HYDRAULIC AND SEDIMENT TRANSPORT ANALYSIS OF EXCAVATION IN CALABACILLAS ARROYO

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corrected to 10/28/85

Prepared for:

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I. Introduction

The Arroyo de las Calabacillas (hereafter Callabacillas Arroyo) drains an area of about 100 square miles and is tributary to the Rio Grande River near Albuquerque, New Mexico. Typical of channels and arroyos in the Southwest, Calabacillas Arroyo is a dynamic system with significant potential for lateral and vertical instability, particularly in response to large-scale natural or man-made changes. To assess channel response to sand and gravel extraction, the Albuquerque Metropolitan Arroyo Flood Control Authority (AMAFCA) contracted Resource Consultants, Inc. (RCI) for hydraulic, erosion, and sedimentation analyses of a proposed borrow operation. The specific scope of work is detailed in Table 1.

The proposed borrow operation would be in the reach from below Golf Course Road to Coors Road. Based on existing knowledge of the hydraulic and fluvial responses of Calabacillas Arroyo, any significant modification of the channel in this reach should be carefully evaluated. Of particular concern are the stability of the new Golf Course Road bridge and the existing Black's Diversion Outlet relative to a potential headcut from the borrow area and the stability of the Coors Road culverts from undermining due to degradation downstream of the borrow area. Lateral stability is also of concern, particularly in relation to established prudent lines for development considering flooding and erosion risk. The following analyses address these concerns, after a general discussion of fluvial response to sand and gravel extraction and a review of information from previous studies that is pertinent to this investigation.

Table 1
Scope of Work for Borrow Pit Analysis
Calabacillas Arroyo

1. Conduct site visit to gather necessary data, including Golf Course Road bridge plans and/or field measurements and to excavate a soil pit in the proposed borrow area.

2. Prepare discussion of the general theory and concepts governing fluvial response of a borrow pit.

3. Review hydrology from 1983 study and summarize information relevant to this study.

4. Modify Flood Insurance Study HEC-2 input file to reflect new bridge at Golf Course Road. Run HEC-2 to establish hydraulics in reaches 1-5.

5. Conduct Level I qualitative geomorphic analysis including, as a minimum:

    a. Site visit observations

    b. Summary of relevant Level I results from 1983 study

    c. Research refilling of borrow pit at confluence of the West Fork

    d. Discuss observations from soil pit

6. Conduct Level II quantitative geomorphic analysis including, as a minimum:

    a. Discuss bed and bank stability based on 1983 report and soil pit observations

    b. Evaluate incipient motion characteristics

    c. Determine armoring potential

7. Conduct Level III physical process mathematical modeling of borrow area response. This effort will include:

    a. Review and confirmation of sediment transport relationships

    b. Application of the RCI "gravel pit" model

    c. Interpretation of gravel pit model output to assess headcut potential, stability of Golf Course Road bridge, downstream degradation, and potential for lateral instability

8. Prepare brief report summarizing analysis approach and results.

II. Channel Stability Considerations

Excessive sand and gravel extraction in a river system can induce downstream degradation and upstream headcutting; however, under proper management, sand and gravel extraction can also increase the stability of a river system, particularly one that is overloaded with sediment. An overload of sand and gravel generally results in large bar formations throughout the channel. These bar formations are relatively stable compared to the typically finer material of the channel banks. Consequently, the bar formations can direct flow toward the relatively erodible bank material resulting in bank failure and lateral migration. Under this condition sand and gravel extraction can enhance channel stability. Hence, proper river management is required to maintain an equilibrium between excess production of sand and gravel and extraction of sand and gravel. Where this equilibrium is disturbed by a borrow operation, the primary concerns are the potential for degradation downstream of the borrow area and headcutting upstream or laterally from the borrow area.

The basic physical process responsible for degradation downstream of an extraction area is the deficit in sediment supply to the downstream reaches. In any channel reach the amount of material transported, eroded, or deposited is a function of two basic processes: (1) sediment supply and (2) channel transport capacity. Sediment supply to any given reach is the sediment quantity delivered to that reach by the adjacent upstream reach. Channel transport capacity describes the ability of a given reach to transport sediment. In any given reach, if the supply is less than transport capacity, that reach will be "out of balance" and will attempt to reach equilibrium by eroding sediment from the bed and banks. Therefore, excessive sand and gravel extraction can reduce supply to the point of causing degradation and bank erosion in a downstream reach.

The basic physical process responsible for initiating a headcut is the local increase in energy resulting from the sudden drop in bed elevation at the upstream end of the excavation, or pit. The drop in bed elevation can increase velocities and consequently the erosive power in the vicinity of the bed elevation change. Any factor that minimizes this effect can reduce the headcut potential and/or the distance that it will travel upstream.

Factors that will influence this effect include initial water volume in the pit, volume and depth of the excavation, ground-water levels, flood hydrograph characteristics, channel hydraulic conditions, sediment inflow rates and volumes, and bed-material size.

Headcut potential is strongly correlated with the initial level of water in the pit. For ephemeral or intermittent channels, gravel pits are often dry or only partially full depending on ground-water levels. Under these conditions no downstream hydraulic control exists and water will flow into the gravel pit with high erosive power. These conditions exist until the pit fills with water, at which time the overall channel hydraulic response will begin to control flow conditions. For a pit that is initially full of water, for example in a perennial stream or in a region of high ground water, overall channel hydraulics will control flow immediately as the storm inflow begins.

The potential for headcutting under the control of the overall channel hydraulic response depends on whether the flow is subcritical or supercritical through the extraction area. Application of specific energy concepts indicates that the flow depth through a depression (such as a borrow area) will increase for subcritical flow and decrease for supercritical flow (assuming the discharge per unit width remains the same). Therefore, in subcritical flow the channel velocities entering the borrow area would be expected to decrease, effectively eliminating any headcut potential that may have existed during the infilling process. Conversely, for supercritical flow, velocities may increase resulting in similar, if not greater, headcut potential relative to infilling conditions.

The volume of the pit and the inflow hydrograph influence how long conditions are favorable for headcutting in an initially dry or partially full pit. For a low-flow event, the pit will not fill with water and reach equilibrium as soon as it will for a high-flow event. During a high-flow event the rising limb of the hydrograph fills the pit with water rapidly and quickly drowns out the effect of a steeper energy slope. This concept is illustrated in Fig. 1 for representative low- and high-flow hydrographs. The cross hatching indicates the relative times required to fill the pits to the level where channel hydraulics control the flow conditions.

III. Hydrology

Basic peak flow hydrologic data for Calabacillas Arroyo were available from the Drainage Management Plan, Western Albuquerque Metropolitan Area (Matotan, 1975), and the Flood Insurance Study for the City of Albuquerque, Bernalillo County. A comprehensive review of this information and an update to reflect additional water diverted by the 7-Bar channel into Black's Diversion is provided by the prudent line report (Simons, Li & Associates, Inc., 1983). Peak flow information from these reports was accepted as correct. Information pertinent to this study is reviewed in Table 2.

The prudent line report also presented an analysis to establish hydrograph shape, since original calculations from the previous reports were not available. Similar to peak flow data, this hydrograph analysis was accepted as correct. Fig. 2 presents the hydrographs utilized for this analysis.

Table 2
Peak Discharge Data

Location	Recurrence Interval (yrs) 2	10	25	50	100
Above Black's Diversion	390	2,460	5,038	7,800	11,874
Below Black's Diversion	418	2,797	5,556	8,782	12,987

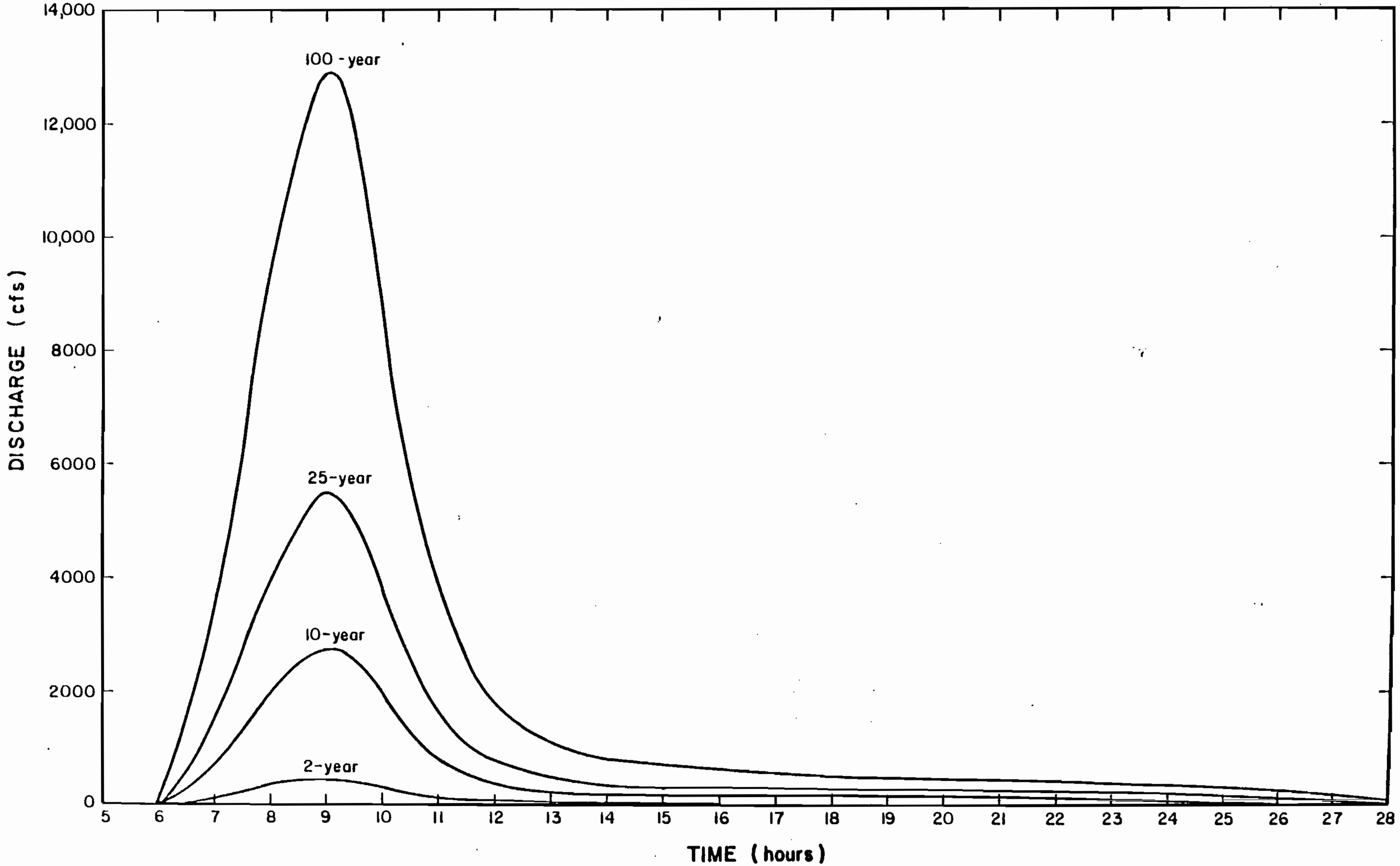

Fig. 2. Flood Hydrographs (100-, 25-, 10-, and 2-year) below Black's Diversion.

IV. Hydraulics

4.1. Data base

The HEC-2 data base used for the flood insurance study of Calabacillas Arroyo was available for this project from Bohannan-Huston, Inc. Data were provided on a magnetic tape which was loaded on an IBM PC computer for use in this analysis. Cross-section data on the HEC-2 tape were based on 1980 photography, and topographic maps were based on 1972 photography. A total of 33 cross sections labeled alphabetically (A-Z, AA-AG) upstream from the confluence with the Rio Grande were used. The cross sections from A to R were based on the 1980 aerial photography and from Section R upstream on the 1972 topographic map. Fig. 3 depicts relative locations of the cross sections.

4.2. Modifications to HEC-2 deck

For analysis of borrow area stability it was not necessary to analyze flow conditions upstream of Golf Course Road; however, since flow conditions are supercritical, it was necessary to account for the influence of the new Golf Course Road bridge on downstream hydraulic conditions. Available information for updating the HEC-2 deck included the report "Drainage Analysis for Golf Course Road Improvements" (Bohannan-Huston, Inc., 1984) and construction plan and profile sheets. As part of the bridge design, Bohannan-Huston, Inc., completed the HEC-2 analysis and presented summary output in the drainage analysis report. This information was used to establish a stage-discharge relation (Fig. 4) at Station 8+10.00, or 190 feet downstream of the bridge centerline. From plan-and-profile sheets, this location is in the natural channel 90 feet downstream of the end of the soil cement transition section below the bridge. Cross sections above this location were deleted from the HEC-2 input and the stage-discharge relation used to establish the initial water-surface elevation for supercritical profile computation.

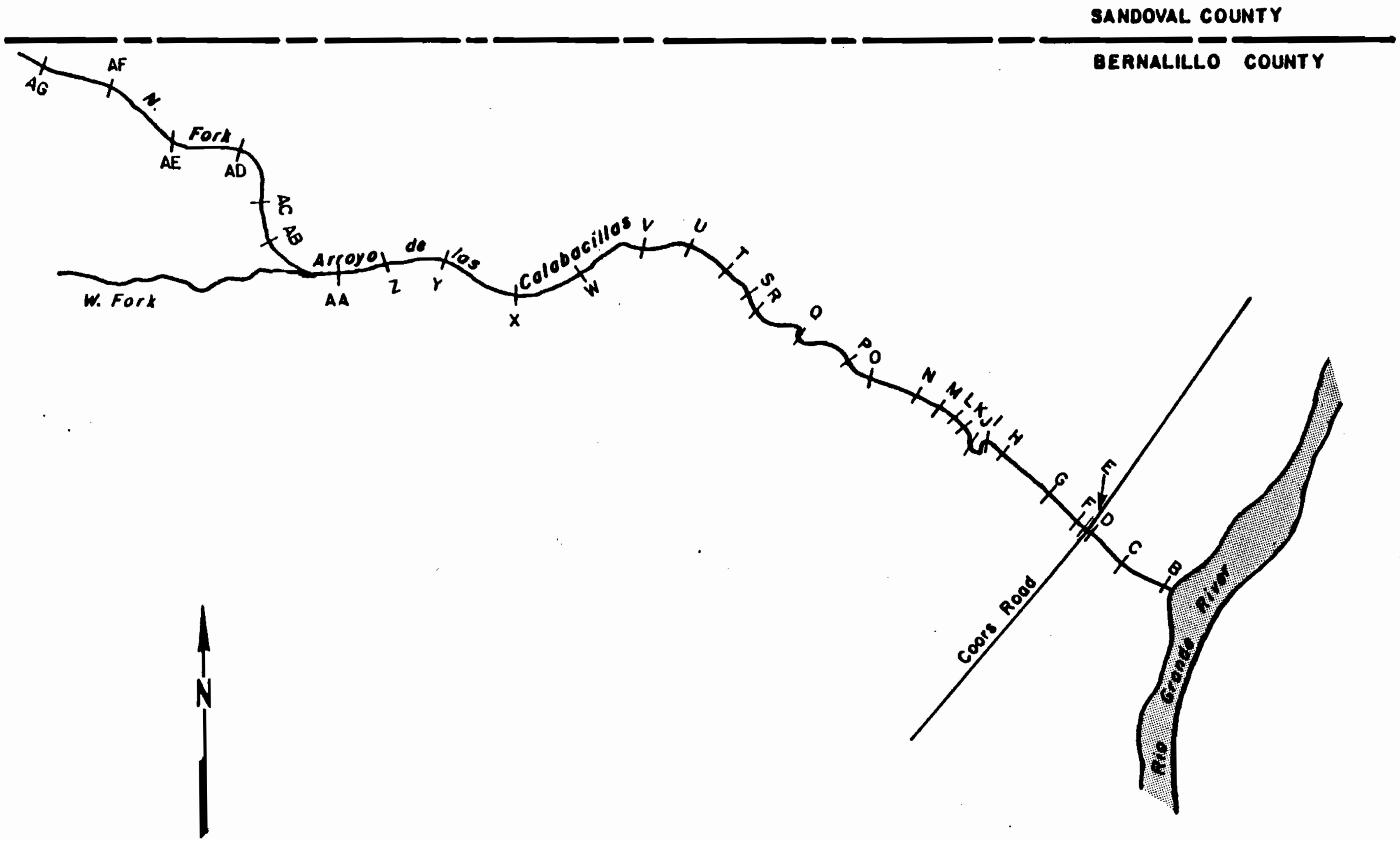

Figure 3. Approximate location of cross sections in study reach.

4.3. HEC-2 results for existing conditions

To establish baseline conditions and for purposes of incipient motion analysis, the HEC-2 deck as established above was run for discharges representative of the 10-year hydrograph and for the peak flow of the 100-year flood. A summary printout of results is given in Table 3.

V. Qualitative Geomorphic Analysis

5.1. Review of prudent line report

A comprehensive qualitative geomorphic analysis of Calabacillas Arroyo was presented in the prudent line report (Simons, Li & Associates, 1983). Results and conclusions from that analysis are still applicable and useful for understanding the fluvial response and dynamics of this arroyo. Pertinent information is reviewed below.

Calabacillas Arroyo is a steep, relatively straight channel with a large width-to-depth ratio. Characteristics of the watershed and the large alluvial fans present at the mouths of tributaries indicate that a large sediment load is delivered to the system. Old meander scars in the middle third of the arroyo document the long-term historical lateral instability that is possible. More recent activities, as documented by aerial photographs spanning 45 years, have included straightening of the channel in the lower third and significant disturbance due to excavation of borrow material in the upper third. The presence of this large borrow pit at the confluence of the north and west forks will impact the entire system for many years to come (an estimated 40 years to refill). The most significant potential impact will be a general reduction in downstream sediment supply and degradation downstream of the borrow pit as the pit refills with sediment.

From the Sandoval-Bernalillo county line downstream to the Golf Course Road crossing, channel banks are predominantly low (1 to 3 feet) and nearly vertical. Downstream of the Golf Course Road crossing, channel characteristics begin to change. In particular, the arroyo becomes more incised and in places exhibits high, nearly vertical walls. In plan view the arroyo alternates between highly sinuous, meandering reaches and fairly straight reaches. Fig. 5 is a definition sketch of the study reach which shows the approximate location of the two most significant meander bends. These will be referred to as the "S" bend, located below Golf Course Road, and the horseshoe bend, situated downstream of the Black's Diversion confluence. The remainder of the study reach, from the horseshoe bend downstream to the Coors Road crossing, is a reasonably straight incised channel with fairly steep banks on both sides.

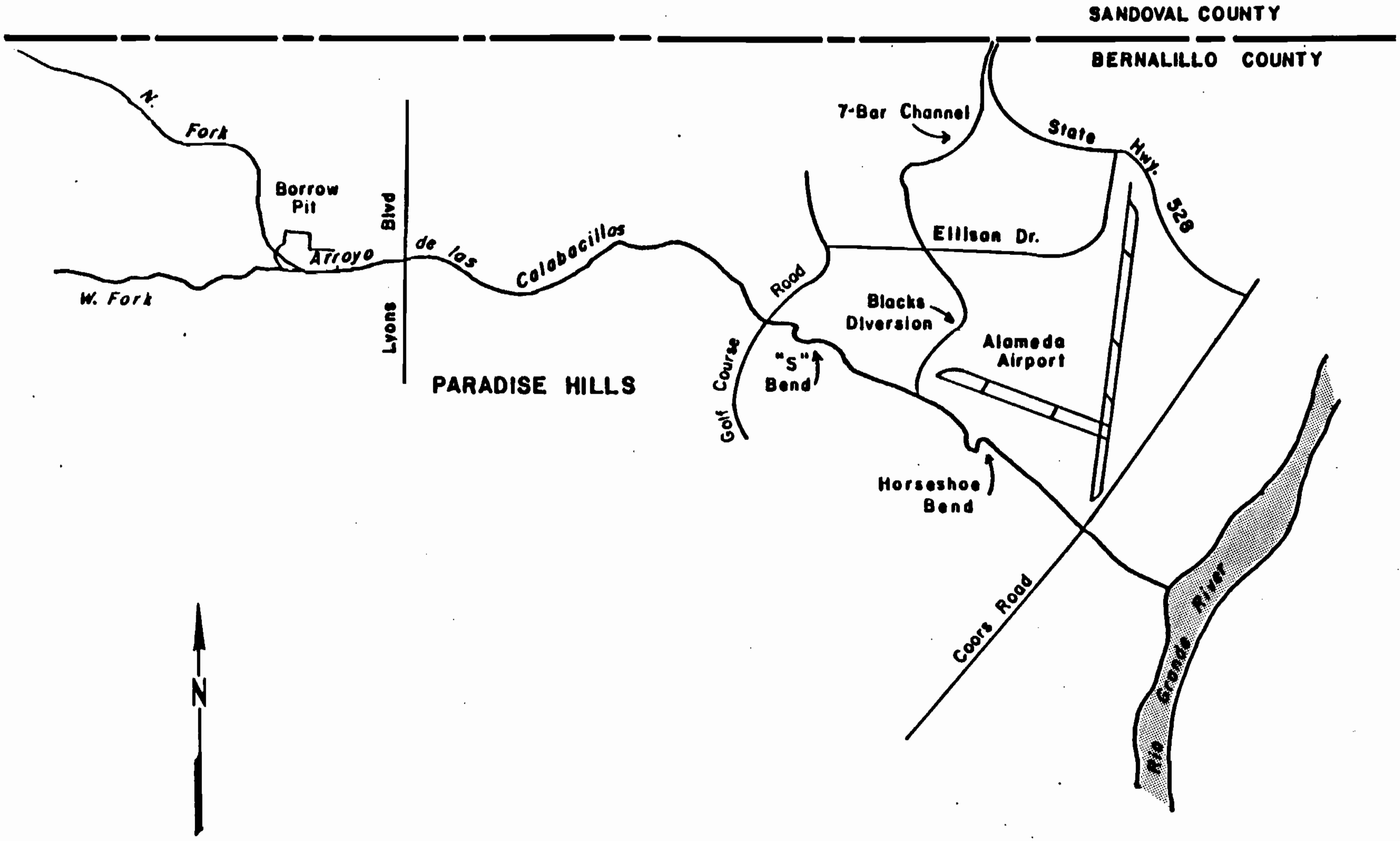

Figure 5. Study reach with major features identified.

Data available for the lower third are adequate for a longitudinal profile analysis. Changes in the thalweg elevation from 1972 to 1980 in this reach suggest significant excavation of material had occurred or that vertical instability is possible over relatively short time periods. Degradation of 4 to 5 feet along the thalweg was documented with both degradation and aggradation occurring over a relatively short reach of the channel. The observed headcut in the vicinity of Black's Diversion channel was well documented by this analysis. Given the upstream grade control provided by the Coors Road crossing, it is most likely that the observed degradation in this reach is the result of previous sand and gravel extraction.

An alluvial fan deposit from a tributary entering above the confluence of the north and west forks provides evidence of the large sediment loads delivered to the main channel from tributary sources. A reconnaissance of Black's Diversion, which discharges into Calabacillas Arroyo above the horseshoe bend, also indicates the large sediment loads delivered to the arroyo main channel. From its entrance near Cibola High School to its outlet in Calabacillas, the entire length of concrete-lined channel often contains significant sediment deposits.

Erodibility of the sandy soil found throughout the Calabacillas system is indicated by large eroded areas observed below drainage rundowns from developed areas. Drainageways consisting of asphalt pavement and revet mattresses had been constructed to convey runoff from streets to Calabacillas Arroyo. However, in many cases, flows have completely undermined the mattress protection, and large headcuts have been observed to be working up the rundowns.

5.2. Site visit observations

A recent site visit provided insight on changes since the prudent line report was prepared and more specific conclusions on channel substrate from soil pit observations. The site visit consisted of a walking/driving tour of the arroyo from the confluence of the West Fork downstream to Coors Road.

The borrow area at the West Fork confluence does not appear to have changed since the prudent line report was prepared. It is important to realize that fluvial system response in an arid area is hydrologically dependent; therefore, it is not unusual to experience long periods of no change in channel conditions. However, seeing the borrow area again, particularly the constriction at the outlet, underscored how significant this excavation will be to downstream fluvial response when hydrologically significant runoff events do occur.

In the reach between Golf Course Road and Coors Road where the proposed borrow operation will occur, a total of four soil pits were dug. The primary objective in digging the soil pits was to develop a better qualitative understanding of substrate conditions. Sediment sampling for the prudent line report considered primarily surface conditions; however, for purposes of evaluating borrow pit stability, it is necessary to establish substrate characteristics such as homogeneity, armoring potential, and presence of lenses of more or less erodible material. Fig. 6 illustrates the locations of the soil pits. The pits were dug with a backhoe to a depth of about 6 feet. Visual observations were made and when necessary a sample was collected for gradation analysis. Fig. 7 summarizes the field observations from the soil pits. The larger deposit of fine material (i.e., similar to surface sediments) just above Coors Road is probably the result of the backwater that exists in this reach under high flow conditions. At the other locations (which are more removed from Coors Road) the surface layer is typiccally 1.5-2.0 feet deep. A 1-2 foot layer of coarser material underlies the surface layer, followed by 2-3 feet of material that resembles the surface layer. The consistency in the depth location of the coarser layer suggests that it was deposited during a reasonably large flood, which had the transport capacity necessary to move larger sediments from the watershed and upper reaches of the arroyo.

Below Coors Road, degradation and undermining of the culverts is occurring. This could be the result of previous borrow operations in this reach or the result of sediment trapping upstream. In any case, some reconstruction and possibly revetment and/or grade control should be considered by the responsible agency.

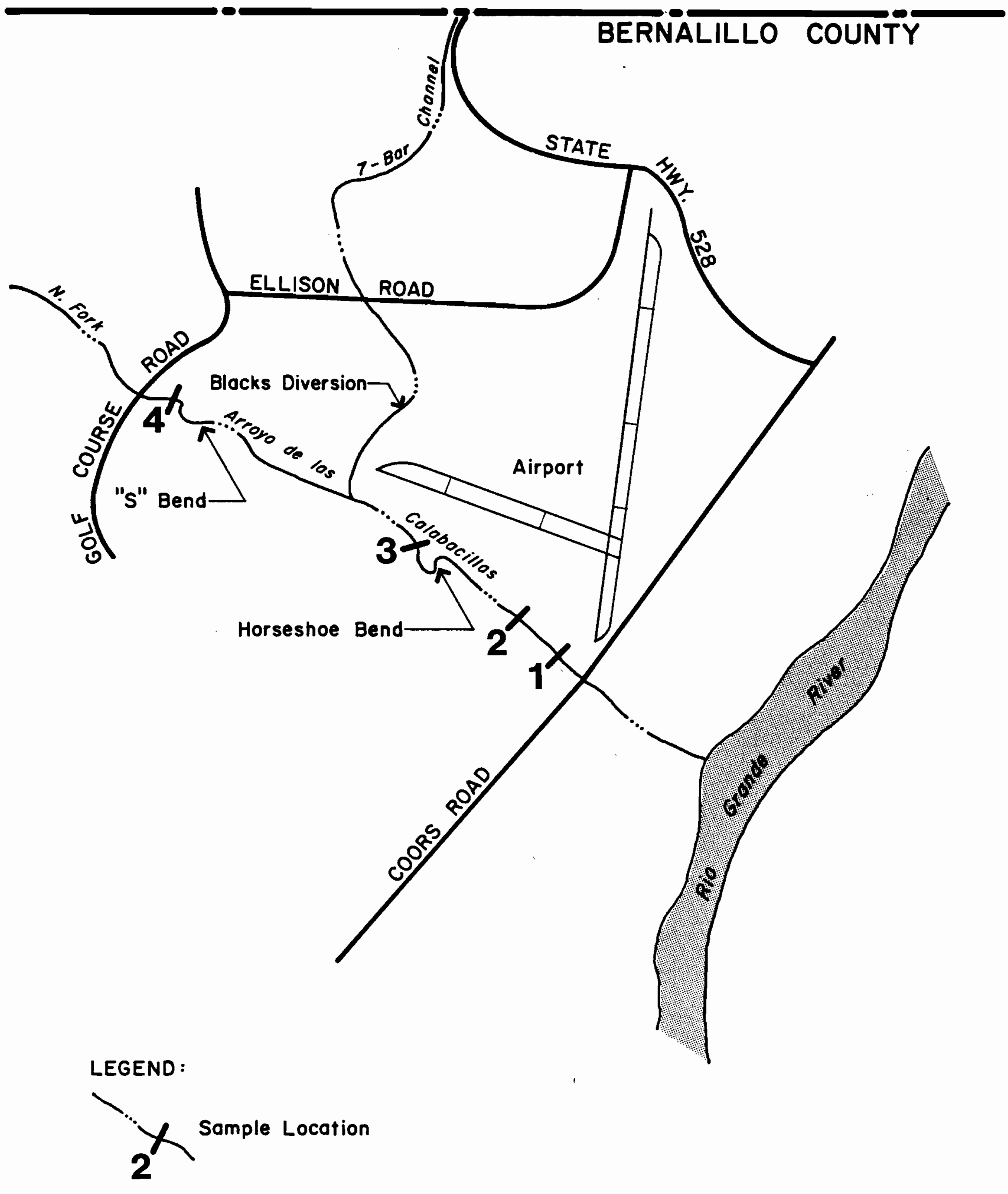

Fig. 6. Soil Pit Locations

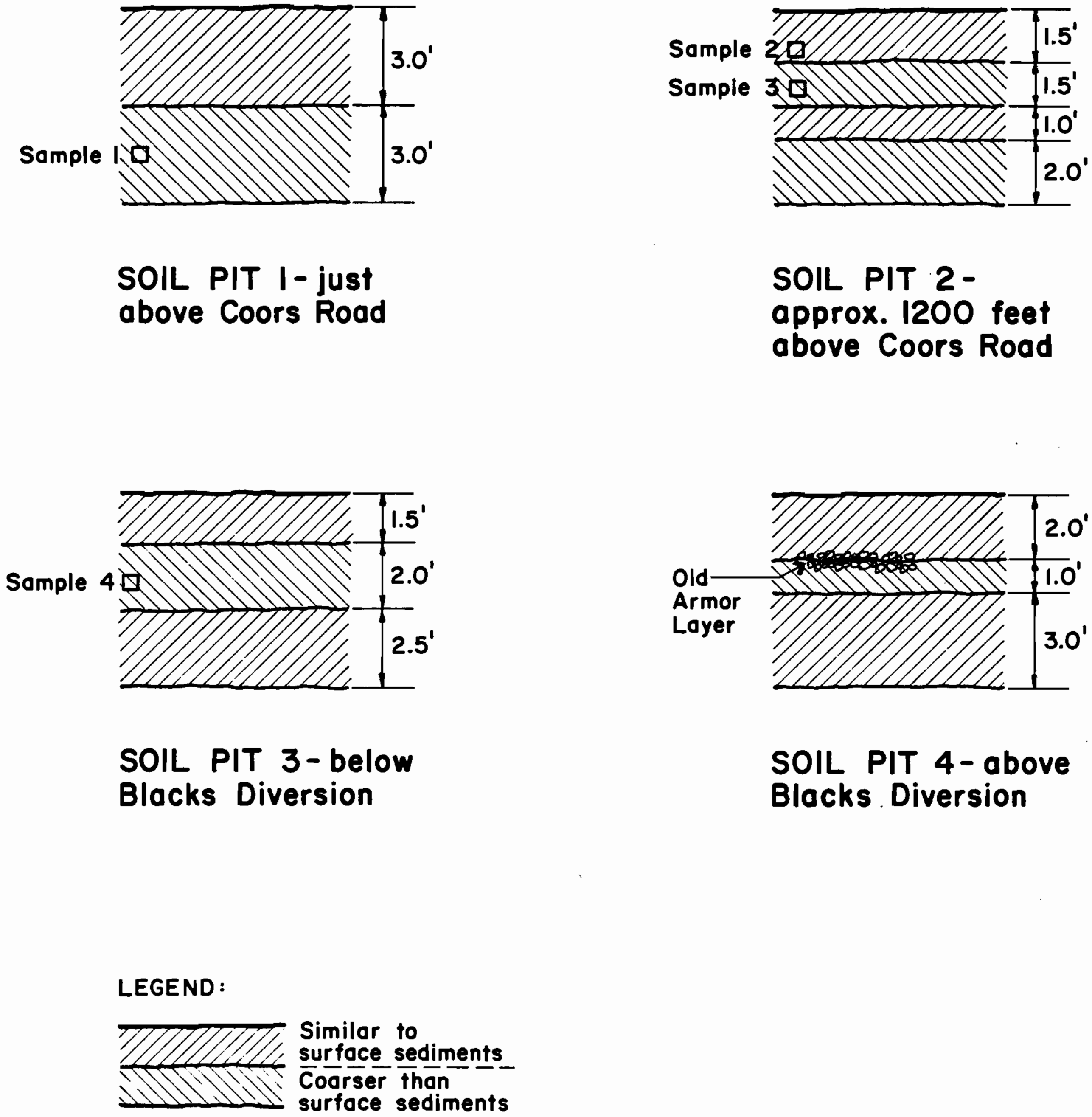

Figure 7: SUMMARY of SOIL PIT OBSERVATIONS

VI. Quantitative Geomorphic Analysis

6.1. Bed and bank stability

Assessment of bed and bank material is important in evaluating aggradation/degradation trends, as well as the potential for bank erosion and lateral migration. Bed material is the sediment mixture of which the streambed is composed and can vary widely between river systems and even within a given river system. Erodibility or stability of a channel depends largely on the size of particles in the bed. It is not sufficient to know only the median bed material size (D_{50}) in determining the potential for degradation. Knowledge of the bed material size distribution is also important. For example, in certain river systems the armoring process can be a significant factor in evaluating degradation. As water flows over alluvium consisting of a wide range of particle sizes, the smaller, more easily transported particles are carried away, while the larger particles remain, armoring the bed. Development of the armor layer through this process of hydraulic sorting prevents further degradation until a flow large enough to disrupt the armor layer occurs. Evaluation of armoring potential requires first understanding the bed sediment characteristics and incipient motion parameters (Section 6.2).

Extensive sampling of the bed (0-6 inch) and bank sediments was conducted for the prudent line report. Review of the prudent line report and gradation curves indicates there is a noticeable shift toward finer material downstream of Section Q. This was attributed to the small drainage entering from the right bank at Section Q and to Black's Diversion Channel entering near Section M. A sample of alluvial fan material deposited by the small drainage and a sample of material depositing in Black's Diversion Channel documented these channels as sources of fine material. In consideration of the sediment characteristics throughout the arroyo a single representative bed material gradation was adopted for the prudent line report (Fig. 8). However, it is important to realize that this gradation curve was representative of surface conditions (0-6 inches). To establish sediment characteristics below the surface, samples collected from the soil pits were analyzed.

Fig. 6 illustrated the location of the soil pits and Fig. 7 the location of samples in each soil pit. Gradation curves for the soil pit samples are given in Fig. 9. It is interesting to note that samples 2 and 3 are nearly identical to the representative gradation curve developed for the prudent line report. Samples 2 and 3 were taken from about 1.5 to 2.0 feet below the surface; therefore, except for the finer sediments deposited on the surface downstream of Section Q, as discussed above, the initial 2 feet of sediment is relatively consistent throughout the arroyo. Samples 1 and 4 are coarser and are representative of the layer typically 2-4 feet below the surface. Maximum particle size in this layer was about 1 inch and might provide enough material to form an armor layer (see Section 6.2).

Banks in the Calabacillas Arroyo are of varying heights consisting of both stratified and relatively noncohesive soils. In general, the banks are higher and the channel better defined in the lower half of the study reach as compared to the upper half. Where taller vertical banks exist, the soil is typically stratified. This is particularly true in the S- and horseshoe-shaped bends. Otherwise, the taller banks, particularly in the lower half of the study area, exist at or slightly less than the angle of repose.

6.2. Incipient motion analysis

An evaluation of relative channel bed stability can be made by evaluating the incipient motion parameters. Incipient motion analysis considers the critical or threshold condition where the hydrodynamic forces acting on the grain of sediment particles have reached a value that, if increased even slightly, will move the grain. Under critical conditions, or at incipient motion, the hydrodynamic forces acting on the grain area are just balanced by the resisting forces of the particle. For given hydrodynamic forces, or equivalently for a given discharge, incipient motion conditions will exist for a single particle size. Particles smaller than this size will be transported downstream and particles equal to or larger than this size will remain in place. The Shields relation can be used to evaluate the particle size at incipient motion for a given discharge:

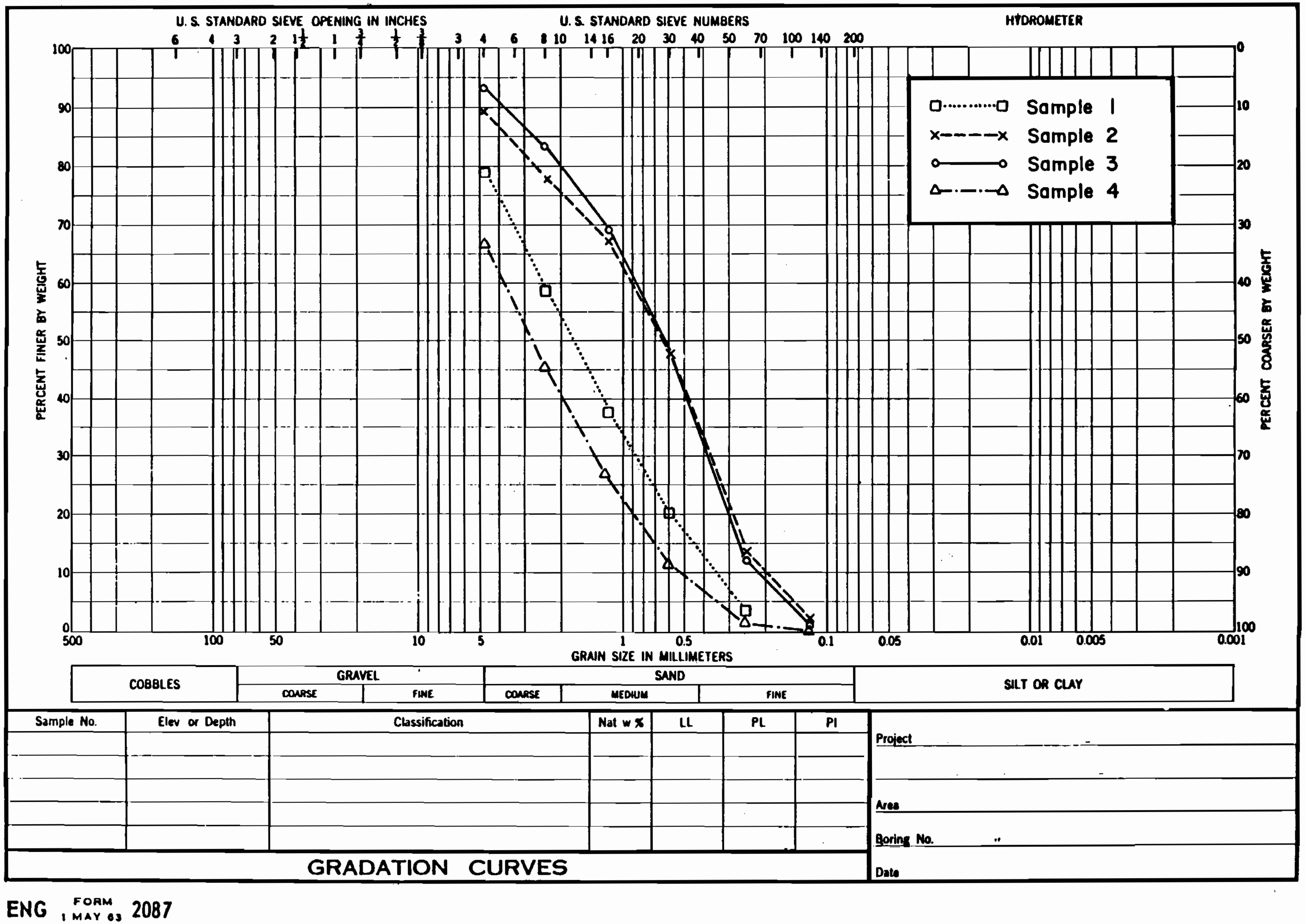

Fig. 9. Soil Pit Gradation Curves

$$D = \frac{T}{0.047\ (\gamma_s - \gamma)}$$

where D is the diameter of the sediment particle, T is boundary shear stress, γ_s and γ are the specific weights of sediment and water, respectively, and 0.047 is a dimensionless coefficient referred to as the Shields parameter.

For a given discharge the HEC-2 output provides the hydraulic information necessary to evaluate the boundary shear stress at various locations in the study reach. Using HEC-2 results representative of the 10-year hydrograph (from Section 4.3) and assuming standard values for water and sediment specific weights, incipient motion particle sizes for bed and substrate material in the borrow pit reach were calculated. Results are given in Table 4 and indicate that for even low discharge the channel velocity, and therefore shear stress, is large enough to transport even the largest particles in the coarse sediment layer 2-4 feet below the surface (see gradation curves, Fig. 9). Consequently armoring is not a significant factor in controlling the bed of Calabacillas Arroyo and significant degradation could occur, unless other controls are present. Other possible controls include geologic controls (i.e., rock outcrops) or man-made structures.

6.3. Conclusions from qualitative and quantitative geomorphic analyses

Results of the qualitative and quantitative geomorphic analyses suggest Calabacillas Arroyo is a very dynamic system that can respond rapidly to natural and man-made alterations. Furthermore, there is insignificant armoring potential to limit these large-scale responses. While it appears that appreciable quantities of sediment are supplied to the arroyo by the surrounding watershed, extraction of sand and gravel beyond a "safe yield" can promote large-scale instability. Evaluation of any given extraction at any given time must be in terms of cumulative effects and overall system response. The existing borrow area at the confluence of the west branch will act as a sediment trap for many years to come, signficantly reducing the source area available to refill any borrow taken below Golf Course Road. Also, as urbanization continues, the sediment supply

Table 4
Incipient Motion Calculations

Q (cfs)	$\overline{V}$ (fps)	D_c (ft)	D_c (mm)
500	7.24	0.16	49
1000	9.11	0.25	76
2797	12.85	0.50	152

from the watershed will become smaller. The estimated 40-year refill period of the existing borrow area balanced against the anticipated large-scale urban development over this same period implies that the sediment supply available downstream for extraction may never again be as large as it has been historically. By the time the existing upstream borrow area is refilled and significant sediment is again supplied downstream, urbanization will have reduced the overall supply from the watershed.

A number of recommendations can be made from the qualitative and quantitative geomorphic analyses concerning borrow operations in the near future between Golf Course and Coors roads. Since Black's Diversion is the first significant point source of sediment below the existing borrow area, any new extractions should occur downstream of the Black's Diversion confluence. Second, any borrow should be far enough downstream of the confluence to minimize adverse impacts from headcutting on the confluence or the new Golf Course Road bridge. Given the proximity of the horseshoe bend to the confluence and the potential instability of the banks in the horseshoe bend, any excavation should be limited further to the reach below the horseshoe bend. At the downstream end of this reach, an adequate buffer zone should be allowed between the borrow area and the Coors Road crossing to minimize potential for undermining. Therefore, based on these analyses, it can be concluded that there is only a relatively short segment of the reach from Golf Course Road to Coors Road where borrow operations should be permitted. The following chapter provides the basis for establishing recommended limits for borrow operations between Black's Diversion and Coors Road.

VII. Mathematical Modeling of Borrow Pit

7.1. Modeling methodology

As discussed in Chapter II, headcut potential for an initially dry pit in an ephemeral or intermittent channel occurs under the control of two completely different sets of hydraulic conditions. During the infilling process water flows into the excavation area with relatively high erosive potential. This period is referred to as the infilling period throughout this report. After infilling, overall channel hydraulic response establishes whether this initally large headcut rate increases or decreases. This period is referred to as the period of channel hydraulics control throughout this report. For supercritical flow conditions such as in Calabacillas Arroyo below Golf Course Road, the headcut rate during the period of channel hydraulics control is expected to increase due to acceleration of flow through the depression created by the excavation.

The modeling approach assumes that during the infilling process channel hydraulics upstream of the pit, and on the sloping upstream face of the pit, can be established by normal depth calculations. After the pit fills with water, the complete water-surface profile must be determined. Therefore, at any given time step on the inflow hydrograph, the method for calculating channel hydraulics is established based on the volume of water in the pit. With an appropriate sediment transport equation, the sediment continuity principle is then applied at each time step to determine the volume of erosion occurring between an upstream supply reach and the reach at the entrance to the excavation.

At each time step, the volume of erosion is distributed by assuming a pivot point located on the upstream face. The geometry of the channel and volume of erosion determine the upstream headcut distance. Downstream of this point the sediment eroded, or some fraction thereof, is assumed to deposit in the excavation area. After updating the geometry, the next time step is executed. The headcutting process generally continues until the initially abrupt slopes into and out of the excavation have been eliminated.

7.2. Initial conditions

As discussed in Section II, in ephemeral/intermittent channels small floods may result in greater headcutting than large floods, due to the length of the infilling period. For purposes of this project, the analysis was based on the 10-year flood. The headcut distance during the infilling period was evaluated for four excavation area geometrics. Response under control of channel hydraulics (i.e., after infilling) was then evaluated for the geometric condition considered to be the most reasonable, realistic alternative for implementation.

Results and conclusions of the qualitative and quantitative geomorphic analysis suggested that any excavations should be limited to the reach between the horseshoe bend and Coors Road. Based on cross sections in this reach, a typical borrow area width would be about 40 feet. The maximum possible excavation length in this reach is about 2,600 feet. Allowing for assumed buffer distances, a more reasonable maximum length of 1,500 feet was adopted for analysis. For a more conservative analysis a length of 750 feet was also studied. Excavation depths of 5- and 10-feet were considered, assuming removal would be by scraping operations. A 2:1 (horizontal:vertical) slope at the entrance to and exit from the excavation was used for all configurations based on the assumption that equipment would move in and out of the excavation area at the upstream end. Table 5 summarizes the geometric configurations considered during the infilling analysis.

7.3. Sediment transport equation

For the prudent line report, sediment transport equations by size fraction were developed for the representative particle gradation curve (Fig. 6). The coarser layer of sediment below the surface, identified from soil pit observations and gradation curves, will influence channel response to sand and gravel extraction; therefore, it was necessary to establish sediment transport relationships representative of both the finer surface sediments and the coarser subsurface sediments. For purposes of the gravel pit model, a single transport equation (rather than by size fraction) was utilized. Similar to the methodology employed in the prudent line study, a power curve relationship was developed from the Meyer-Peter, Muller bed load equation combined with the Einstein suspended bed material transport procedure. The final form of the equation was

Table 5
Excavation Geometrics Considered
During Infilling Analysis

Configuration number	Width (ft)	Depth (ft)	Length (ft)	In-situ volume (CY)
1	40	5	750	5,555
2	40	5	1,500	11,110
3	40	10	750	11,110
4	40	10	1,500	22,220

$$Q_s = 9.19 \times 10^{-6} V^{4.059} YH^{0.054} TW$$

where Q_s is the bed material transport rate (cfs), V is the mean channel velocity (fps), YH is the hydraulic depth (ft), and TW is the water surface top width (ft).

7.4. Results of infilling analysis

The 10-year hydrograph was discretized into 6-minute time steps. Table 6 gives the discharges for each time step for the initial portion of the hydrograph for the infilling analysis. The infilling analysis progressed step by step until the combined water/sediment volume in the pit exceeded the initial excavated volume. Table 7 summarizes the headcut distance at each time step for each geometric configuration. Results indicate the channel response during infilling was relatively rapid with about 1.5 foot of headcut occurring each minute. The relatively constant rate of headcutting illustrates the significant influence of the duration of infilling on the total headcut distance. For larger pit volumes or lower inflow hydrographs, it is apparent the headcutting distances would increase proportionally. Configurations 2 and 3 illustrate that significantly greater headcut potential exists for short, deep pits compared to long, shallow pits of the same volume. Bank stability along both the excavation area and along the headcut zone would also be expected to be improved for shallow excavations.

The objectives of this study can best be met by the analysis of the potentially least damaging excavation in order to establish a representative "baseline" of channel response to borrow operations. Based on these observations, geometric configuration 1 was selected for further analysis (during the period of channel hydraulics control).

7.5. Results under channel hydraulics control

Analysis of conditions under control of channel hydraulics involved HEC-2 analysis for each time step beyond the infilling period. These calculations started with the geometric conditions existing at the end of infilling and for the discharge of the next time step. After each time step, the geometric conditions were updated and the next time step

Table 6
Discharge at Each Time Step
for 10-Year Hydrograph

Time step	Time (min)	Discharge (cfs)
1	6	25
2	12	75
3	18	140
4	24	200
5	30	260
6	36	330
7	42	400
8	48	475
9	54	550
10	60	650

Table 7
Headcut Distance as a Function of
Time for Each Geometric Configuration

Geometric configuration (see Table 5)	Time (min)							
	6	12	18	24	30	36	42	48
1	5	20	32	40	-	-	-	-
2	5	20	32	40	44	46		
3	3	15	30	44	55	66		
4	3	15	30	44	55	66	79	

executed. The analysis continued until the bed slope into the excavation area was within 20 percent of the original bed slope. Beyond this point in time, long-term erosion/sedimentation processes are assumed to ultimately fill and reestablish the bed profile throughout the excavation area.

Results of the analysis are summarized on Fig. 10. As suggested in Chapter II, the rate of headcutting under supercritical flow conditions is significantly greater than that during the infilling period. The average rate is almost 9 feet/minute and the ultimate headcut distance is nearly 1,500 feet in just under 3 hours. This illustrates the much greater potential for headcut damages in a supercritical flow channel. In a subcritical flow channel the headcutting after infilling would have been relatively minimal, while for supercritical channels the headcut rate can increase significantly, in this case by as much as 3 or 4 times after infilling is complete.

As a final note, it is important to realize that these results were derived assuming that the reach immediately upstream of the excavation area was a supply reach (i.e., where equilibrium exists between supply and transport capacity). However, because of the possibility of sediment overloading in the system, particularly immediately downstream of major tributaries such as Black's Diversion, equilibrium may not exist at this location and a greater sediment supply may be available to the excavation reach than was assumed by the analysis procedure. The analysis also does not consider the potentially large non-point sediment supply from lateral inflow along any given reach. Assessment of sediment supply questions would require an analysis of watershed sediment yield rates, which would also quantitatively establish a "safe yield" for excavation. Therefore, it can be concluded that the analytical approach reflects the worst-case conditions and that there are some circumstances where the headcut may not be as severe. In contrast it is important to reemphasize that the potentially least damaging excavation geometry was selected for analysis to establish a representative baseline condition (see Section 7.4).

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As a final note, it is important to mention that the analysis was based on reasonably conservative assumptions for estimating sediment supply conditions. A more complete assessment of sediment supply questions would require an analysis of watershed sediment yield rates, which would also quantitatively establish a "safe yield" for excavation. Therefore, it can be concluded that the analytical approach reflects the worst-case conditions and that there are some circumstances where the headcut may not be as severe. In contrast it is important to reemphasize that the potentially least damaging excavation geometry was selected for analysis to establish a representative baseline condition (see Section 7.4).

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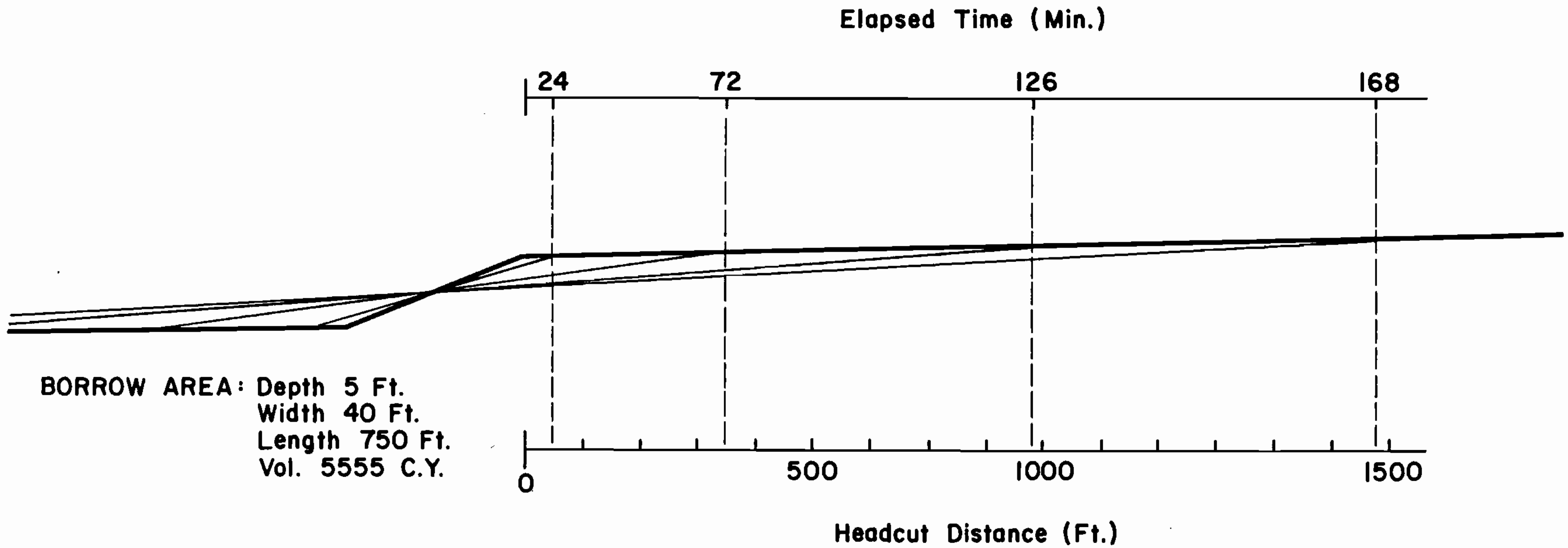

Fig. 10. Summary of Headcut Analysis Results.

VIII. Conclusions and Recommendations

Conclusions

1. Ephemeral/intermittent channel response to sand and gravel extraction can be more sensitive during low-flow events due to the longer duration of the infilling period.

2. In supercritical flow channels such as Calabacillas Arroyo, the headcut potential is significantly greater than it is for subcritical flow channels.

3. Qualitative and quantitative geomorphic analyses suggest that Calabacillas Arroyo is a very dynamic system that can respond rapidly to natural and manmade alterations.

4. Given the size and gradation of bed material in Calabacillas Arroyo, there is an insignificant potential for armoring to limit large-scale responses.

5. The existing borrow area at the confluence of the West Branch of Calabacillas will act as a sediment trap for years to come, significantly reducing the sediment source area for downstream reaches.

6. Continued urbanization north and south of Calabacillas Arroyo will also reduce the long-term sediment supply to downstream reaches.

7. Considering sediment supply issues, any borrow taken below Golf Course Road should be limited to the reach below Black's Diversion. Considering stability issues of the horseshoe bend, any excavation should be further limited to the reach downstream of the bend.

8. For the relatively small excavation volume assumed for purposes of this analysis (5,555 CY), the headcut during infilling for the 10-year flood is reasonably insignificant; however, due to supercritical flow conditions, the headcut after infilling can be quite significant (1,500 feet).

9. With the borrow operation limited to the reach below the horsehsoe bend, an adequate buffer (about 1,700 feet) will exist to minimize impacts on Black's Diversion, and for all practical purposes eliminate any danger to the new Golf Course Road bridge.

10. Results of the prudent line report indicated that the typical bank height in the excavation reach is about 30 feet and the maximum stable height, based on slip circle analysis, was 40 feet. Therefore, excavations less than 10 feet deep are not anticipated to promote lateral instability.

11. The relatively insignificant headcutting during infilling, compared to after infilling, suggests that the initial volume of the pit (as it affects infilling duration) should not significantly influence overall headcut distance; however, the initial volume can have significant influence on downstream degradation.

12. Complete understanding of the potential for downstream degradation, including evaluation of the stability of Coors Road, requires a comprehensive safe yield analysis. If the channel is significantly overloaded with sediment, as historical evidence suggests, excavation up to the safe yield could be beneficial.

Recommendations

1. A small one-time borrow operation of the magnitude analyzed in this study could be approved with minimal risk. To allow required buffer distances, the borrow area should be centered in the reach between the horseshoe bend and Coors Road. Prior to approving subsequent excavations a monitoring program should be established to assess infill of the excavation area or a safe yield analysis should be performed.

2. If approval of large-scale borrow operations is anticipated, a sediment yield/safe yield analysis should be conducted as part of an overall drainage master plan for Calabacillas Arroyo.