starting at Milepost 1022.2 act in conjunction to protect the tracks between them.
- Alternate alignment:
  - 900 feet parallel to tracks.
  - All within 70 feet of the tracks and the right-of-way.
  - This alignment protects the immediate vicinity and does nothing to protect the downstream stretch.

22. Milepost 1022.4 to Milepost 1021.6
    - Levees at mouth of Montosa Canyon are perpendicular to flow and create a hard point.
    - Flow can attack from any angle.
    - Approximately 2400 feet of existing riprap.

- Preferred alignment:
  - Extend Montosa Canyon levee roughly 200 feet to protect the head of the bend.
  - 3900 feet long with radius of 5600 feet.
  - 2200 feet within 70 feet of tracks.
  - Tail alignment directs flow to the Amado bridge opening and away from tracks.
  - Requires cooperation of mining companies for cnstruction outside of right-of-way.
- Alternate alignment:
  - 3100 feet long, parallel to the tracks.
  - 2600 feet within 70 feet of the tracks.
  - Tail does not direct flow in any direction.

23. Milepost 1021.6 to Milepost 1020.5
    - Channel bank varies from 1500 to 800 feet from the tracks.
    - No vegetation between channel and tracks.
    - Overbank flow is evident.
    - No protection necessary, but this stretch should be reassessed after the next flood.
24. Milepost 1020.5 to Milepost 1019.4
    - Large headcut caused by overbank flow from Milepost 1020.5 to Milepost 1020.3.
    - Sopori Wash enters from opposite bank at Milepost 1020.0 and its flow directly attacks the tracks.
    - Approximately 2100 feet of existing riprap.

- Preferred Alignment:
  - 4600 feet long with a radius of 7200 feet.
  - 2800 feet within 70 feet of the tracks.
  - Requires cooperation of the mines for construction outside the right-of-way.
  - The tail alignment is essential to direct the flow away from the tracks and protect all the way to the Canoa Road Bridge.
- There is no alternative except to protect parallel to the tracks from Milepost 1020.5 to Milepost 1018.0, a distance of 2.5 miles.

25. Milepost 1019.4 to Milepost 1018.0
    - Channel bank varies from 100 to 800 feet from tracks.
    - Area between tracks and channel consists of abandoned, unvegetated fields with little resistance to erosion.
    - This stretch is highly vulnerable to damange in the next flood.
    - The tail of the preferred alignment at Milepost 1019.4 directs flow away from the tracks into the existing channel.
    - Protecting the entire 2-1/2 miles is not feasible.

IV. RECOMMENDATIONS

The results of this study indicate ten locations that are vulnerable to damage in the next large flood. Horizontal alignments for bank protection are proposed and alternatives are provided where feasible. The types of bank protection and design details will be detailed in the next phase of the project.

The proposed alignments show the maximum amount of protection required to maintain the integrity of the Nogales branch. As the site specific design and cost analysis proceed, the lengths and alignments will be modified. The recommended alignments are discussed in geater detail in the Discussion and Results Section.

The recommendations are as follows:

1 Milepost 1040.2 to Milepost 1039.9

- Preferred alignment:
  - 2800 feet along the east bank, all outside of right-of-way.
  - 400 feet of abuttment protection on west bank, all outside of right-of-way.
- Alternate alignment:
  - 400 feet of abuttment protection along the east bank, all inside right-of-way.
  - 400 feet of abuttment protection along the south bank, all outside of right-of-way.

2. Milepost 1038.4 to Milepost 1037.4

- Preferred alignment:

  - 2800 feet of bank protection, all outside of right-of-way.

- Alternate alignment:

  - 4000 feet of bank protection, all within right-of-way.

3. Milepost 1035.4 to Milepost 1035.0

- Preferred alignment:

  - 2300 feet of bank protection, with 400 feet inside the right-of-way.

- Alternate alignment:

  - 1300 feet of bank protection, with 600 feet inside the right-of-way.

4. Milepost 1034.2 to Milepost 1033.8

- Preferred alignment:

  - 2100 feet of bank protection, with 300 feet inside the right-of-way.

- Alternate alignment:

  - 1800 feet of bank protection, all within right-of-way.

5. Milepost 1033.1 to Milepost 1032.7

- Preferred alignment:

  - 1800 feet of bank protection, with 850 feet inside the right-of-way.

- Alternate alignment:

  - 1200 feet of bank protection, with 850 feet inside the right-of-way.

6. Milepost 1028.8 to Milepost 1027.9

   - Preferred alignment:

     - 4300 feet of bank protection, with 850 feet inside the right-of-way.

   - Alternate alignment:

     - 4700 feet of bank protection, all inside the right-of-way.

7. Milepost 1026.6 to Milepost 1025.9

   - Preferred alignment:

     - 3200 feet of bank protection, all inside the right-of-way.

     - No feasible alternative.

8. Milepost 1023.3 to Milepost 1022.4

   - Preferred alignment:

     - 1900 feet of bank protection, with 200 feet inside right-of-way.

   - Alternate alignment:

     - 900 feet of bank protection, all inside the right-of-way.

9. Milepost 1022.4 to Milepost 1021.6

   - Preferred alignment:

     - 3900 feet of bank protectin, with 2200 feet inside right-of-way.

   - Alternate alignment:

     - 3100 feet of bank protection, with 2600 feet inside right-of-way.

10. Milepost 1020.5 to Milepost 1019.4

- Preferred alignment:
    - 4600 feet of bank protection, with 2800 feet inside right-of-way.
- No feasible alternative.

The total length of bank protection with the preferred alignments is 30,100 feet, or 5.7 miles. The total length under the alternate alignments is 25,600 feet, or 4.9 miles.

The preferred alignments generally are located outside of the right-of-way and require construction in the river bed. They do provide a greater degree of protection than the alternates. The preferred alignments control the flow direction and fix bends and therfore protect a reach for thousands of feet downstream of the actual structure. They are river training structures and provide more protection through more floods.

The alternates are generally parallel to the tracks and within the right-of-way. They do little or nothing to direct the flow and their effect stops where the structure ends. Since bends and flow directions are not fixed, the points downstream where the flow will attack the tracks again are not predictable. To get the same degree of protection as with the preferred alignments, much longer stretches of track would have to be protected.

V. REFERENCES

1. Cooper Aerial Survey Company, Aerial photos from 1967, 1977, 1980, and 1983 for Santa Cruz River Between Canoa Road and Nogales.

2. Engelund, F.A. and Manch - Peterson J., Steady Flow in Contracted and Expanded Rectangular Channels, La Houille Blanceh, Vol. 8 No. 4, August-September, 1953, p. 464.

3. Engelund, F.A., Basic Research Progress Report No. 6, Technical University of Denmark, Copenhagen, June, 1964.

4. Federal Emergency Management Agency, Flood Insurance Study for Santa Cruz County, February, 1980.

5. Federal Emergency Management Agency, Flood Insurance Study for Pima County, December, 1982.

6. Henderson, F.M., Open Channel Flow, Chapter 10, University of Canterbury, Christchurch, New Zealand.

7. Leopold, L.B. and Wolman, M.G., River Meanders, Bulletin of the Geological Society of America, Vol. 71, June, 1960.

8. Pima County Department of Transportation and Flood Control District, Pima County Drainage Standards and Guidelines, 1982.

9. Pima County Department of Transportation and Flood Control District, Hydrologic Evaluation of the Santa Cruz River Basin, Arizona, October, 1974.

10. Wolman, M.G. and Leopold, L.B., River Floodplains:Some Observatics on Other Formation, U.S. Geological Survey, Professional Paper No. 282-C-1957.

11. U.S. Department of Transportaion, Highways in the River Environment, May, 1975.

APPENDIX

Maps, Sheets 1-20