Order Number 1331418

Performance of drainage channels in Pima County, Arizona

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The University of Arizona, 1987

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PERFORMANCE OF DRAINAGE CHANNELS IN PIMA COUNTY, ARIZONA

by

PETER SCOTT MILLER

A Thesis Submitted to the Faculty of the

DEPARTMENT OF CIVIL ENGINEERING
AND ENGINEERING MECHANICS

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE
WITH A MAJOR IN CIVIL ENGINEERING

In the Graduate College

THE UNIVERSITY OF ARIZONA

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ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to my advisor and thesis director, Prof. E. M. Laursen and also to Prof. Margaret Peterson for her valuable assistance and support.

I would also like to thank Messers. Bud Dooley and Jerry Jones for the use of their records and engineering facilities. Their information made this research topic possible.

I must also thank my parents, Lorraine and Bill, for their patience and constant encouragement through this challenging ordeal.

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ABSTRACT

An analysis of drainage channel stability in urbanizing watersheds was completed in this study for areas in Pima County, Arizona. Existing channel geometry and longitudinal slope were compared to original design channel geometry and longitudinal slope. Original design channels existed in undeveloped watersheds. Information on current amounts and types of development were gathered for each channel location as well as current channel geometry and longitudinal slope. The analysis of these data showed a significant relationship between basin urbanization and reduced channel stability.

CHAPTER 1

THE UNCERTAINTY OF STABLE CHANNEL DESIGN

The impetus for this study of drainage channel stability resulted from the author's difficulty in applying the Pima County recommended stable channel criteria to subdivision-size channels. The difficulty in using these criteria in design came in establishing the spacing between grade control structures, which is determined by multiplying the difference in top elevation of two adjacent structures by a constant and dividing by the difference between the ground slope and the designed stable slope. These slopes are in percent form, making the constant equal to one hundred. A maximum difference in top elevation of adjacent grade control structures of two feet is recommended by the Pima County Drainage Design Manual (1982). Using the stable slope equation for the calculation generally gave a very small value of approximately 0.1 to 0.3 percent for the ultimate, designed stable slope. This approximate value was encountered using the equations both for clear-water flow and for sediment transport conditions. These small values of slope were a cause for wondering about the actual stable slopes produced by basins in this area.

The first step in this study was to research the stable slope equations. Two stable slope equations are used by Pima County for the design of grade control structures, one for clear-water flow and one for sediment transporting flow.

The two-year discharge is used in computations with both stable slope equations. The equation for clear-water conditions is satisfied by only two parameters, flow per unit width and the Manning roughness factor, as follows:

$$Sc = ((1.45 * n)/(q^{0.11}))^{2} \tag{1}$$

where

Sc = calculated stable slope (ft./ft.);

n = Manning's roughness coefficient;

q = flow per unit width (c.f.s./ft.).

The clear-water equation was based on the assumption that for a stable channel a Froude number of 0.35 must be established, as recommended in a study conducted by the U.S. Bureau of Public Roads, Keeley (1961) for roadside drainage channels in Oklahoma. Those channels were in soils that are not commonly found in Pima County. Soils in that area have more silt and clay, while sand predominates in Pima County. The Oklahoma channels also had a different geometry than channels in the Pima County area, being generally deep and narrow, whereas Pima County channels are wide and shallow, as generally found in alluvial pediment areas. The Oklahoma vegetative cover density was also greater than in Pima County.

The stable slope equation, which considers sediment transport, was determined by a study conducted by Simons and Li and Associates (1981) for Pima County using data from watercourses having much higher discharges than the channels to which the equation is generally applied in design in Pima County. The roughness coefficients used in that study were lower than values normally used for minor drainage channels. The sediment-transporting equation is as follows:

$$Seu = (nu/nn)^{2} * (Qwu/Qwn)^{-1.4} * (Tu/Tn)^{0.5} * (1-R)^{0.9} * Sn \qquad (2)$$

where

Seu = stable equilibrium slope after urbanization;

nu = Manning´s roughness coefficient (urbanized);

nn = Manning´s roughness coefficient (natural);

Qwu = 2-year peak discharge (urbanized);

Qwn = 2-year peak discharge (natural);

Tu = 2-year flow top width (urbanized);

Tn = 2-year flow top width (natural);

R = reduction factor for sediment supply;

Sn = natural slope or existing slope.

The lower roughness value used in the Simons and Li study would result in high velocities in the smaller channels, and in order to obtain non-eroding velocities, flatter slopes would be needed. If the roughness value were increased, velocites would be less erosive, and this would steepen the value of slope needed for a stable channel. The sediment-transporting stable slope equation includes the ratio of the channel top width prior to and after development. This ratio sometimes is meaningless because of alteration of drainage patterns. The designed channel could be shorter or longer than the natural channel while the difference in elevation generally remains constant. A change in length will affect the numerical value of the slope, and could lead to discontinuities of calculated values when applying the stable slope equation.

The sediment-transporting stable-slope equation includes a sediment reduction factor that reduces the calculated stable slope by a factor between unity and one tenth to account for a reduction of the sediment supply. This factor should only be used when the impervious cover of the upstream basin is greater than 50%.

The two stable slope equations used by Pima County typically produce excessively flat design stable slopes that minimize spacing of grade control structures, thus increasing the cost of channel construction.

These factors pose questions as to the suitability of applying these equations in Pima County. Both the above arguments and the author's design experience applying these equations indicate they should be used with great care.

Study Description

In order to explore the stable slope question, an understanding of the actual channel responses was required. While in the employment of a local consulting engineering company, the author made use of twenty years of records from the design and construction of Pima County subdivisions in this analysis. Work files, drainage reports, and design plans were used to compile a source of historical channel data to compare to actual existing field conditions. Other information was obtained from plats of subdivisions and aerial photographs, including zoning and the age of subdivisions.

Field measurements were then conducted to assess current channel conditions. At each site a sediment sample and a photograph were taken. The channel slope and bottom width were measured with the use of a hand level and a cloth tape. These data were used to determine adjusted slope ratios, width to depth ratios, Froude numbers, and sediment concentrations.

For natural basins the adjusted slope ratio is the ratio of the existing slope to the design slope. The adjusted slope ratio for urban areas utilizes the basin slope as the "existing" slope. An adjusted slope ratio of less than one indicates that the channel has degraded from its initial steeper slope. The width to depth ratio is a measure of the relative amount of channel adjustment. Once again, the existing width/depth value is compared to the design width/depth ratio. If the ratio is greater than one, the existing channel has aggraded; the existing channel has reduced its depth and increased its width from its original design geometry. An adjusted slope ratio which is less than one will generally have an accompanying width/depth ratio also less than one. These parameters were developed in order to be able to study the changes in the channels with time.

Study Assumptions

Some simplifying assumptions were made to compare certain terms and also to reduce the number of unknown quantities in order to assure accuracy for the validity of the original design. The information is valid only if work was constructed as the drawings specified. When available, as-built design drawings were used in the analysis.

The next assumption dealt with the Manning roughness coefficient. A single "n" value was needed to reduce variability of results. This term is highly subjective and is a critical component of open channel flow computations. A roughness value of 0.025 was used for all calculations because: (1) most channels investigated have a sand bed generally free of vegetation; (2) most vegetation is on the channel banks and in overbank areas; (3) depths of the flow were usually contained by the banks and were not very deep.

A specific flow frequency has to be utilized as a benchmark for studies of this nature, as the starting point for comparing different sites. A 25-year storm recurrence interval was used in this investigation. Work at the sites used in this study had been in place from six to fourteen years as of the fall of 1984. Due to recent weather patterns, it is probable that all the watersheds have experienced a 25-year flow event. A relatively high return frequency flow, such as the 25-year event, should have a greater effect on channel stability than more frequent lower flow values. An adjusting channel will change more with high velocity and long lasting flows, which are representative of less frequent events. The flow events of October 1983 dramatically illustrated this concept. Higher flow events have long sediment-transporting durations, which moves more sediment through the channel system.

The 25-year return interval flow is a reasonable choice also when considering the change in runoff due to increase of imperviousness of a basin. For a storm with a given intensity and duration, a typical developed basin will probably produce more runoff than the same basin prior to development. If a hydraulic structure was designed for a 10-year discharge in an undeveloped basin, the same storm can be expected to produce a higher discharge value when the basin is developed. This higher value could approach a 25-year storm under natural conditions.

Another assumption used in this study was that the drainage channels were not maintained after initial construction, an assumption generally easy to check by a field investigation. Any channel which obviously was maintained was not included in this study; thus, channel adjustments were initiated by development of the watershed and not by mechanical means. Also, it was assumed that the channels were relatively straight and showed little or no meandering.

Degradation, as used in this study, does not refer to uniform lowering of the channel bed relative to the design profile as constructed, but rather refers to the channel bed flattening upstream from a control point at which the bed pivots downward to flatten the slope. (The channel control point is downstream of the slope adjustments, and degradation progresses in an upstream direction.) This location of the channel control point is not valid for aggrading systems because aggradation progresses in a downstream direction.

The erosion process has general limits of extremes governed by two possible conditions. One is the natural undeveloped condition, with the channel slope closely related to the local watershed basin slope. This slope value is determined by natural geologic and meteorologic processes and sets an upper limit for channel slope for natural undeveloped conditions. The second condition is the fully developed watershed, a condition assuming maximum density of development where the watershed is not a signifi cant source of sediment supply to the channel system. After sufficient time, channels in such watersheds will achieve a stable slope, which is the lower limit for channel slope, reflecting the above constraints. These limiting conditions give the extreme limits for values of channel slope. This study addresses the effects of development on channel stablilty.

CHAPTER 2

DESCRIPTION OF STUDY SITES

This chapter presents a qualitative description of the sites included in this study. Each site was assigned a number/letter plotting designation. The numbers are from one to three, designating the age of the basin. Number one represents basins from six through eight years old from the time of final platting to the time when the field measurements were obtained. Number two designates basins from nine through eleven years old; number three stands for basins from twelve through fourteen years old. The letter designation is the size of the basin in its relative age group. The larger the letter, the larger the basin size. Table 1 summarizes basic basin data for the convenience of the reader, and is preceeded by paragraphs describing each site and a current photograph.

Figure 1 shows a constructed drainage channel with approximately 3.5 feet of drop at the inlet of the channel due to scouring. This drop was not a part of the original design. This is not local scour but the whole channel degrading longitudinally. At the end of the constructed bank protection, the channel has gotten wider and shallower as the result of sediment deposited from the eroded upstream section. Present condition of the channel is due to a sediment supply rate which is too small for the design slope. Grade control structures are necessary to control the slope adjustment of the channel.

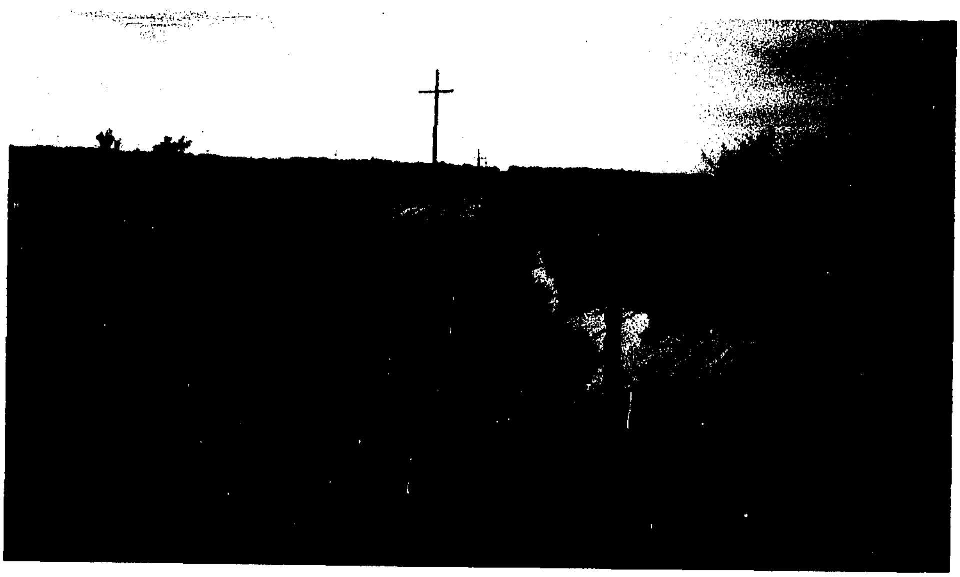

Figure #1. Plotting Designation 1H
Rancho Feliz #4

Figure 2 shows a drainage channel constructed on a very steep grade with no grade control structures. As a result, the upper portion of the channel has degraded severely while the lower section of the channel has heavily aggraded. In the degraded section the channel has narrowed and the slope flattened. In the downstream aggraded section, the width of channel has drastically increased, and its slope has remained steep. The capacity of the channel in this reaach is greatly reduced and poses a flooding hazard to adjacent residences. Deposition at the end of the channel fills the entrance of a drainage pipe used by site number three, and flow must travel over a road.

Figure #2. Plotting Designation 1D
Rancho Feliz

The third site, Figure 3, is a constructed channel designed with a very flat slope compared to the upstream reach. The culverts contributing to this channel are completely blocked at their entrances, and flow entering the channel must come over the adjacent roadway. Sediment from the badly aggraded upstream section is filling in this reach of channel. In an effort to accommodate the large sediment load, the channel slope has steepened, and some sediment has dropped out at the beginning of the channel. The hydraulic capacity of the channel has been only partially reduced.

Figure #3. Plotting Designation 1J
Rancho Feliz

Figure 4 shows a constructed drainage channel that has not changed from its original construction geometry. It is controlled by geologic conditions and cannot be eroded nor can it sustain vegetation. This site was not used in the quantitative section of this study.

Figure #4. Plotting Designation 1B
Rancho Feliz

Figure 5 shows a constructed drainage channel downstream of site number four. The channel has not exhibited much adjustment from its design state and does not show signs that much flow has traveled down the channel. The channel is full of vegetation, and there is no low flow channel. This site was not used in the quantitative section of this study.

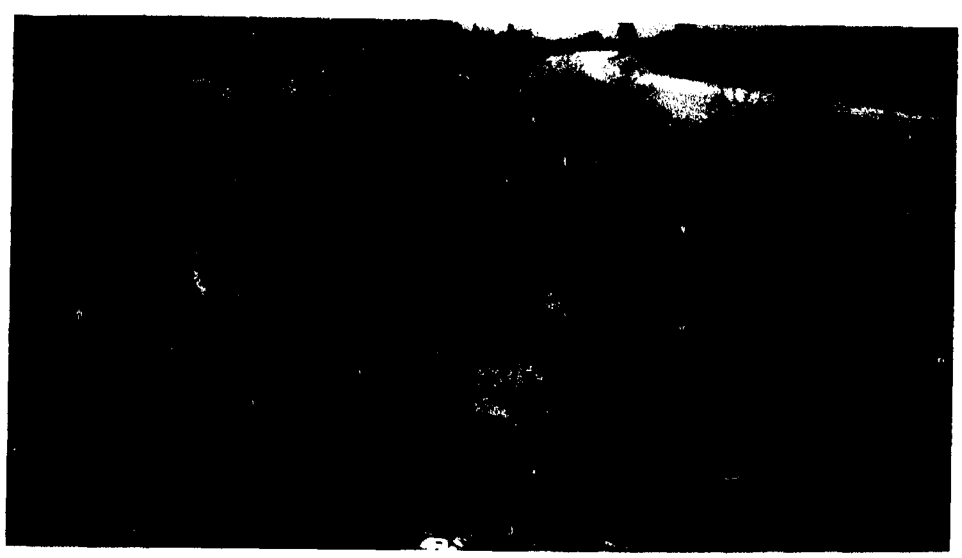

Figure #5. Plotting Designation 1G
Rancho Feliz

Figure 6 shows a natural drainage channel with a very wide and shallow dip crossing. The channel reach upstream of the dip is extremely braided, and the opening width of the dip crossing is larger than the upstream reach; this causes a fair amount of sediment to be deposited on the roadway. Downstream of the dip, the flow is concentrated to a single smaller section. The change from braided to a single channel and sediment deposition in the dip crossing have combined to change the slope of the channel downsteam of the crossing. There is a 1-foot drop from the edge of pavement to the bottom of the wash, but this adjustment is considered to be minor relative to its discharge.

Figure #6. Plotting Designation 2E
Tangerine Meadows

Figure 7 shows a natural drainage channel with a 2-foot drop at the beginning of the section. This drop did not cause a great adjustment of the channel because the reach is approximately eighteen hundred feet long. This channel is classified as stable. It has not shown any damage or excessive sedimentation. Slope adjustment has not affected the hydraulic efficiency of this channel.

Figure #7. Plotting Designation 3D
New Day North

The constructed channel shown in Figure 8 has the same alignment as the original natural channel. Layout of the subdivision and grading of the lots have not appreciably changed the drainage pattern of the tributaries. As the photo shows, this channel actively transports sediment. There basically have been no changes in channel slope and no adjustments to channel geometry. It is a very stable channel. The design Froude number was 0.9 and the corresponding velocity about six feet per second. This section was classified as an urban channel.

Figure #8. Plotting Designation 3J
Casas Adobes

Figure 9 shows a constructed channel with a natural alignment. It is classified as an urban channel, and is located directly downstream of the eighth site. This channel has widened by a small amount. At the inlet the flow has increased about twenty percent from the upstream section and the channel has steepened by twenty-five percent. These changes have not had an adverse affect on channel stability. Because the channel exhibits no undesirable qualities, it was considered to be stable.

Figure #9. Plotting Designation 3L
Casas Adobes West

The site shown in Figure 10 has basin characteristics similiar to sites eight and nine. The channel has changed quite drastically from its original 'V' shaped geometry and has cut a 4-foot bottom width, indicating that this shape is probably not a stable configuration. At the location of the latest slope measurement, the slope has doubled from the original design slope, most likely due to local slope adjustments. The dip crossing was constructed at grade, and there was no drop into the channel from the dip crossing.

Figure #10. Plotting Designation 3A
Casas Adobes West

Figure 11 shows a natural drainage channel prior to development. The dip crossing was constructed very close to the existing channel grade, and drop of one foot was measured at the downstream portion of the crossing. The channel has reduced its slope approximately thirty-six percent from the design value, and the width has reduced about fifty percent from the original width. There is little or no sediment in the dip crossing, due to either lack of available sediment or ability of adjacent reaches to transport the given sediment load. This channel is in good shape and is considered stable. The Froude number has reduced from a value of 1.0 to a value of 0.8 with development.

Figure #11. Plotting Designation 3G
Rancho Verde

The channel shown in Figure 12 follows the natural alignment prior to construction. The dip crossing was constructed at existing channel grade, and there was a small amount of scour at the downstream portion of the dip crossing, very similiar to that at the previous location. This site is located upstream of the last section, and the slope of this channel has adjusted to a value similiar to that of the previous location. There are definite similarities between this channel and the previous section with respect to channel geometry, Froude number, and slope. The distance between control points is approximately 460 feet.

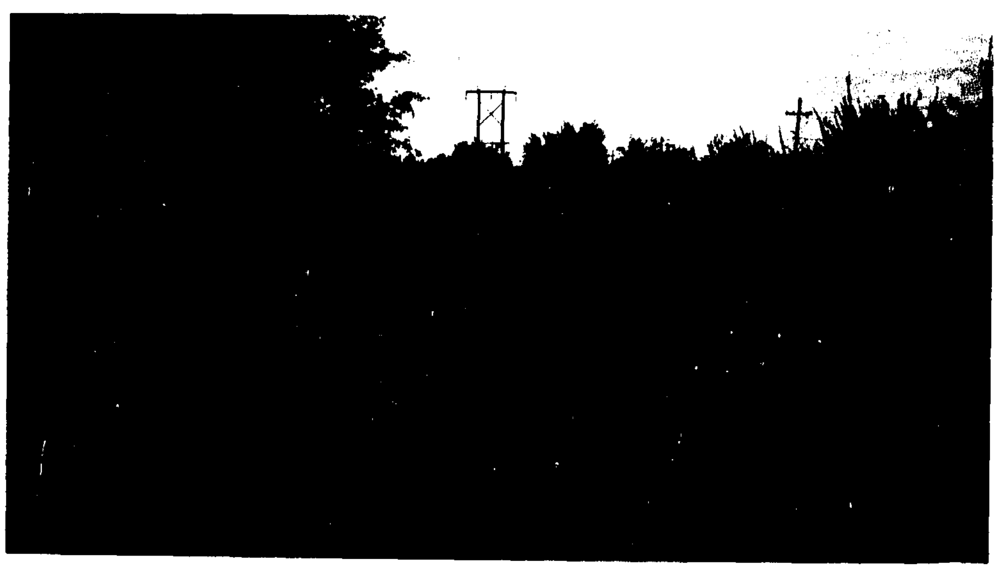

Figure #12. Plotting Designation 3E
Rancho Verde

The channel shown in Figure 13 was a natural drainage course before development, with a narrower and steeper configuration than the two downstream sites. There is a 1-foot drop at the end of the dip crossing. The slope changed more in this section than in the preceding two sections because it had the smallest amount of sediment inflow. The slope has reduced about sixty percent from the original value, to the lowest value for the three sites. Sediment which came from this channel helped increase the available sediment supply to downstream sections. The size of this channel was a major influence in the decision to chose this as an example of a stable channel.

Figure #13. Plotting Designation 3C
Rancho Verde

Figure 15 shows a constructed urban drainage channel just downstream of the last section. This channel carries more flow, draining the more densely developed part of the basin. This has caused the slope to adjust more than in the upstream reach. The added clear-water flow also helps to transport sediment from the badly eroded upstream section through this reach. A fair amount of the sediment is deposited in the dip crossing. Both these sections have shown some meandering tendencies in response to slope flattening. Despite the large amount of adjustment, this channel does not yet show that it is reaching a stable condition.

Figure #15. Plotting Designation 3B
Verde Catalina Townhouses

The location shown in Figure 16 is very similiar to the channel pattern established by the second site of this study. The upstream part of the channel is incised and meandering, while the downstream portion is steeper and wider. This channel is very unstable and shows no clear trend toward stability. These two geometries in one channel reach are similiar to a mountain stream and a lowland river course. This type of instability is not very common and is caused by extreme conditions. This case was probably due to a starved sediment supply, while site number two was due to excessive design slope.

Figure #16. Plotting Designation 3I
Verde Catalina Townhouses

The channel shown in Figure 17 is an urban constructed drainage channel, located just downstream of site number sixteen. This reach is in poorer condition than the upstream reach, and the measurements were taken in the straight portion of the channel. The present channel slope is steeper than the original design slope, with a 1-foot drop at the end of the dip crossing. This section receives more clear water than does the upstream reach and has cut a larger channel than the upstream reach. Lack of sediment supply is the major cause for the worsening condition of this reach. This reach is unstable.

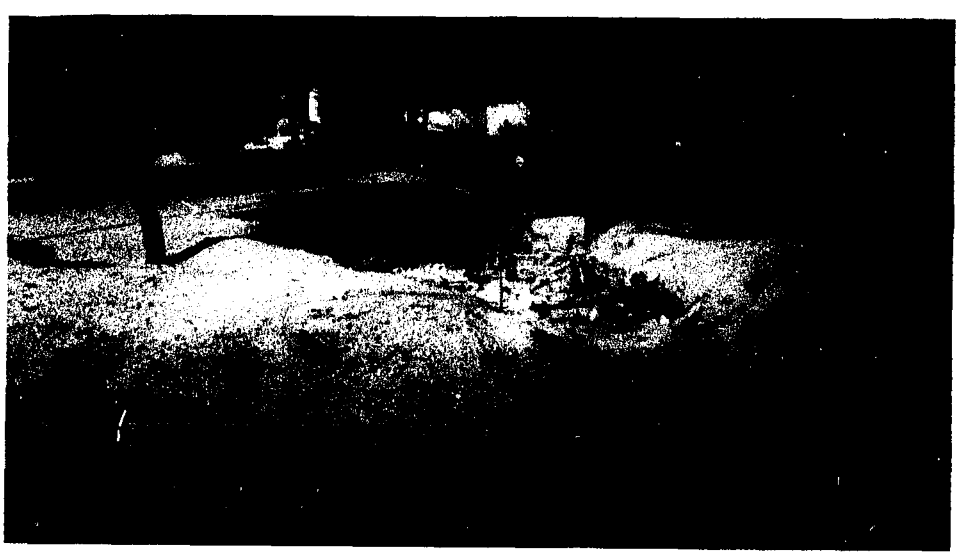

Figure #17. Plotting Designation 3M
Verde Catalina Townhouses

Figure 18 shows an urban constructed drainage channel in a basin that produces a great amount of sediment. The culverts in the photo are almost totally filled with sediment. This channel was initially constructed with a flat slope and a corresponding Froude number of 0.3. The channel has responded by becoming considerably wider and steeper due to inability of the channel to transport the available supply of sediment. This basin has no unusual characteristics. Vegetation grows readily in the channel and does not contribute to channel stability. The slope has doubled and so has the Froude number.

Figure #18. Plotting Designation 3H
La Esperanza Townhouses

The channel shown in Figure 19 was a natural drainage channel prior to development, and development has not changed the natural classification of the site. The dip was constructed at existing channel grade, with about 1-foot of drop at the end of the crossing. The distance between control points is about 1000 feet. Existing drainage patterns were not altered, and channel geometry change and slope adjustment have been minimal. The Froude number for existing conditions was about one. This channel is in good condition and actively transports sediment.

Figure #19. Plotting Designation 2B
Rancho del Este

The channel shown in Figure 20 was a natural drainage course prior to development. Drainage patterns were altered to accommodate development, and the channel classification was changed to an urban channel. There is a 3-foot drop at the end of the dip due to drainage from the roadway entering the channel. The dip crossing was constructed almost one foot above the existing channel grade. This is a fair amount of scour downstream of the dip with little or no sediment being deposited on the roadway. The channel geometry has changed to reflect the additional clear water flow. This reach is stable.

Figure #20. Plotting Designation 1K
Rancho del Este

The reach shown in Figure 21 is a natural channel even after subdivision development. The dip crossing was constructed at the existing channel grade, and there is a drop of approximately 1-foot at the end of the dip. The dip crossing and subdivision layout did not alter tributary patterns. Channel adjustments due to development have reduced hydraulic capacity. The channel had a steep initial design slope, which has decreased by about thirty percent. The width has reduced about fifty percent. However, the adjustments have not seriously affected this channel. This channel was determined to be a stable channel.

Figure #21. Plotting Designation 1S
Rancho del Este

The reach in Figure 22 is a natural channel even after development of the basin. Construction of the dip crossing did not interfere with established tributary patterns. The dip crossing was constructed about 1-foot above natural channel grade, and there is a drop of over two feet at the downstream section of the dip crossing. The real amount of drop is very similiar to that at upstream site number twenty. This site exhibits slope and geometry adjustments similiar to those at site number twenty. The slope is near one percent, and the Froude number is about one. Hydraulic capacity of the channel has been reduced, but not enough to make it unstable.

Figure #22. Plotting Designation 1M
Rancho del Este

Figure 23 shows a constructed urban drainage channel built to convey flows originating in the subdivision. There is only a slight drop at the end of the dip crossing, and measurements were taken just downstream of the dip. This portion of the wash is only slightly incised, and the reach is not in the process of adjustment. This is a stable urban channel secton.

Figure #23. Plotting Designation 3K
Discovery Ridge

Figure 24 shows a natural channel with the subdivision constructed around the channel. Most of the basin is developed [with a 1 R.A.C. density], and construction of the subdivision did not alter the tributary pattern. The dip crossing was constructed at grade. This channel has adjusted its slope only a slight amount, and the channel has not changed enough to warrant concern. This is a stable natural channel.

Figure #24. Plotting Designation 3N
Discovery Ridge

Figure 25 shows a natural drainage channel. The upstream basin is in its natural desert state, and the system transports a fair amount of sediment. The dip crossing is located at grade, and sediment from the upstream reach has deposited in it. The distance between control points is about 250 feet. One reason for sediment being deposited on the roadway is the expansion of flow over this portion of the dip crossing. The dip itself produces only minor changes at the inlet to the channel. The bed of the wash has degraded about 1.5 feet, and the channel has reduced its slope approximately thirty percent from the design slope. The channel has narrowed about forty percent.

Figure #25. Plotting Designation 1P
Rancho del Este

The reach shown in Figure 26 is a natural drainage channel. Most of the upstream basin is undeveloped, and there has been little change in sediment yield. This dip crossing was constructed at the natural channel grade and collects sediment from all storm events. The dip is very wide relative to the channel, and this also contributes to sediment build-up in the dip crossing. The measurements for this location were taken earlier than the photograph which do not show the dip having a one foot drop at the end of the channel. The differences in the conditions shows how dynamic natural drainage basins are relative to sediment transport.

Figure #26. Plotting Designation 1Q
Rancho del Este

The channel shown in Figure 27 follows a natural channel alignment, and construction of the culvert has not had a negative effect on the channel. The upstream basin is totally undeveloped. As a result, this channel actively transports sediment. The channel has reduced its slope by about 50 percent, while the width of the channel has not changed. The change in the slope is not due to development; it is due to placement of the culverts. Still this channel remains in good condition and is considered a natural stable channel.

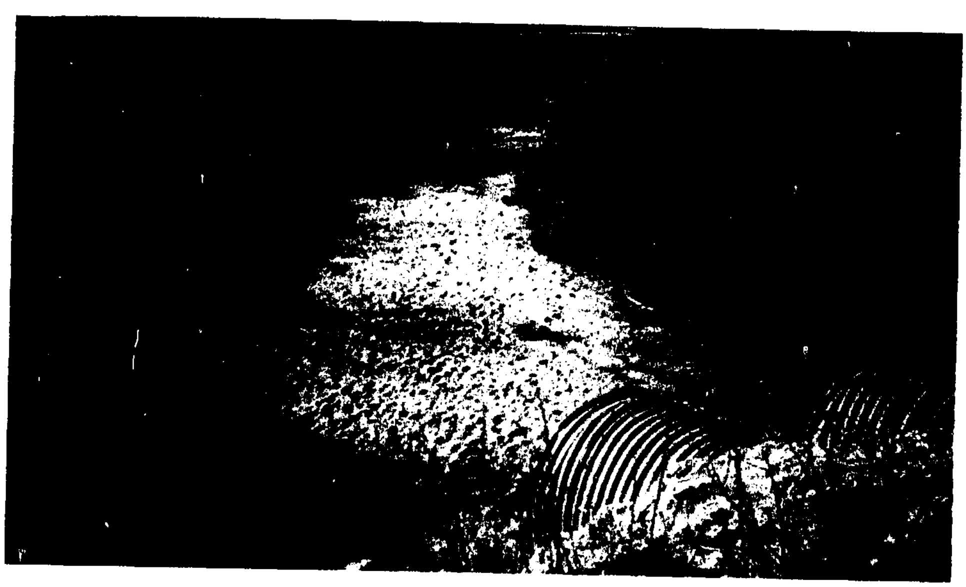

Figure # 27. Plotting Designation 1R
Rancho del Este

Figure 28 shows a natural drainage channel located at the downstream end of the subdivision, with a dip crossing constructed at the existing channel grade. The channel slope has reduced by about 25 percent and has become narrower by a slightly larger percentage. These changes have not had a great effect on channel stability. This channel is a natural stable drainage structure.

Figure #28. Plotting Designation 1X
Rancho del Este

The channel shown in Figure 29 is classified as an urban drainage channel. The field measurements were taken a sufficient distance below four 48-inch culverts. The culvert placement and urbanization have had an effect on channel gradient and geometry. Upstream of the culverts, deposition has made the channel wider, which resulted in the upstream slope being flattened. Deposition at the inlet of the culverts has resulted in excessive downstream scour of the outlet. The amount of upstream deposition is approximately equal to the scour downstream. This is a stable urban channel.

Figure #29. Plotting Designation 1U
Rancho Sierra

Figure 30 shows a natural channel that has not changed due to placement of the culverts. Measurements were taken upstream of the culverts near a channel control point. The density of the basin is 1 R.A.C. Since there was no adjustment, this site was not considered in the quantitative portion of this study.

Figure #30. Plotting Designation 1L
Rancho Sierra

The channel shown in Figure 31 was constructed to drain roadways and lots of the subdivision. This flow is relatively sediment free because of the density of the subdivision. The original channel geometry was a ´V´-shape with flat side slopes. Currently the channel has a trapezoidal-shaped geometry. The slope has decreased by about 25 percent, and the distance between control points is about 230 feet. The changes in the channel are fairly moderate relative to the original geometry. It is considered to be a stable urban channel.

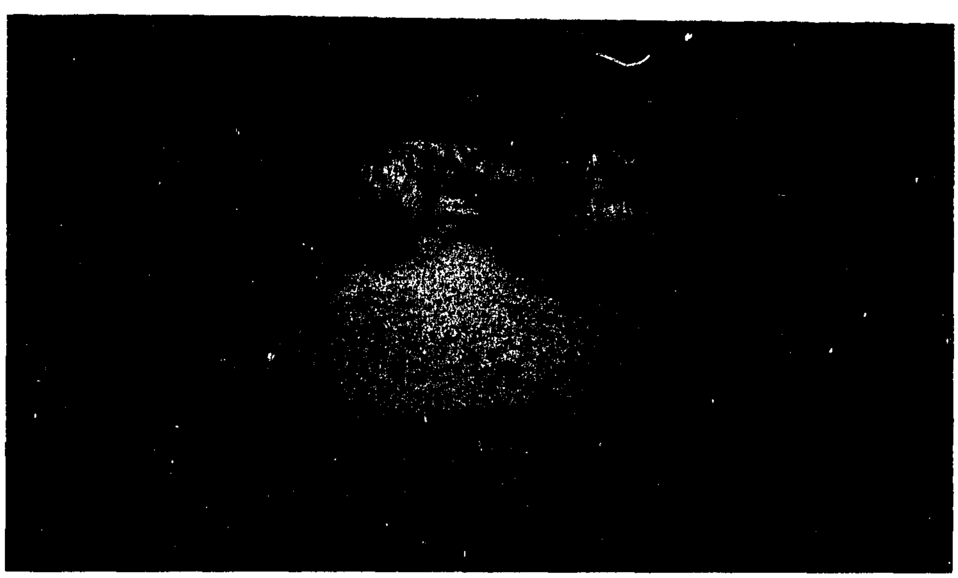

Figure #31. Plotting Designation 1A
North Pointe Terrace

The site shown in Figure 32 is located just downstream of the previous site. It is an urban channel carrying only clear water flow from the subdivision. Significant changes have occured in this channel. The original design had a 10 foot bottom width. The channel has cut a 4-foot wide channel and the slope has decreased about 50 percent. There is a 4.5 foot drop inlet to this reach. At this point grade control structures would have little effect on current stability of this channel because the length between channel control points is 200 feet. This channel has adjusted to a stable condition, based on given flow conditions.

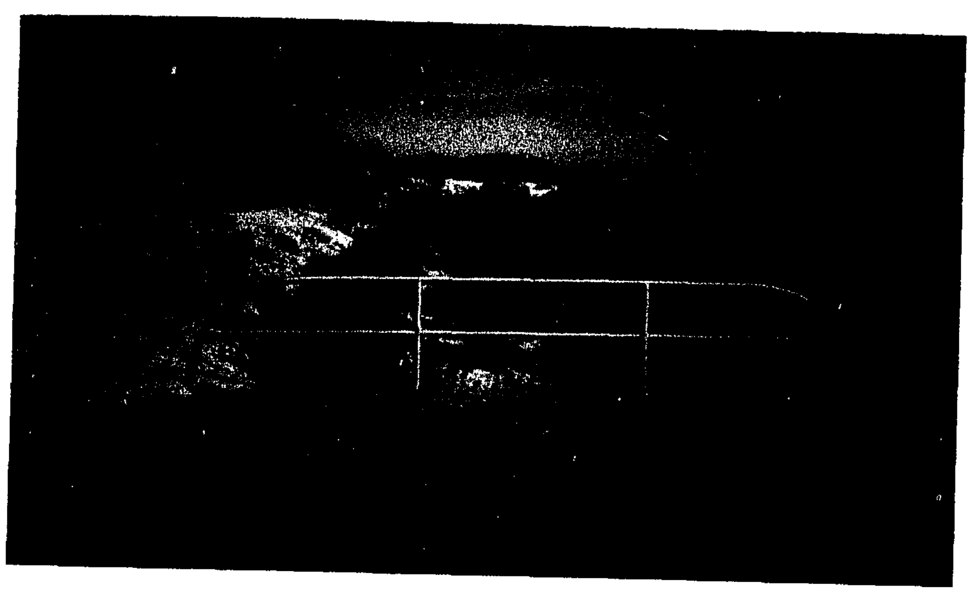

Figure #32. Plotting Designation 1C
North Pointe Terrace

The channel shown in Figure 33 is a stable urban drainage channel which has about 2 feet of scour below the channel outlet. This is not due to local scour; the bottom width has remained fairly constant, but the slope has reduced by about 50 percent. This channel has shown a fair amount of adjustment. The eroded material from the upstream sections have helped to keep the bottom width from adjusting as much as the upstream sections. The distance between control points is just over 200 feet. Grade control structures would not be necessary if there were adequate toedown of the upstream structures.

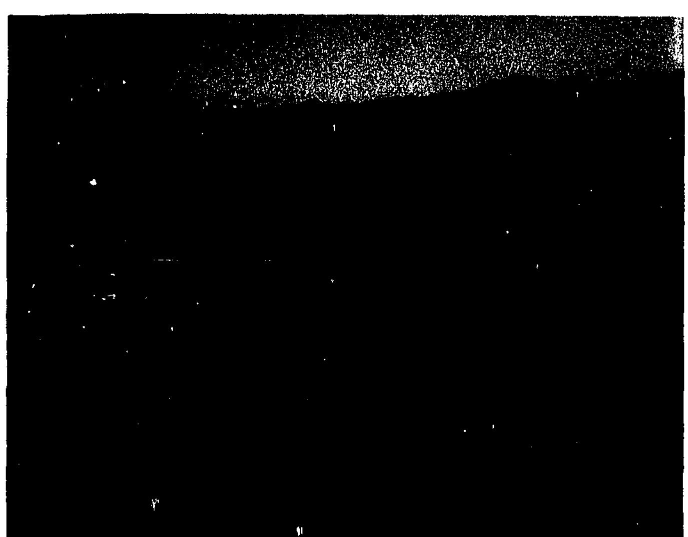

Figure #33. Plotting Designation 1E
North Pointe Terrace

The channel shown in Figure 34 is a constructed drainage channel located downstream of the previous sections. It discharges to a larger channel. There is a 2-foot drop just below the culvert outlet due to channel slope adjustment. Channel side slopes have shown little signs of erosion. This section is the last in a system of four channels. It has the largest slope of all the channels because it is the furthermost downstream section in the system, and it has the largest sediment load of all the channels. This would account for the steepest slope and the least amount of adjustment in the channel system. Therefore, it is a stable section.

Figure #34. Plotting Designation 1F
North Pointe Terrace

The urban channel shown in Figure 35 was constructed along a natural channel alignment, but the original geometry was altered when bank protection was installed. The channel has filled with a considerable amount of sediment, and the culverts are filled about half full with sediment. The slope has increased by just over 10 percent due to the effects of deposition. The constructed channel was placed about three to four feet above existing natural channel grade. The designed channel was too wide and shallow to carry the available sediment load. As a result, the channel has aggraded about two feet. Due to the adjustments, this is an unstable channel.

Figure #35. Plotting Designation lV
Casas Adobes Estates

Figure 36 shows an urban drainage channel which actively transports sediment. It is located just downstream of the previous site. The channel was constructed about 3 to 4 feet below natural grade. The channel has widened by a factor of 1.5 and the slope has steepened by a factor of five. The channel has aggraded about 2 feet, and the culverts show no signs of scour at the outlet. This section and the upstream reach have adjusted closely to the original channel grade, and the system is trying to re-establish its natural stream location. Because of its large magnitude of change, this section was classified as an unstable urban drainage structure.

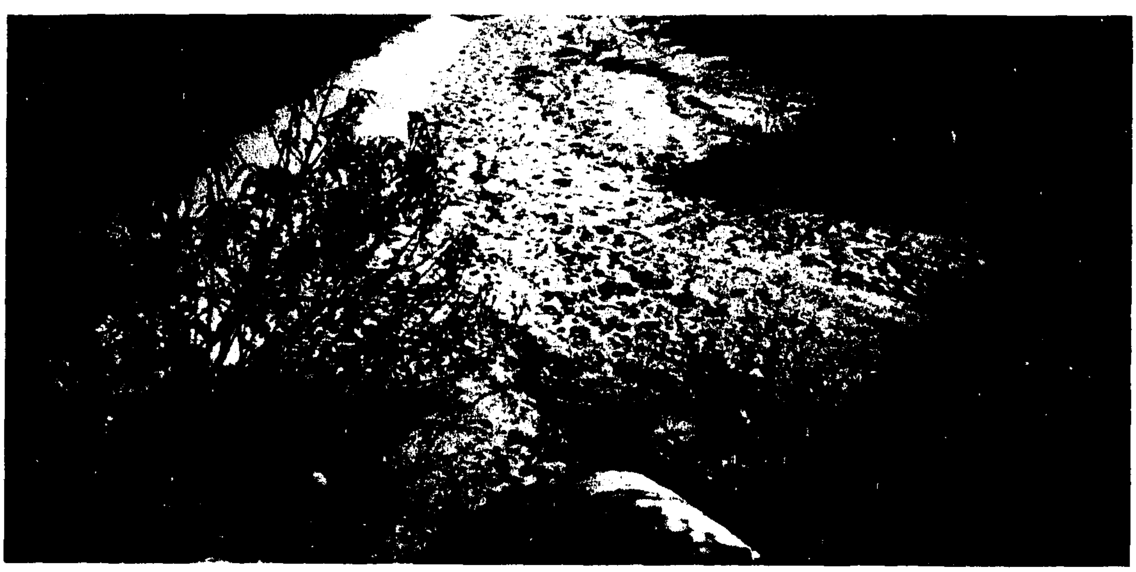

Figure #36. Plotting Designation 1W
Casas Adobes Estates

Figure 37 shows a reach where culverts were constructed about 4 feet above the natural channel grade. This has upset the sediment balance in two ways. First, it has flattened the upstream channel, thus reducing its sediment carrying ability. Secondly, placing the culverts up in the 'air' has increased the scour below the outlet of the pipes. These two conditions have resulted in removal of an excessive amount of sediment from the channel and deposition in the downstream sections (sites 35 and 36). The width of this channel has not changed much, and this site remains a stable section.

Figure #37. Plotting Designation 1T
Casas Adobes Estates

The urban drainage channel shown in Figure 38 was constructed on a natural alignment. There is a slight drop at the downstream portion of the dip crossing which is very wide. The crossing is abruptly constricted when it joins with another channel of excessive width. A low-flow channel has been cut due to this excessive channel width, and the slope has increased to compensate for this design inadequacy. The transition from the dip and the excessive width make this an unstable urban reach.

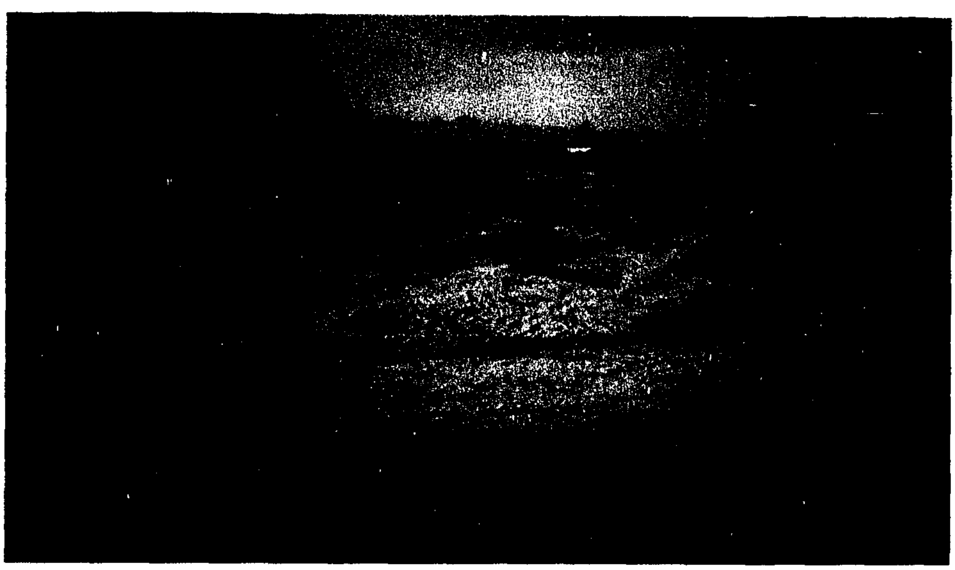

Figure #38. Plotting Designation 1N
Casas Adobes Estates

The site shown in Figure 39 is located just upstream of the previous section and is a natural channel. It shows no signs of significant changes or past adjustments. It is much wider than the downstream reach, and its slope is also steeper than that of the downstream reach. Design information was not available for this site, and it was not used in the quantitative portion of this study.

Figure #39. Plotting Designation 1D
Casas Adobes Estates

Figure 40 shows an urban channel located along a natural drainage alignment. The design channel had a steeper slope than the existing ground slope, which was not a good design condition. This channel has adjusted its slope by over 35 percent, and the width of channel has been reduced over 80 percent. It is readily apparent that the design slope and width were excessive. The newly cut channel was in good condition although it is full of vegetation. The channel was sufficiently wide so it had space to adjust towards a stable channel. The channel is stable after its adjustments.

Figure #40. Plotting Designation II
Casas Adobes Estates

Figure 41 shows a natural drainage channel. Most of this basin lies in the Coronado National Forest. The up-stream culverts were constructed at the existing channel grade, and there is a one foot drop at the outlet of the culverts due to local effects only. A low flow has been cut in the channel and is at a shallower slope than the larger natural section. The sediment balance was not affected by the sparse development or the large sediment supply. Construction of the box culverts did not alter the tributary pattern of this wash.

Figure #41. Plotting Designation 1Y
Pusch Ridge Estates

The natural drainage channel shown in Figure 42 was left in its natural state when the subdivision was developed. The dip crossing was constructed at existing channel grade. A small amount of subdivision drainage contributes to the channel, and the channel has shown some adjustment. The slope has reduced about 25 percent, and the width has reduced about 50 percent. Even with these changes the channel has remained in a stable condition. It still has sufficient hydraulic capacity to convey the design storm event.

Figure #42. Plotting Designation 2F
Rancho Feliz

Figure 43 shows a natural channel. Construction of the dip had little effect on stability of the channel. Measurements were taken at some distance upstream of the dip crossing to achieve an undisturbed representative sample of the geometry. The slope decreased from one percent to 0,8 percent. This change is considered to be in keeping with the amount and density of development of the upstream basin. This was classified as a natural stable channel.

Figure #43. Plotting Designation 2G
Rancho Feliz

Figure 44 shows a natural drainage channel located just downstream from the last site and having similiar geometry and flow characteristics similiar to those of the preceding location. This site was not considered in the quantitative portion of the study because no design information was available. This site has a slope which is one half that of the upstream reach. The reason for this difference is not known due to lack of information.

Figure #44.
Rancho Feliz

The stable urban channel shown in Figure 45 starts downstream of a dip crossing which has a 3-foot drop at the entrance to the channel. There is no defined channel upstream of the dip crossing and the flow is sheet flow which acts quite differently from channel flow. Sheet flow has different capacity for sediment trasport. Slope of the channel has decreased by 50 percent, and width of the channel has also adjusted, mainly by the width of the various incisions at the channel entrance. Channelization of the sheet flow is the major reason for the channel adjustments. Measurements were taken downstream of any conflicting channel controls.

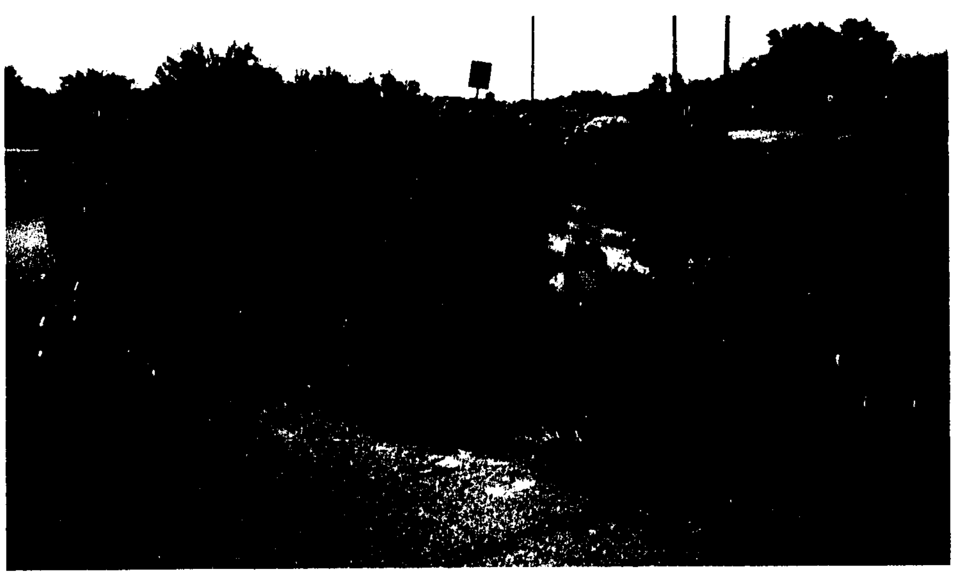

Figure #45. Plotting Designation 2C
Rancho Feliz

Figure 46 shows a constructed urban channel in a basin with a density less than one residence per acre. The channel has widened only a small amount, and its slope has adjusted by a minor amount. The Froude number for the current section is approximately 0.6. This section and the upstream section are very different in size and shape, and this reach shows none of the effects shown by the upstream section. The channel system has been able to adjust to the effects of unbalanced sediment conditions at the upstream portion of the system. Portions of the upstream sections are in need of repair, but this site is in very good condition.

Figure #46. Plotting Designation 2D
Rancho Feliz

The channel shown in Figure 47 was a natural drainage channel prior to development, and the upstream portion of the parcel is still undeveloped hillside. There is about 2 feet of scour below the culverts. Channel slope has reduced from the design slope by about 50 percent, while the width has remained unchanged. This type of response is not characteristic of this type of channel, and the cause is due to channel excavation. Because there were clear signs of excavation in this channel, the site was not considered in the quantitative portion of this study.

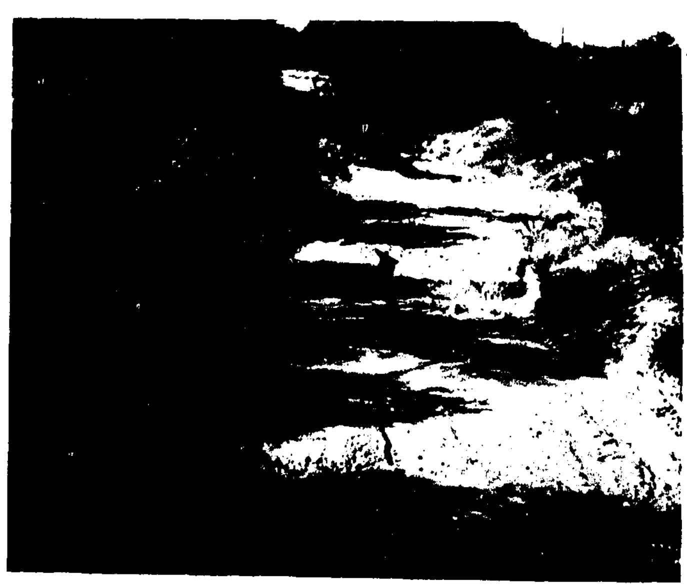

Figure #47.
Smoke Tree Estates

Figure 48 shows a constructed drainage channel; the entire upstream portion of the channel remains in a natural desert condition. Riprap in the photo was placed at the downstream edge of the dip crossing. Channel slope has changed drastically from design conditions, cutting a smaller low flow channel. It is fairly apparent that the slope was too steep for the design width. The Froude number has been reduced to about half of its design value. Small amounts of roadway drainage enter the channel perpendicularly, causing some local erosion at the inlet of the channel. This channel needs maintenance and it is considered to be an unstable natural channel.

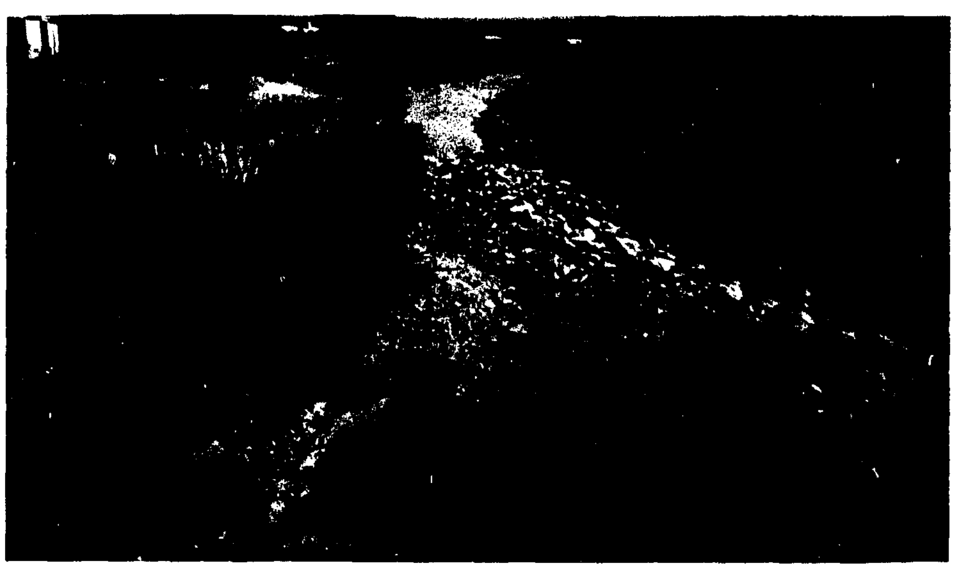

Figure #48. Plotting Designation 30
Tierra Bonita

Table 1

Summary of Basin Data

Development Name	Plotting Symbol	Basin Type	Density	Channel Age(yr)	Channel Condition	d-50 (mm.)
Rancho Feliz Fig.#1	1H	Urban	1	6	Unstable	0.48
Rancho Feliz Fig.#2	1D	Urban	1	7	Unstable	0.55
Rancho Feliz Fig.#3	1J	Urban	1	7	N.A.	0.90
Rancho Feliz Fig.#4	1B	Urban	1	7	N.A.	1.10
Rancho Feliz Fig.#5	1G	Urban	1	7	N.A.	1.50
Tangerine Meadows Fig.#6	2E	Natural	1	11	Stable	0.90
New Day North Fig.#7	3D	Natural	1	14	Stable	1.30
Casas Adobes Fig.#8	3J	Urban	>1	13	Stable	1.20
Casas Adobes Fig.#9	3L	Urban	>1	13	Stable	1.20
Casas Adobes West Fig.#10	3A	Urban	>1	13	Unstable	1.30

Table 1--Continued

Summary of Basin Data

Development Name	Plotting Symbol	Basin Type	Density	Channel Age(yr)	Channel Condition	d-50 (mm.)
Rancho Verde Fig.#11	3G	Urban	>1	14	Stable	N.A.
Rancho Verde Fig.#12	3E	Urban	1	14	Stable	N.A.
Rancho Verde Fig.#13	3C	Urban	1	14	Stable	N.A.
Verde Catalina Townhouses Fig.#14	3F	Urban	6	13	Unstable	1.20
Verde Catalina Townhouses Fig.#15	3B	Urban	6	13	Unstable	1.20
Verde Catalina Townhouses Fig.#16	3I	Urban	6	13	Unstable	1.10
Verde Catalina Townhouses Fig.#17	3M	Urban	6	13	Unstable	1.10
LaEsperanza Townhouses Fig.#18	3H	Urban	>1	12	Unstable	2.30
Rancho del Este Fig.#19	2B	Natural	1	9	Stable	0.90
Rancho del Este Fig.#20	1K	Urban	1	7	Stable	2.30

Table 1--Continued

Summary of Basin Data

Development Name	Plotting Symbol	Basin Type	Density	Channel Age(yr)	Channel Condition	d-50 (mm.)
Rancho del Este Fig.#21	1S	Natural	1	7	Stable	2.20
Rancho del Este Fig.#22	1M	Natural	1	7	Stable	1.10
Discovery Ridge Fig.#23	3K	Urban	2	12	Stable	0.90
Discovery Ridge Fig.#24	3N	Natural	2	12	Stable	0.90
Rancho del Este Fig.#25	1P	Natural	1	8	Stable	2.10
Rancho del Este Fig.#26	1Q	Natural	1	8	Stable	2.10
Rancho del Este Fig.#27	1R	Natural	1	8	Stable	0.95
Rancho del Este Fig.#28	1X	Natural	1	8	Stable	0.95
Rancho Sierra Fig.#29	1U	Urban	1	7	Stable	1.20
Rancho Sierra Fig.#30	1L	Natural	1	7	N.A.	1.10
North Point Terrace Fig.#31	1A	Urban	4	7	Stable	0.50

Table 1--Continued

Summary of Basin Data

Development Name	Plotting Symbol	Basin Type	Density	Channel Age(yr)	Channel Condition	d-50 (mm.)
North Point Terrace Fig.#32	1C	Urban	4	7	Stable	0.50
North Point Terrace Fig.#33	1E	Urban	4	7	Stable	0.50
North Point Terrace Fig.#34	1F	Urban	4	7	Stable	0.50
Casas Adobes Estates Fig.#35	1V	Urban	1	8	Unstable	1.15
Casas Adobes Estates Fig.#36	1W	Urban	1	8	Unstable	1.15
Casas Adobes Estates Fig.#37	1T	Urban	1	8	Unstable	1.65
Casas Adobes Estates Fig.#38	1N	Urban	1	8	Unstable	0.85
Casas Adobes Estates Fig.#39	1D	Natural	1	8	N.A.	0.85
Casas Adobes Estates Fig.#40	1I	Urban	1	8	Stable	0.85

Table 1--Continued

Summary of Basin Data

Development Name	Plotting Symbol	Basin Type	Density	Channel Age(yr)	Channel Condition	d-50 (mm.)
Pusch Ridge Estates Fig.#41	1Y	Natural	1	6	Stable	1.40
Rancho Feliz Fig.#42	2F	Natural	1	10	Stable	2.80
Rancho Feliz Fig.#43	2G	Natural	1	10	Stable	0.68
Rancho Feliz Fig.#44	N.A.	Natural	1	10	N.A.	0.68
Rancho Feliz Fig.#45	2C	Urban	1	10	Stable	0.85
Rancho Feliz Fig.#46	2D	Urban	1	10	Stable	0.85
Smoke Tree Estates Fig.#47	N.A.	Natural	1	8	N.A.	2.00
Tierra Bonita Fig.#48	3O	Urban	1	13	Unstable	5.60

CHAPTER 3

THE EROSION PROCESS

In Pima County the stability of drainage channels is partly controlled by the amount and type of development which occurs in the watershed. Prior to development of a basin there exists a natural equilibrium in the channel system that is governed by several factors, including basin size, slope, sediment yield, sediment size and distribution, rainfall amounts and distribution, and type and amount of vegetative cover. The channel geometry and slope are formed in response to these factors, and the sediment transport rate is closely governed by the sediment yield of the basin. Because the natural channels are located in alluvial fills between mountain ranges, local basin slope will roughly equal channel slope. The influencing factors remain relatively constant for an undisturbed natural channel, although they do vary with varying patterns and amounts of rainfall. The channels are somewhat dynamic, fluctuating about their mean natural state.

When a basin is developed, the natural equilibrium is altered to reflect the type and amount of development. The channel evolves to a different, but similiar, state of equilibrium when the basin is completely developed and has had ample time to establish a mature vegetative cover.

Several changes occur when a basin is developed, all related to the density of development. Developments with one residence per acre usually are designed with local drainage systems very similiar to the natural drainage patterns. In contrast, townhouse-type developments, four residences per acre, will usually totally change the natural patterns, concentrating runoff at fewer locations. This concentration of tributaries tends to "shock" channels with relatively large inflows of water and sediment at a few points. Also, large quantities of sediment are eroded during subdivision construction, and local scour or aggradation are thus more likely to influence overall stability of the channel system. Localization of channel responses was observed during field investigations and when measurements were obtained. Such localization usually is responsible for most of the problems associated with property damage and excessive maintenance and repair for channels in such areas. Natural channels have a more evenly distributed tributary system than urbanized basins. Localization of channel responses is a process which affects natural watercourses less than urban channels, helping with the steady state equilibrium notion of stability of natural channels.

The increased imperviousness of developed basins, which is one of the most important influencing factors, has a two-fold effect. First, runoff volume is increased and peak discharge values are higher from a given amount of rainfall. Channels in developed basins will have more frequent flow events which accelerate the channel erosion process related to basin development. Second, sediment suppply to the channel is reduced, and the supply deficiency is made up by using the channel boundary as a sediment supply source until the channel is again in an equilibrium state. A natural channel formerly in a less dense development also tends to do this, but to a far lesser extent.

A channel in a basin that is 100 percent developed will be governed by the following boundary conditions. The sediment yield of the basin will be reduced to some fractional amount of that of the natural basin. How much reduction is governed by the density and kind of development. The channel slope will be less (i.e. flatter) than the local basin (natural) slope. Also, the sediment concen tration carried by streams in a developed watershed will be less than in a natural channel. The amount of sediment concentration reduction is closely related to the fractional reduction of sediment yield of the basin. The end result of these reductions is reduction of channel slope, but the exact relationship between sediment yield reduction and resultant sediment concentration (channel slope reduction) is difficult to quantify due to several unmeasurable quantities. Sediment yield is controlled by both individual residents of the development and grading practices of the developer. The sediment concentration reduction can be quantified to a certain extent via channel slope reduction. The above argument is valid assuming that the basin has fully mature vegetative cover. Channels will become incised due to the flattened slopes of the developed basin. The following is a qualitative analysis which was used to develop the above conclusions.

The following three figures qualitatively illustrate the change of channel configuration due to basin development. Figure 49 uses an extreme example to show obvious possible channel changes. Figure 49 shows a culvert and channel combination with a type of channel response found in only a few locations. The channel response was induced not only by basin development, but mainly by excessive constructed bed slope. The upper portion of this reach has degraded severely, while the lower portion has aggraded a corresponding order of magnitude. The width of the upper portion has been greatly reduced, and the width of the lower portion has greatly increased. The slope of the upper

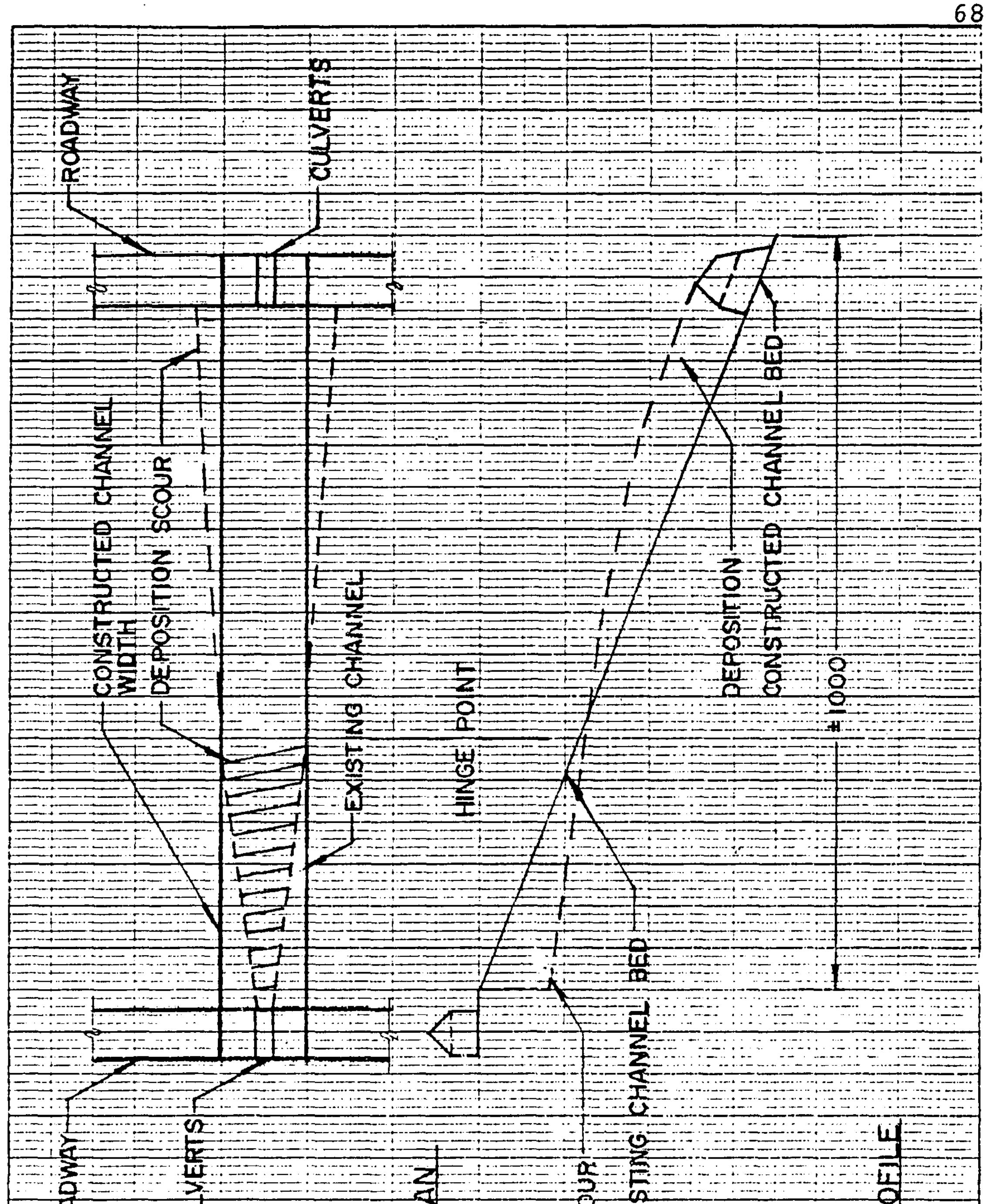

Figure # 49. Excessive Slope, Channel Adjustment
Plan and Profile Views

portion has flattened, and the lower portion has remained as steep as the original constructed slope.

From field observations, the amount of sediment deposited near the downstream control point is generally more than the sediment scoured from the upstream portion of the reach. The differences in sediment ´balance´ in the reach are caused by a deficient contribution of sediment from the upstream channel. The imbalance is ultimately due to reduction of sediment supply to the channel system due the urbanization of the basin.

Figure 50 shows the response for a channel with a dip crossing installed for vehicular access. The dip crossing acts as the channel control point, a point where the channel bed is fixed. The channel response for this condition is similiar to that in Figure 49, but to a lesser degree. The Figure 49 condition is definitely an unstable condition, while Figure 50 illustrates channel response for a stable channel. A channel which has adjusted due to basin development should show some signs of the slope flattening just downstream of the channel control point where the width generally is reduced by an amount related to the slope adjustment. Upstream of the control point, the channel will widen by just a small amount. Again, the larger the slope adjustment the more the channel width will change to reflect this adjustment. The shape of the dip crossing also can

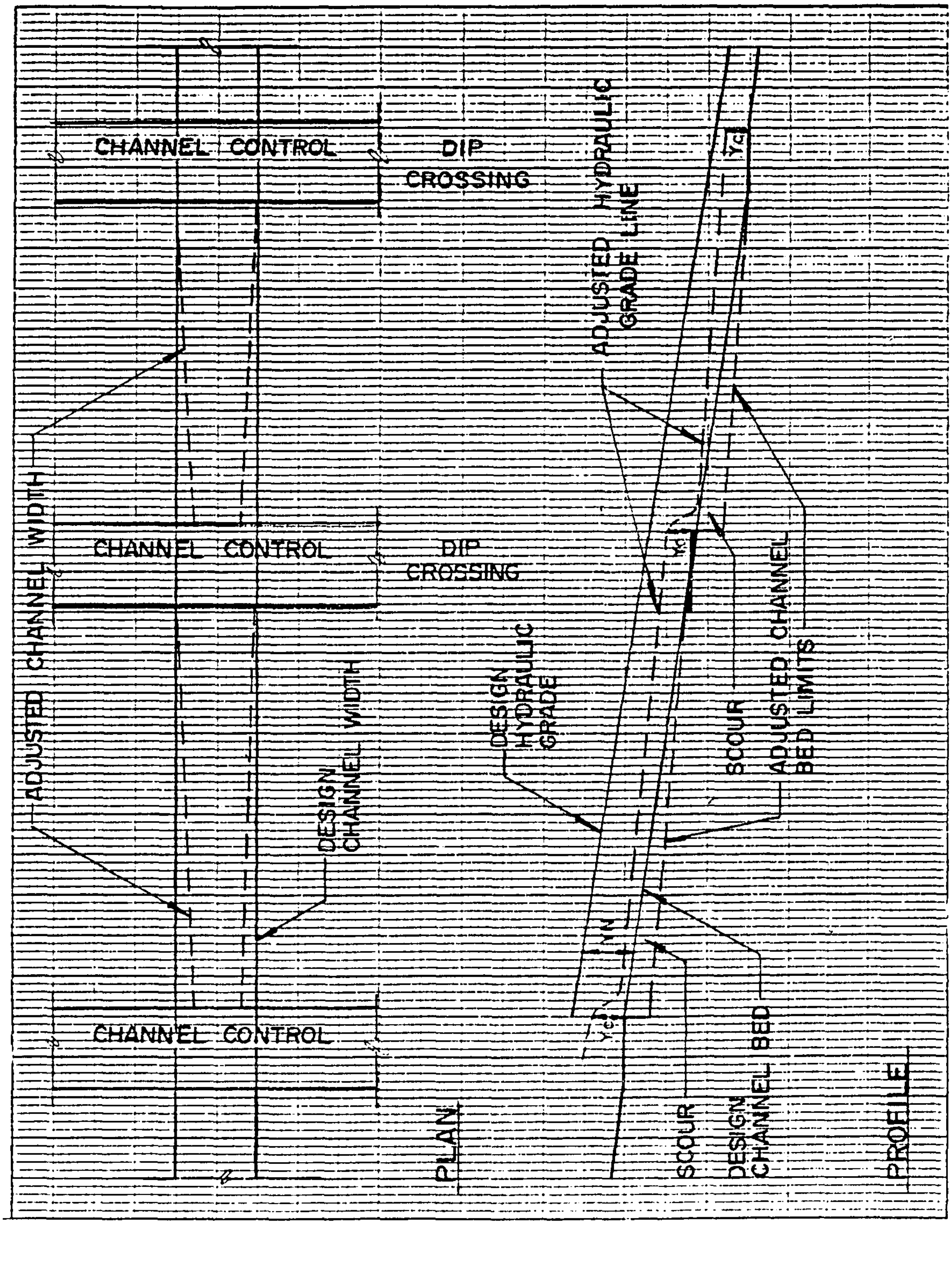

Figure # 50. Typical Dip Crossing Adjustment
Plan and Profile Views

affect the channel response. If the dip crossing geometry is shallow, there is a greater possibility for sediment to accumulate in the crossing. The basic cause for deposition in a degrading channel reach is alteration of the hydraulic grade line. When a sudden change in conveyance of a channel is encountered, the channel bed adjusts itself to smooth out the irregularity. Depositon of sediment in a dip crossing or in a channel system is a response to conditions which warrant a steeper bed slope to adjust for a loss of channel conveyance. The more a constructed channel or dip crossing deviates from the natural hydraulic grade line, the more likely it is that an unstable condition will develop in the channel system.

This conclusion is much more evident when a culvert is the channel control point. Figure 51 shows the typical channel response a for culvert placed in an adjusting reach. A culvert poses a greater obstruction to flow than a dip crossing, and response to adjustment of the hydraulic grade line by a culvert is more dramatic. The greater the adjustment, the easier it is to observe the channel response. Field observations indicate that sediment will fill the culvert entrance and deposit upstream, tending to make the channel area larger near the opening. Conversely the reach downstream of the culvert will reduce its channel width, as shown on Figure 51. As previously discussed for conditions

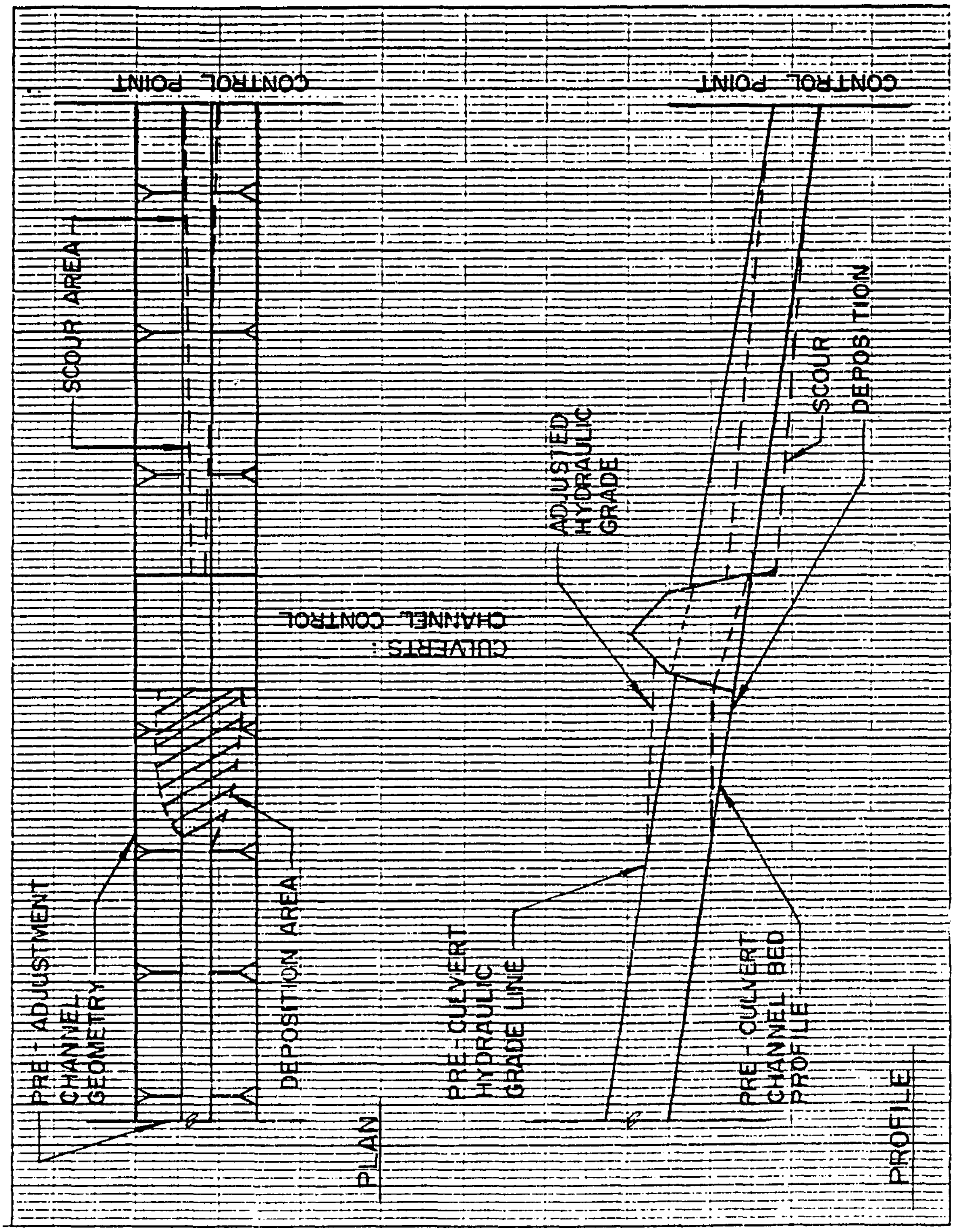

Figure # 51. Typical Culvert Adjustment
Plan and Profile Views

shown in Figures 50 and 51, the amount of sediment deposited upstream of the culvert is not equal to that scoured below the culvert outlet. These figures served as a guide for the quantitative portion of this study and in the designation of the erosional state (stable or unstable) of particular channels.

Basin Designations

Initially forty-eight locations were chosen for this investigation. After preliminary analysis, some of the sites were found to be unacceptable for quantitative study and were used only as a guide to obtain general understanding of the erosion process. The useable sites were grouped in three separate categories: natural channels, stable urban channels, and unstable urban channels. For each location, the original design criteria (or existing conditions in the case of a natural site) and the present existing field condition were compiled. The decision as to whether or not a site was stable was based upon the author's judgment, judgment heavily influenced by the observed degree of change from the design information. A stable section would not exhibit a great amount of alteration from its original design concept if the initial design was correct. An unstable channel section would definitely show major changes in its hydraulic efficiency and signs of failing, in properly designed hydraulic structures (i.e. culvert or energy dissipator). An unstable reach would require a great deal more maintenance than a stable reach, which might even require no maintenance. Unstable or improperly designed channels probably would have a negative impact on public safety and property values in the vicinity of the channel. Each location was labeled as to type, based on its construction or present condition.

In some cases, a channel changed from an unstable channel to a stable channel. In such cases, the channel was analyzed as a stable channel section. The original channel was generally not highly unstable, and the channel adjusted in a positive manner. This type of adjustment occurred in very few sections. Generally when a channel had an improper slope, future basin development did not contribute to increasing that channel's stability.

Sites were designated either natural or urban type. A natural type channel was not physically altered by development in the basin. This was often the case when the development was not very dense, less than 1 R.A.C. A natural channel will show adjustment, but generally less than an urban channel. It was assumed that all natural channels had a stable configuration. Stability, as defined for this study, is a stable condition imposed by the type and amount of basin development. An urban designation could be a constructed channel where previously there had been no existing channel or a channel having a natural alignment that was significantly modified.

CHAPTER 4

QUANTIFICATION OF THE EROSION PROCESS

Once a qualitative understanding of the erosion process is established, numerical analysis can be used to obtain a mathematically patterned response to problems related to this natural process. The basis for quantification of the erosion process is the consistent grouping of sites in categories which represent expected conditions or results. The results of this study will be useful if they are related to conditions encountered by channel designers. Channels have been designated as stable urban, natural, and unstable urban sites to clearly exhibit the results of this study.

Stable Urban Sites

Sixteen sites used in this study were in the category of stable urban; four sites were not used for various reasons as discussed in Chapter 2; and one site was subject to aggradation. Four of the sites had a density of 4 R.A.C. The average channel width to depth ratio was 5.7, and the average unit discharge was about 12 cfs/ft. The average percent of development for these basins was 69 percent. Slopes of the stable urban sites ranged from 0.4

to 1.6 percent, with the average slope 0.9 percent. The average slope ratio (ratio of measured slope to basin slope) was 0.66 (computed without the aggraded site because this study is concerned primarily with the flattening of slopes due to development). Neglecting the aggraded site does not significantly change the data analysis. Average basin imperviousness (the weighted runoff coefficient ´c´ from the Rational Equation) was 0.16. Table 2 lists pertinent characteristics for channels of this category.

Natural Sites

Fifteen sites were stable natural sites; two sites were not suitable for analysis as discussed in Chapter 2. All sites had a density of 1 RAC or slightly less. The average channel width to depth ratio was 8.12, and the average flow per unit width was 26.2 cfs./ft. The amount of development in an average basin was about 33 percent for the stable natural classification. Channel slopes for this category ranged from 0.6 to 1.6 percent, with the average measured slope 1.3 percent. The average slope ratio (ratio of measured slope to the pre-construction natural slope) was calculated to be 0.70. Basin imperviousness for this category averaged 0.06. Table 3 lists pertinent characteristics for channels of this category.

TABLE 2
Urban Basins

Basin Design. /basin#	Ref. Page #	Drain. Area ac.	Basin Slope %	Meas. Slope %	Slope Ratio	Channel Width ft.	w/y Meas. ft/ft	Q-25 CFS
3J/8	6	56	1.3	1.0	0.77	10	10.4	100
3L/9	7	71	1.3	0.94	0.72	10	7.4	120
3G/11	8	49	1.0	0.80	0.80	5	3.2	60
3E/12	9	37	1.0	0.80	0.80	8	7.3	50
3C/13	10	17	0.8	0.63	0.78	4	1.9	40
1K/20	15	50	1.8	1.20	0.68	5	2.4	120
3K/23	18	70	1.7	1.00	0.59	10	7.7	115
1U/29	21	110	14.	0.80	0.40	8	4.0	165
1A/31	23	10	1.5	0.80	0.53	3	2.7	40
1C/32	23	14	1.5	0.80	0.53	4	2.9	50
1E/33	24	21	1.5	1.20	0.80	10	10.7	50
1F/34	25	24	1.5	1.60	1.10	10	11.7	50
1T/37	27	92	1.5	0.86	0.57	8	4.7	90
1I/40	29	39	1.5	1.25	0.83	5	4.5	60
2C/45	32	177	2.1	0.60	0.40	6	2.2	280
2D/46	34	190	2.1	0.40	0.27	17	7.9	280

TABLE 3
Natural Basins

Basin Design. /basin#	Ref. Page #	Drain. Area ac.	Pre-Devel. Slope	Meas. Slope %	Slope Ratio	Channel Width ft.	w/y Meas. ft/ft	Q-25 cfs
2E/6	5	403	2.00	1.40	0.70	30	17.9	500
3D/7	6	25	1.00	0.80	0.80	20	27.0	65
2B/19	15	67	1.60	1.50	0.94	12	8.8	185
2E/21	16	82	2.00	1.40	0.70	8	7.6	70
1M/22	17	61	2.10	1.00	0.48	6	2.7	130
3N/24	18	253	1.82	1.40	0.77	22	17.4	250
1P/25	19	65	1.60	1.10	0.69	6	3.4	100
1Q/26	19	72	1.70	1.60	0.94	8	6.2	115
1R/27	20	74	1.50	0.60	0.40	9	3.3	270
1X/28	21	198	1.90	1.60	0.74	5	1.4	330
1Y/41	30	229	5.00	1.60	0.32	20	5.1	950
2F/42	31	951	2.00	1.60	0.80	5	1.4	760
2G/43	31	1409	1.00	0.80	0.80	15	3.4	1365

Unstable Urban Sites

There were twelve sites in the unstable urban category; four of these sites had aggraded. The most severe case of aggradation was a channel which had a design slope of 0.3 percent. The remainder of the sites were altered due to extreme channel modification. All except three sites were totally developed. It was clearly evident that all of these urban channels studied were not stable. They were in need of extensive repair, and some had potential to cause property damage or harm to the public. The major reason for the occurence of unstable slopes stems from the design slope being excessive, except for the one case which had too flat a design slope. In this category there were four sites which had densities of approximately 6 R.A.C. The adjustments shown by these channels were the simplest to observe because they exhibited the most dramatic changes. Table 4 lists characteristics of channels in this category.

The average (final) slope for these sites was 2.8 percent. The average width to depth ratio was 18.7 and the average flow per unit width was 11.5 cfs/ft. These basins had average development of approximately 83 percent. The measured channel slopes for all of the sites ranged from 0.4 to 8 percent. Since there were four sites which aggraded, the average slope ratio (measured slope to basin slope) was determined separately for the two conditions. The average slope ratio for the aggraded sites only was 1.4. For the sites exhibiting degradation, the average slope ratio was computed at 0.38. The average basin imperviousness for this category was 0.32. Table 4 lists pertinent characteristics for channels of this category.

TABLE 4
Unstable Urban Basins

Basin Design. /basin#	Ref. Page #	Drain. Area ac.	Basin Slope %	Meas. Slope %	Slope Ratio	Channel Width ft	w/y meas. ft/ft	Q-25 cfs
1H/1	1	30	4.00	2.00	0.50	10	10.0	85
1D/2	2	20	6.00	8.00	1.30	20	62.5	50
3A/10	8	12	1.50	2.50	1.67	4	1.33	125
3F/14	11	40	3.80	2.20	0.56	4	4.0	40
3B/15	12	13	4.80	2.00	0.42	4	3.8	50
3I/16	12	52	3.80	5.00	1.30	3	2.5	75
3M/17	13	75	4.80	3.60	0.75	5	2.9	100
3H/18	14	49	2.00	0.75	0.38	10	11.4	45
1V/35	26	195	1.60	2.00	1.25	20	20.0	170
1W/36	27	195	1.60	3.40	2.12	18	20.0	170
1N/38	28	64	1.50	2.50	1.17	32	82.0	70
3O/48	35	570	4.00	0.40	0.10	15	4.3	795

Discussion of Results

The unstable urban category had the highest average measured channel slope, close to 3 percent considering both aggraded and degraded sites, or about three times as steep as stable urban channels. Stable urban channels had the flattest measured average slope at 0.9 percent, while stable natural channels were approximately 45 percent steeper than the stable urban category. The differences in average measured channel slopes shows clearly the division between the classification of stable and unstable channels. The density of development was very similiar for all categories, and slight differences in the stable urban and natural channels are closely related to the type and amount of development. The amount of development is responsible for the minor differences in average measured slope values. The differences in basin imperviousness for all categories show a similar trend to that of the measured average slopes.

The average ratio of width of flow to depth for the stable classifications is similiar in numerical value, indicating that these channels have roughy the same hydraulic geometry. The average ratio for the stable urban category is 5.7, and for the stable natural category 8.12. The differences are attributable to differences in average slope. The average width to depth ratio for the unstable urban category was 18.7, much greater than for the stable categories which indicates a different hydraulic geometry that accounts for channel instability.

Even though the two stable categories have similiar width to depth ratios, their flow per unit width values (q) are very dissimilar. The q value for stable natural channels (26.2 cfs/ft) is more than twice that of the stable urban category (12 cfs/ft). The different values reflect the effect of slope on the erosion process. The differences are due to dissimilar effects (or amounts) of erosion in the channel system produced by the two types of development. The width to depth ratios also reflect the effects of channel change. The q value for the unstable urban category is about 11.5 cfs/ft, or slightly less than for the stable urban category, even though the average measured slope and the width to depth ratio are very dissimilar. This similar value of q with dissimilar parameters discussed above reflects the characteristics of unstable channels.

The slope ratio used for both the urban stable and unstable basins utilized the basin slope (local land slope) as the datum for comparing the present measured slope. For natural basins the existing (pre-construction) slope was used as the datum for comparing the measured slope. These datums provided a base which made the slope ratio values of the three categories comparable. The average slope ratio for the stable urban category (0.66) is about six percent; less than for the stable natural category (0.70). The effect of development on channels is illustrated by the slope ratio which is the basic measure of adjustment to basin modification resulting from development.

The adjustments exhibited by urban-type channels were greater than adjustments of natural channels, the difference being determined by the amount and type of watershed development. The type of development is very similar for both the natural and urban basins studied. Natural basins had lower densities than urban basins, but the difference was in the order of less than one half of a RAC. This is a small difference when comparing urban type densities. The reason for the slope ratio differences, then, is based on the extent of development. Basins in the stable urban category had been developed, on the average over 69% of the basin area. This is approximately double the amount of development which exists in stable natural watersheds. Since the type of development is roughly similar, the c value differences should also be similar to differences in the amount of development. The difference in the amount of development is responsible for the urban channels having a flatter measured slope and smaller slope ratio. The smaller the slope ratio the more adjustment is shown by the channels. The flatter slopes with the larger width to depth ratios tend to reduce the q value for these channels. The q value is a measure of the hydraulic efficiency of a channel, and for channels of similar slope, this is an effective parameter to measure hydraulic efficiency.

The average slope ratio for the unstable urban category is 0.71, considering both aggraded and degraded sites. The slope ratio considering only the aggraded sites, was 1.38, and 0.38 for only the degraded sites. Averaged together, these ratios produce a reasonable value for the slope ratio. The slope ratio should be analyzed separately in order to show the real adjustments that these unstable channels exhibit. This category has more development per basin about (83 percent) than the other two categories which are stable. This indicates that increasing basin development leads to increasingly unstable channels.

The accumulated data when graphically analyzed, helped support the above conclusions. Several parameters were plotted against each other. Of the several plots, three sets supported the goals of this study. The plotting designation and the site number are used below to provide a source of cross reference.

These three sets of plots all use the slope parameter as a major component of the plot. Each plot shows both the measured slope and basin slope (for urban basins) or the natural pre-construction slope (for natural basins) on the abscissa so that the slope adjustment can be observed while it is compared against the other variable on the ordinate axis. A single plot of the set is differentiated by plotting either the natural basins, urban basins, or unstable urban basins. The three sets of plots consist of percent basin developed versus slope, basin imperviousness versus slope, and discharge versus slope. The natural basins and urban basins were separated to illustrate the effect that each condition had on its variables. The unstable urban basin plots show a lack of a trend and are included to show the validity of the trends exhibited in the other two stable plots.

Basin Development

The first set of plots, Figures 52-54, show the percent basin developed versus slope. On plots of both stable basin types, two envelope lines of maximum and minimum are shown. To show the effects of basin development over time (past and future), the current basin slope values (urban) or the existing (natural) are projected to the left on the plot, towards the 1 percent basin developed point. The maximum and minimum lines originate at the smallest amount of basin development. The higher limit of these points designates the possible maximum limit of slope and the lower shows the possible minimum limit of slope as the percent of basin development increases over time. These lines were drawn as a best fit approximation for simplicity. The purpose of the lines is to show what may have happened before and what could occur after the sites were measured. Since data were not available for the past and there is general uncertainty about the future, these lines should provide an idea as to the relative slope changes due to basin urbanization from start to finish. Since the amount of development changes with time, the basin slope or existing slope serves as a datum to show how channels will be or have been adjusting. By using this projection technique, the change of channel slope can be observed as a basin develops. This projection technique is used on all the plots. From this starting point, a regression analysis was made to determine the slope of the line for the measured slope points only.

Figures 52, 53, and 54 show urban basin development versus basin slope, natural basin development versus the pre-construction slope, and unstable urban basin development versus basin slope, respectively. The slope of minimum and maximum lines are basically parallel for Figure 52 and 53, for natural and urban basins. The maximum and minimum lines are higher on the natural plot than the urban plot, and the urban basins clearly show more channel adjustment than the natural basins. The slopes of the urban basins are also flatter than the natural basins. As more of the basin is developed, the urban basins will show more adjustment of the channel system relative to the natural basins.

A close look at Figure 52 reveals that there are three measured slope points which do not fit within the envelope lines. Site 2C/45, which is just below the minimum control line, exhibited a shallow slope due to a change in channel flow type. Near the point where the measurements were taken, the flow changed from shallow sheet flow to a concentrated channel type flow. Where the sheet flow enters the channel an incised low-flow channel developed. The measurement was taken in the low-flow area which had a smaller local channel slope.

Site 2D/46, which is also below the minimum envelope line, is immediately downstream of site 2C/45 and has not adjusted from its shallow constructed slope. Overland sheet flow, which is the major contributor of flow to both of these sections, does not have the ability to convey an appreciable amount of sediment. The upstream Site 2C has added sediment to Site 2D, but not enough to affect a change on the channel. The current slope is adequate to convey the small sediment load. From observing other sites, if the sediment load were like that of a "normal" basin, the channel slope would be too small to convey the sediment, resulting in deposition in the channel and probably an unstable channel classification.

Site 1F/34 is above the maximum envelope line. This section does not have a fixed downstream control point, such as a culvert or dip crossing; downstream control is provided by a wash which is very much larger than this section. This channel joins the larger wash immediately downstream of a lined culvert outlet. The channel was constructed and lowered the outlet elevation of the channel before the culvert outlet was constructed. This floating control point prevented the small channel from adjusting as typical channels controlled by a dip or culvert crossing usually do. Also, this channel is fairly young and small and probably has not fully adjusted to changing basin conditions as has the larger controlling channel. Effects of changing basin conditions in the wash are indicated by continuing placement of bank protection along the wash just upstream of the confluence of the small channel.

The majority of the plotted points in Figure 53 congregate about the maximum envelope line. Explanation of the plotting positions of sites 2G/43 and 3D/7 are similar; both are located just upstream of a channel control point. This area is generally characterized by flatter channel slopes. See Figure 2 for a qualitative description.

Site 1R/27 shows the effects of something close to an extreme example. Just upstream of this site, a culvert has trapped sediment, making the channel slope very flat. A qualitative description is found on Figure 3 which shows this type of channel response.

Site 1M/22 has a flatter than "normal" slope due the fact that the dip was constructed above existing channel grade. This elevated dip crossing produced some deposition immediately upstream, which led to increased channel flattening. The excessive channel flattening is indicated by the slope ratio of 0.48.

Site 1P/25 has an average slope ratio near 0.70, slightly flatter than other natural sites simply due to chronic sedimentation in the dip crossing just upstream of the measurement point. Site 2F/42, which has a very high slope, has not yet been subjected to enough flow events to even start adjusting, as is very evident by the large amounts of vegetation in the channel.

The obvious conclusion that can be reached from data for unstable urban basins on Figure 54 is that these sites show no trend toward any single conclusion. Most of the sites are much more steep than those on Figures 52 and 53. Figure 54 is especially useful because it shows how not to design channels. While most of this study deals with channel responses associated with degradation, some insight to channel design can be obtained by analysis of sites, such as those shown on Figure 54, which aggraded.

Site 1D/2 is a good example of the type of channel shown in Figure 1. This channel was designed at an eight percent slope, and the resulting adjustments of such a steep design are easy to observe and explain.

Site 3A/10 has shown signs of aggradation due to excessive channel entrance constriction which caused sediment deposition in the channel entrance where measurements were conducted.

A similiar reason for channel aggradation has also been observed at site 3I/16. The channel is too narrow, causing sediment to be deposited in the channel entrance and raising the upstream channel control point. This, in turn, produces a steeper entrance slope, in an attempt to flush out the deposited sediment, and tends to upset downstream channel responses because the aggradation decreases the available sediment supply downstream.

Several factors contributed to the present silted and hydraulically inefficient channel section at site 1V/35. Placement of the culverts at an angle to the upstream channel produces high entrance losses at the culvert inlets. Any change in the existing hydraulic grade line will produce a change in the elevation of the channel bed. This is also the case for an artificial change in the channel bed such as grade control structures.

The channel section geometry upstream of site 1V/35 is vastly different. In the upper portion of this reach, site 1T/37 empties into the channel. Culverts upstream of site 1T/37 show the effects of improper sizing for sediment transport efficiency, and sediment has deposited behind the culverts and eroded the downstream channel. The eroded material is dumped into the channel of site 1V/35, and the channel is too wide and flat to carry this sediment load. The bed of the excavated channel has filled to nearly the same level it occupied prior to construction.

Site 1W/36 is directly downstream of site 1V/35 and suffers from the same problems that affect the upstream section. More sedimentis supplied to this channel reach than the constructed geometry and slope can convey.

Basin Imperviousness

The second set of plots, Figures 55, 56, and 57, shows a relationship between basin imperviousness and the slope for urban, natural, and unstable urban categories, respectively. As previously discussed, imperviousness for urban basins is more than twice that for the natural basins. This is shown by the lack of similarity of the envelope lines on the natural and urban plots. The envelope lines of the urban plot are steeper, indicating more channel slope change as basin imperviousness increases. The natural basins show little effect of imperviousness on slope adjustments, probably due to the relatively small imperviousness values. This supports the concept that urbanization tends to change channel stability constraints.

The individual points which are not in line with predicted results from the use of the envelope lines are very similiar to the points which exhibited unstable (or other than predicted behavior) with relation to basin development, as previously discussed in the section on basin development. The same result was encountered for the unstable urban classification. This above is possible because of the close relationship between basin development and basin imperviousness when the basins have similar development density.

Streamflow

Figures 58, 59 and 60 show a relationship between basin discharge and slope for urban, natural, and unstable classifications, respectively. These plots are very similiar to the basin imperviousness plots because the actual difference between flow value and basin imperviousness is a constant. This constant is the contributing drainage area when using the Rational Equation to compute the discharge. As expected, the natural basins showed little change of channel slope as discharge increases. The urban basins showed changes in keeping with the trends exhibited by the basin imperviousness plot.

Again, the points were not reexamined for the discharge versus slope plots. Site 3C/13 is below the minimum envelope line for the urban plot, Figure 58. This site is the most upstream section in a three-section channel system. It had a smaller channel width and a lower sediment supply than the two downstream sites. The two downstream sites have sediment supplied by their respective contributing drainage areas and also sediment eroded from the most upstream section, site 13. For these reasons, this site plots below the expected performance of a stable channel.

Site 1K/20 is above the maximum control line for stable urban channels, Figure 58. This site is fairly young and has not fully matured. The associated dip crossing was constructed above the existing channel grade. This has produced some local sediment transport effects which have slowed the rate of change for this channel.

The individual point data for the natural basin and unstable urban plots are very similar for all sets of plots. The similarity of stable and unstable points for each type of plot leads to the conclusion that a channel's stability or instablity consists of interrelated qualities which clearly define or determine their state.

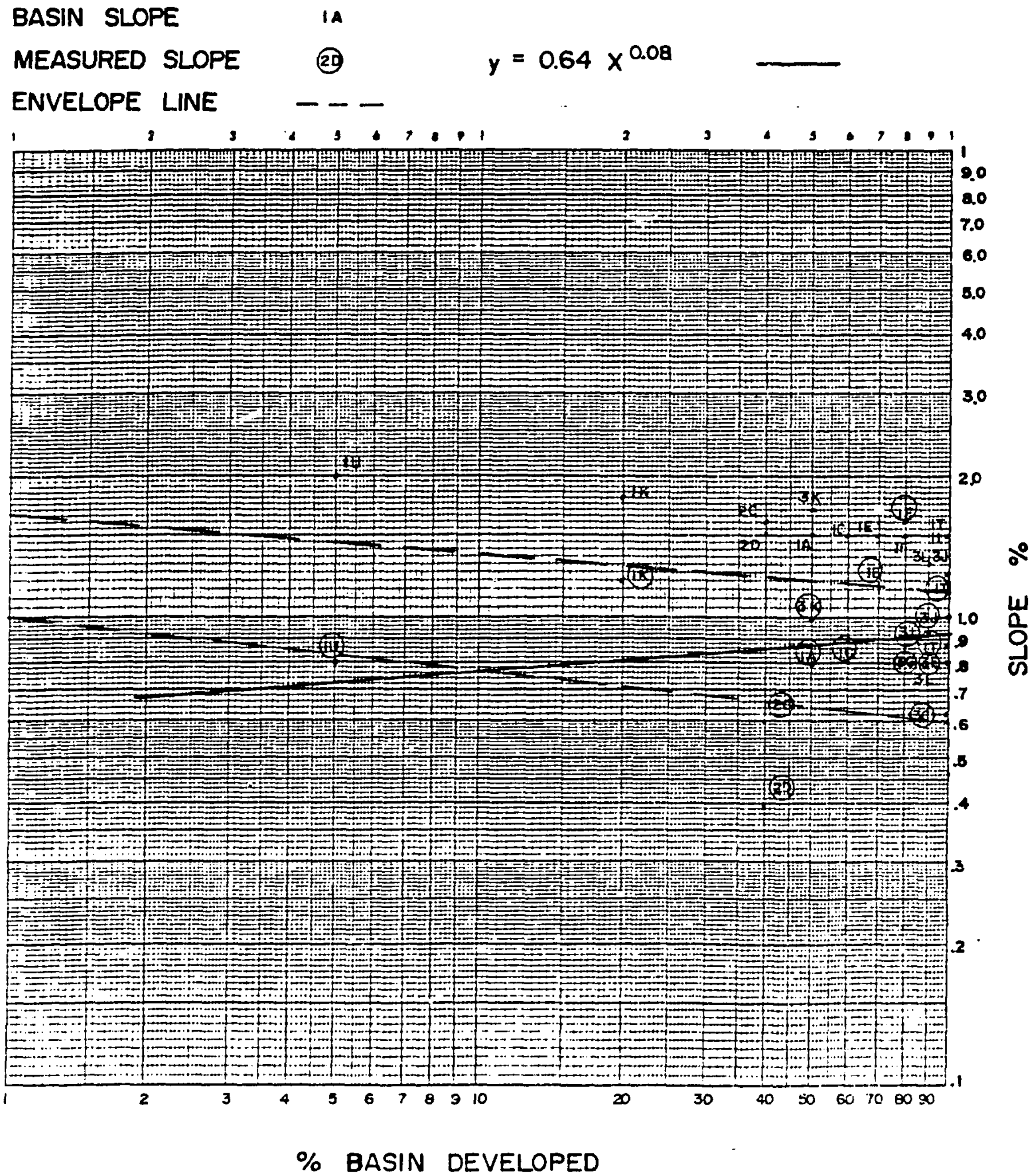

Figure # 52. Urban Basins
Percent Basin Developed versus Slope

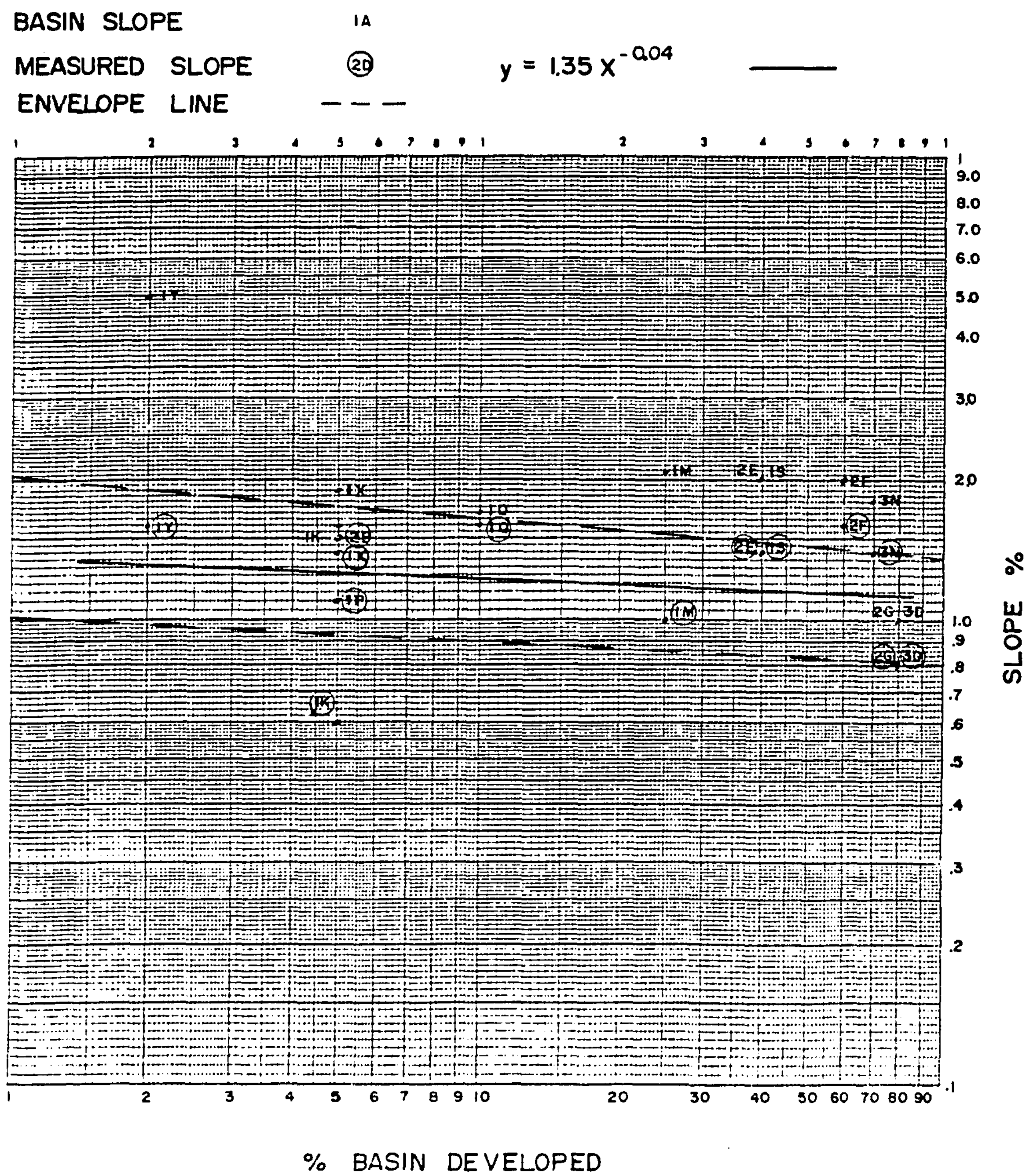

Figure # 53. Natural Basins
Percent Basin Developed versus Slope

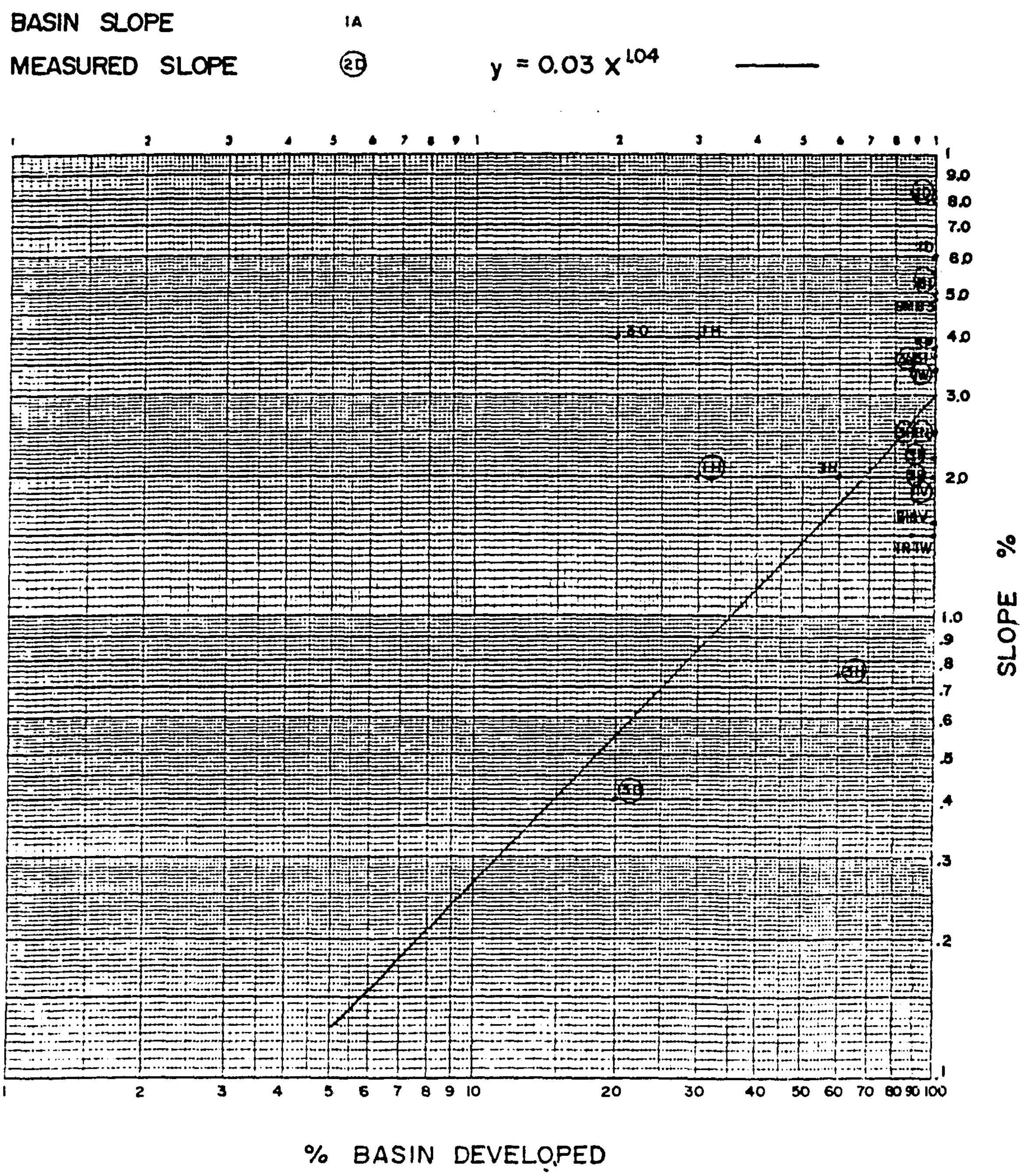

Figure # 54. Unstable Urban Basins
Percent Basin Developed versus Slope

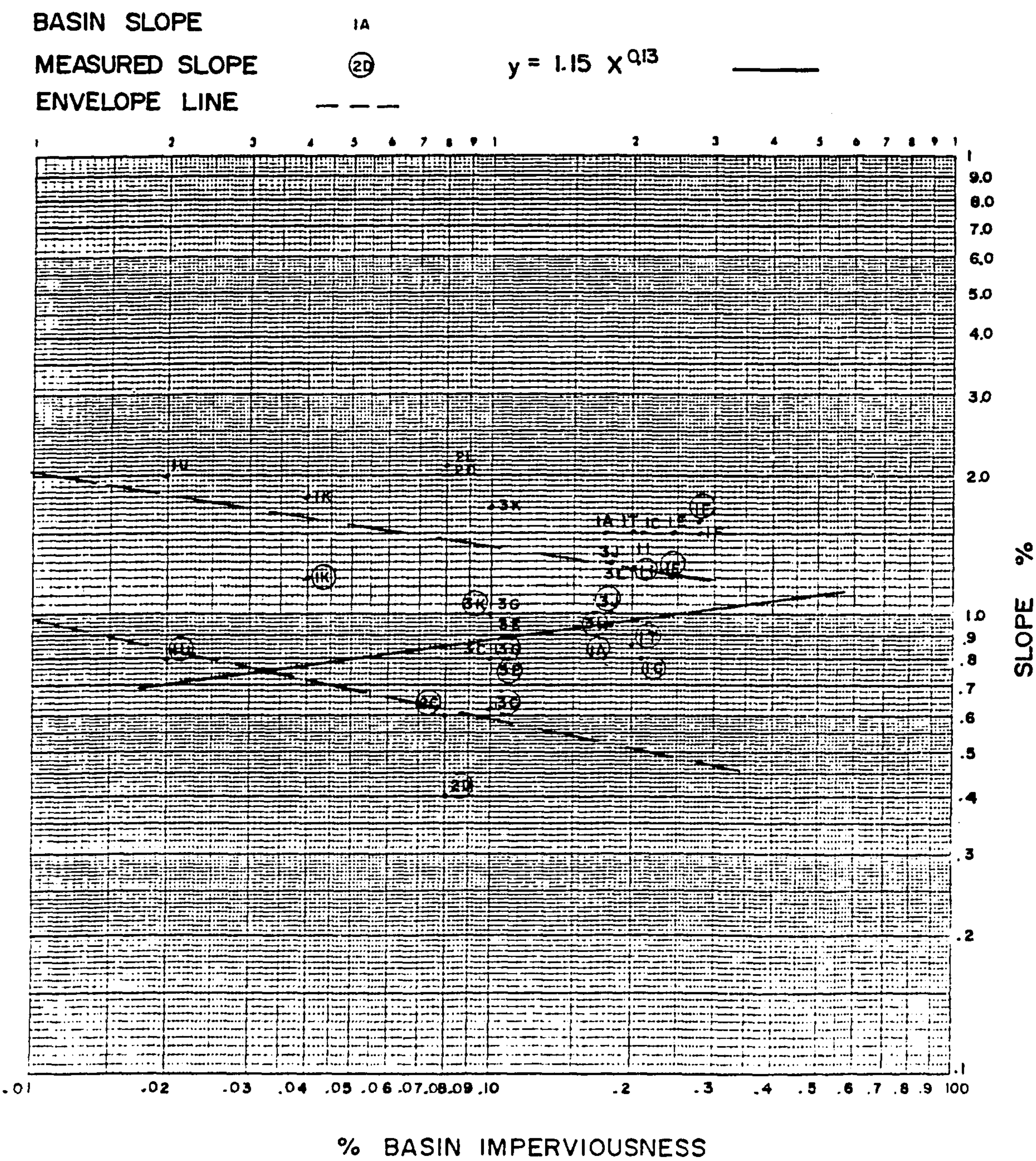

Figure # 55. Urban Basins
Percent Basin Imperviousness versus Slope

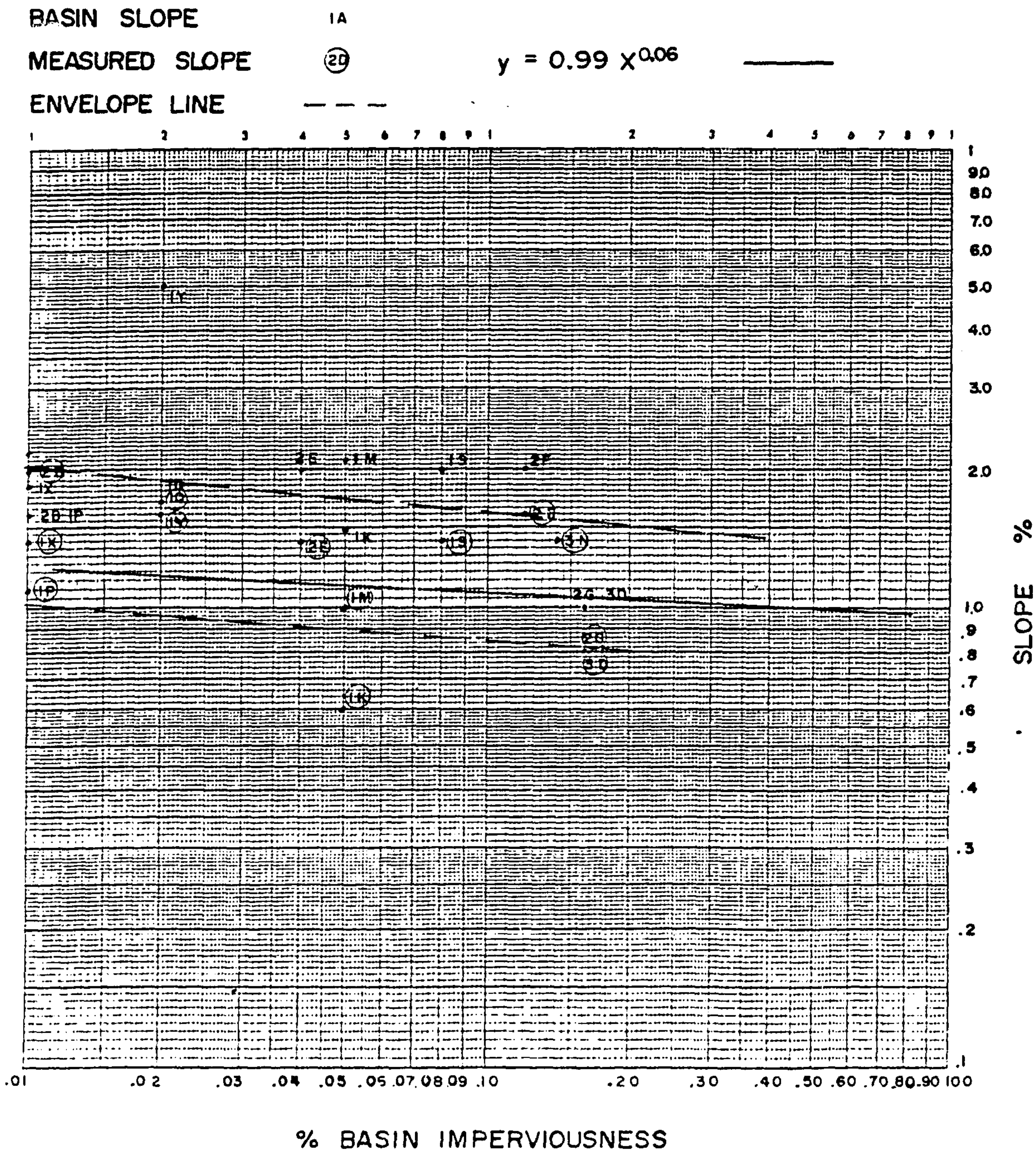

Figure # 56. Natural Basins
Percent Basin Imperviousness versus Slope

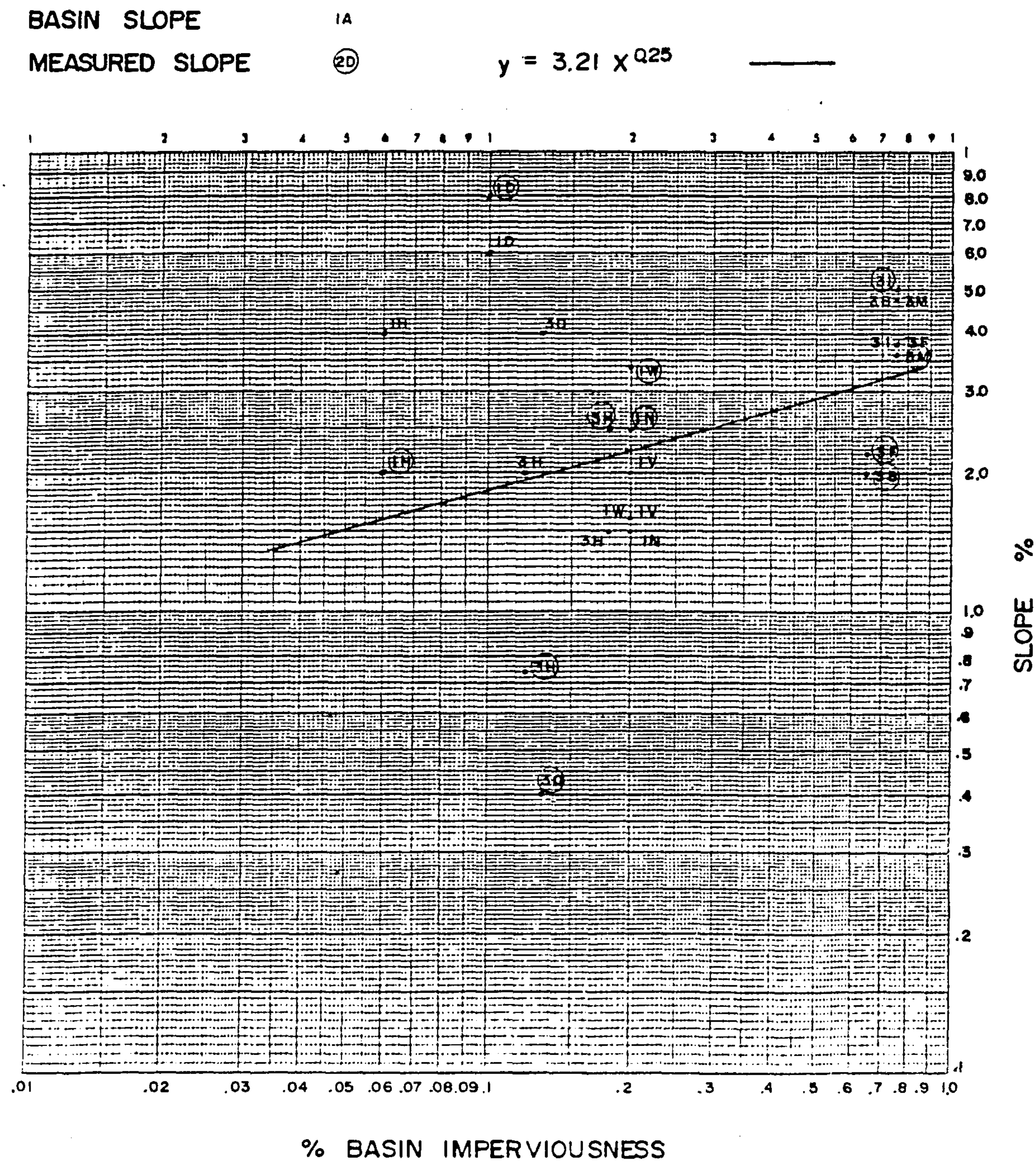

Figure # 57. Unstable Urban Basins
Percent Basin Imperviousness versus Slope

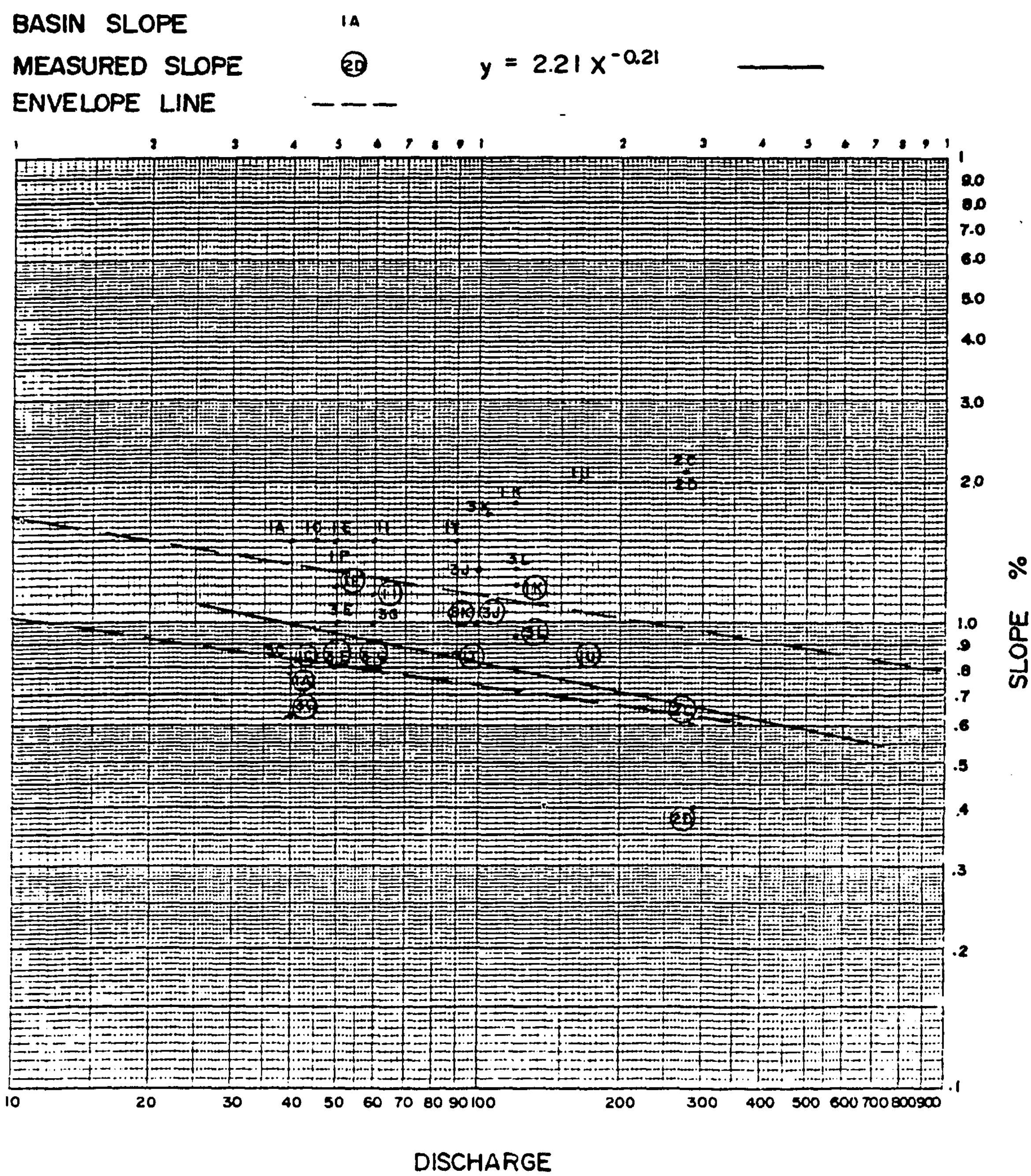

Figure # 58. Urban Basins
Basin Discharge versus Slope

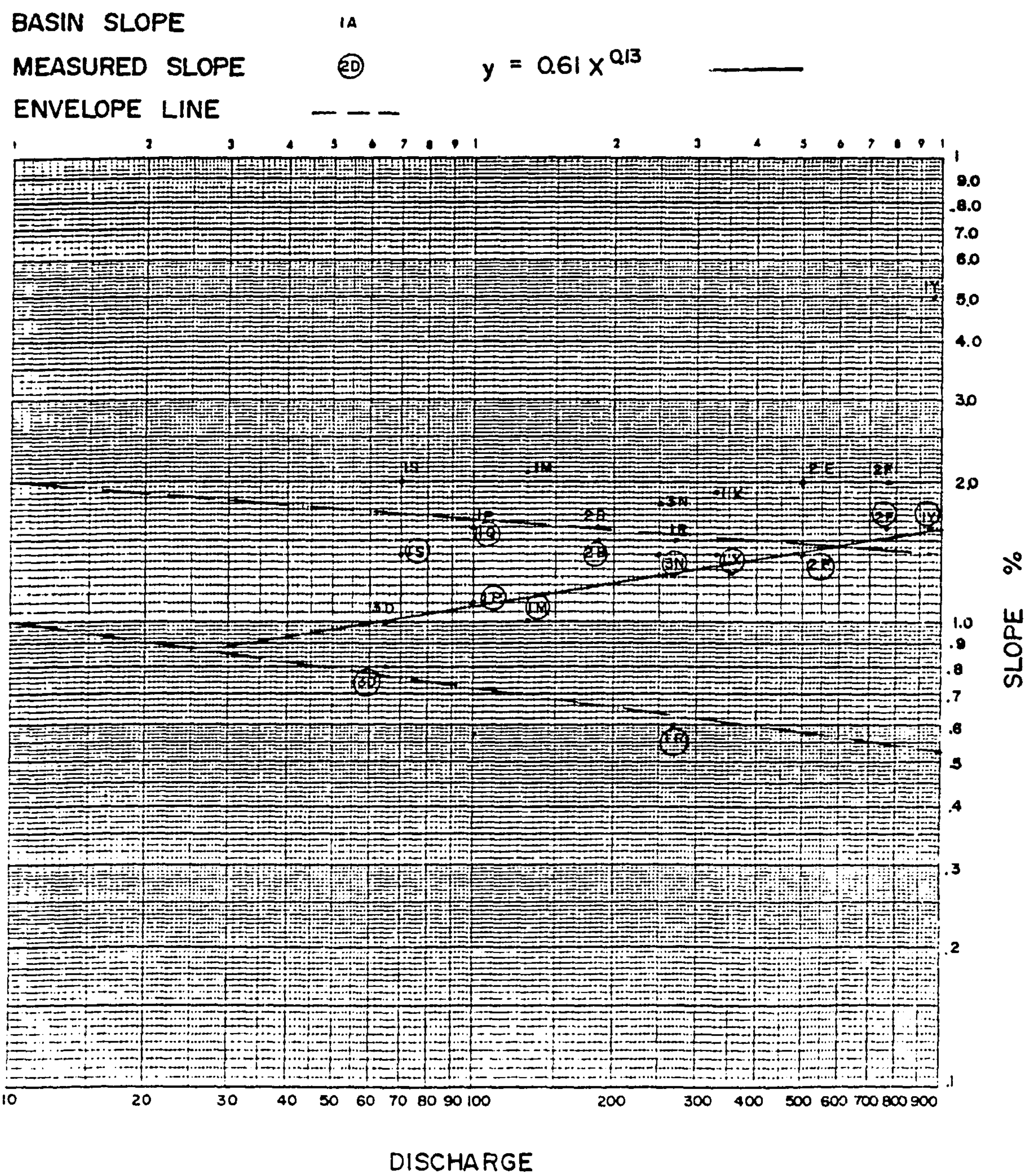

Figure # 59. Natural Basins
Basin Discharge versus Slope

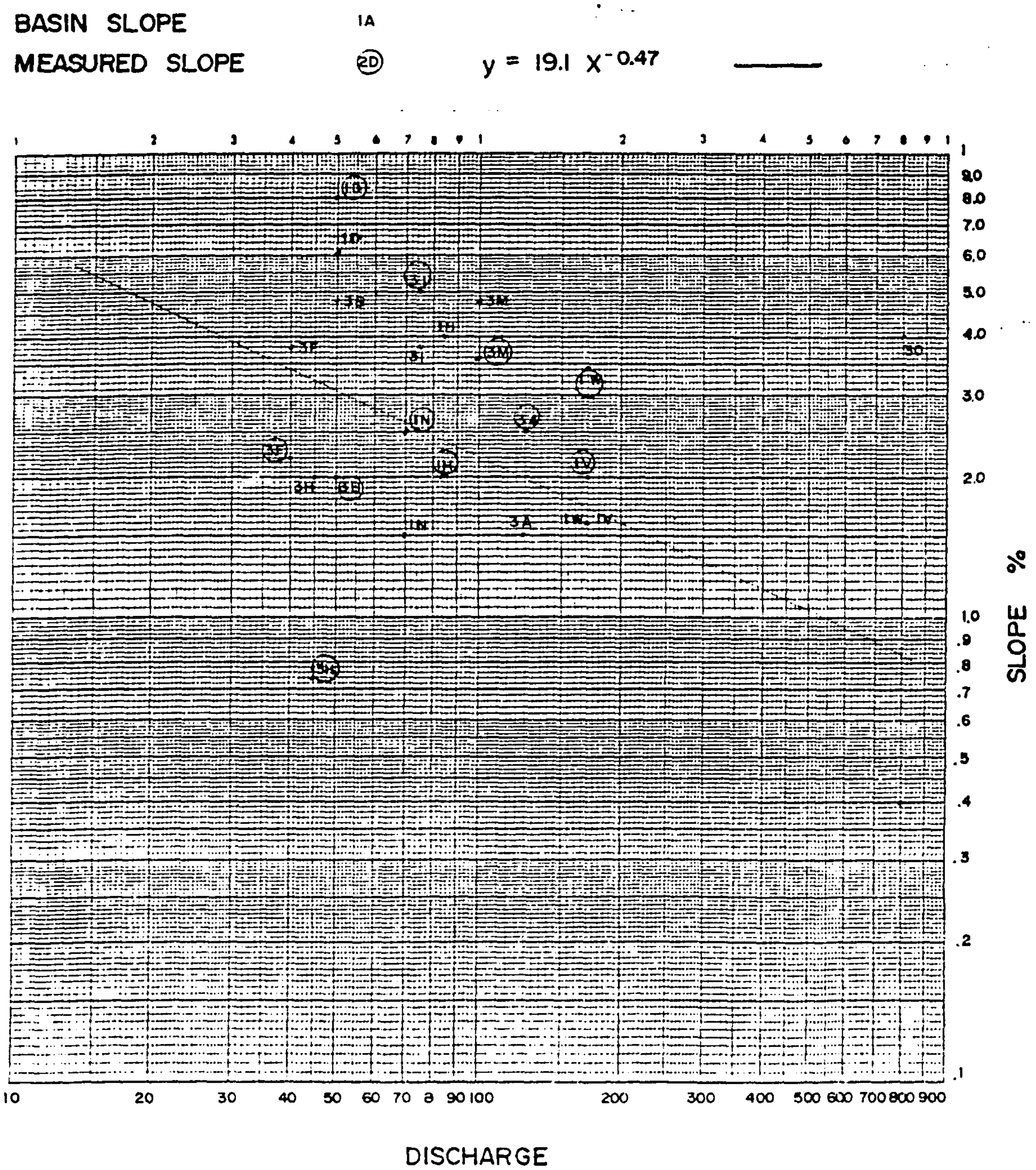

Figure # 60. Unstable Urban Basins
Basin Discharge versus Slope

CHAPTER 5

CONCLUSIONS

The amount and type of development is very important to a channel system because it controls an important factor, sediment supply, which directly governs channel stability. The sediment supply adjustment due to basin development is a very unpredicatable process. A great deal depends on when a parcel of land is rough-graded and when it rains. If a parcel is graded and rainfall events follow immediately, an excess of sediment above the normal supply rate will enter the channel system and will locally upset the sediment balance. The local effect will then be gradually transfered to the whole system. This has its greatest effect on the downstream portion of the system. The magnitude of the effects the from change in sediment supply depends also on the size of the denuded area. The system needs several flow events to purge itself of the temporary upset in sediment balance. When this finally occurs, the sediment balance will be a different quantity due to the permanent change in land use and will be lower because of the change use.

Application to Existing Stable Slope Equations

The stable slope equations used by Pima County, equations (1) and (2), were evaluated using the data obtained in this study. After review of the equations, the clear water stable slope equation, equation (1), was not used because the impervious values of the study basins were too low. A few sample calculations verified this conclusion; the calculated slopes were an order of magnitude lower than the measured slopes. Therefore, further application of equation (1) was not considered.

Due to the lack of quantifiable values for the first two terms of equation (2), some assumptions were used to complete the analysis. For both urban basins and natural basins, a 4 percent reduction of Manning's roughness value from 0.025 to 0.026 was used for the first term in equation (2). A 10 percent increase in flow value was used to simulate increased imperviousness for the second term of equation (2) for urban basins and a 5 percent increase in flow value was used for natural basins. Using these assumptions, the first two terms were multiplied through to produce a coefficient. The urban basin coefficient was 0.81 and the natural basin coefficient was 0.86. This coefficient was then multiplied by the third term, the ratio of 2-year flow top width urbanized to natural. Since values for the third term of equation (2) were available, they were used for the calculations. The sediment reduction factor R in the fourth term was not utilized because basin imperviousness was too low. The coefficient derived from the first two terms mulitplied by the third term in equation (2) then becomes a slope ratio coefficient. When this coefficient is multiplied by the existing slope (or basin slope) term, the predicted slope ratio can be calculated and compared to the measured slope ratio. Tables 5 and 6 present a summary of this analysis.

The computed predicted slope ratios were very similiar to the measured results. The predicted average slope ratio was 0.67, and the measured average slope ratio was 0.66 for urban basins. The predicted average slope ratio for natural basins was 0.73, and the measured slope ratio was 0.70. In general, the sediment transport equation, equation (2), predicted values fairly close to the measured slopes. Individually some points were very close while others were pretty far off. If the above assumptions are valid, then equation (2) should prove to be useful to a channel designer working in basins with similar amounts of development and density.

TABLE 5
Sediment Transport Equation(1)
Urban Basins

Basin	Tn ft.	Tu ft.	$(Tu/Tn)^{0.5}$	$0.86*(Tu/Tn)^{0.5}$ (slope ratio) predicted	Measured Slope Ratio
3J/8	10	10	1.0	0.81	0.77
3L/9	10	10	1.0	0.81	0.72
3G/11	10	5	0.71	0.58	0.80
3E/12	10	8	0.89	0.72	0.80
3C/13	5	4	0.89	0.72	0.78
1K/20	12	5	0.65	0.53	0.68
3K/23	12	10	0.92	0.75	0.59
1U/29	25	8	0.57	0.46	0.40
1A/31	1	3	1.0	0.81	0.53
1C/32	10	4	0.63	0.51	0.53
1E/33	10	10	1.0	0.81	0.80
1F/34	10	10	1.0	0.81	1.10
1T/37	8	8	1.0	0.81	0.57
1T/40	32	5	0.40	0.32	0.83
2C/45	15	6	0.63	0.51	0.40
2D/46	15	17	1.0	0.81	0.27
Average				0.67	0.66

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(1) Where Tn = 2-year channel top width natural condition
Tu = 2-year channel top width urbanized condition

TABLE 6
Sediment Transport Equation(1)
Natural Basins

Basin	Tn ft.	Tu ft.	$(Tu/Tn)^{0.5}$	$0.86*(Tu/Tn)^{0.5}$ (slope ratio) predicted	Measured Slope Ratio
2E/6	50	30	0.77	0.66	0.70
3D/7	20	20	1.0	0.86	0.80
2B/19	12	12	1.0	0.86	0.94
2E/21	15	8	0.73	0.63	0.70
1M/22	17	6	0.59	0.51	0.48
3N/24	25	22	0.94	0.81	0.77
1P/25	10	6	0.77	0.66	0.69
1Q/26	10	8	0.89	0.77	0.94
1R/27	10	9	0.95	0.82	0.40
1X/28	8	5	0.79	0.68	0.74
1Y/41	20	20	1.0	0.86	0.32
2F/42	10	5	0.71	0.61	0.80
2G/43	20	15	0.87	0.75	0.80
Average				0.73	0.70

----

(1) Where Tn = 2-year channel top width natural condition
Tu = 2-year channel top width urbanized condition

Sediment Concentration

There is no information available regarding sediment transport measurements of small streams in this area. In an effort to determine at least the magnitude of the effect of slope changes on sediment transport rates, Laursen's (1958) total sediment load equation was used to quantify the sediment concentration of the study sites. The equation was used to determine sediment concentration rates for only the natural sites because the pre- and post-development channel slopes and geometry were known values for this study; results are summarized in Table 7. For natural basins the measured average slope reduction is approximately 35 percent, which produced a 50 percent reduction of the average sediment transport rate. These numbers seem significant in themselves, but there is another factor not accounted for which could reduce the significance of these averages. The ability of the channel to transport sediment is diminished by the slope reduction, and the cause of the slope reduction is reduced sediment supply. The channel, after adjustment, does not need to transport such a high concentration because the amount of material to transport has been reduced. Hence, the concept of sediment supply interruption by development causing channel flattening can be observed in the sediment transport rates.

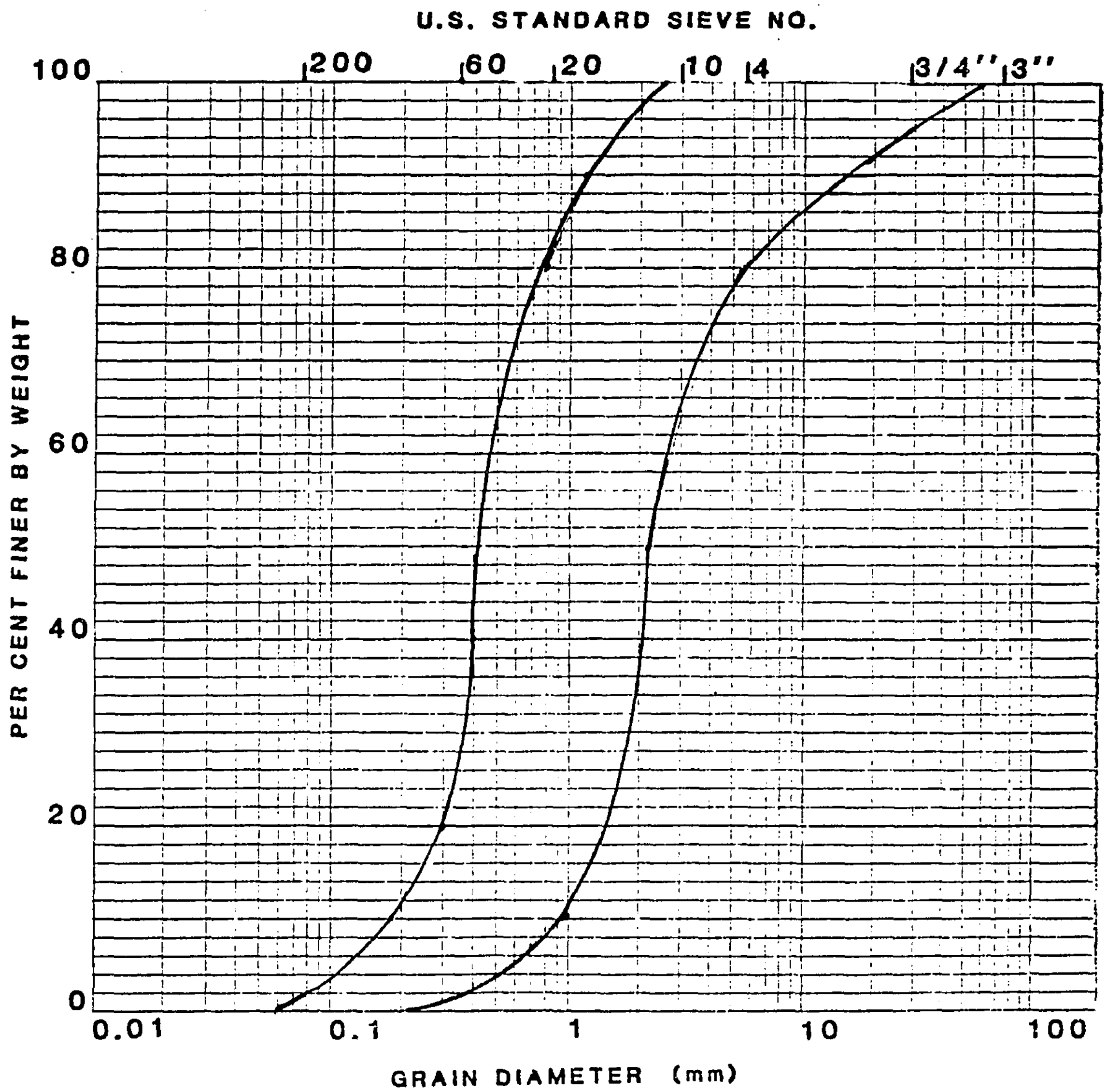
TABLE 7

Sediment Concentration
Natural Basins

Basin	Pre-Development Slope %	Measured Slope %	Sed. Conc. Pre-Dev.	Sed. Conc. Measured
2E/6	2.0	1.4	0.83	0.58
3D/7	1.0	0.80	0.26	0.15
2B/19	1.60	1.50	0.62	0.55
1S/21	2.00	1.40	0.48	0.28
1M/22	2.10	1.00	0.58	0.24
3N/24	1.82	1.40	0.72	0.52
1P/25	1.60	1.10	0.34	0.26
1Q/26	1.70	1.60	0.42	0.40
1R/27	1.50	0.60	0.63	0.14
1X/28	1.90	1.60	0.80	0.60
1Y/41	5.00	1.60	3.30	0.41
2F/42	2.00	1.60	0.70	0.50
2G/43	1.00	0.80	0.65	0.51
Ave.	1.94	1.26	0.80	0.39

Since the cause of differing sediment transport rates is due to the sediment supply, the sediment reduction factor R should have some application in equation (2). The ratio of measured sediment concentration to pre-development sediment concentration could serve as a guide to determine how R should be utilized in the sediment transport equation (2). If the above ratio, which is 0.49, is inserted as the R term in equation (2), the predicted average slope would reduce to 0.39. This would substantially reduce the calculated predicted value to well below the actual mesaured average slope ratio value. This would support the conclusion that the sediment reduction factor R in equation (2) should not be utilized for basins of this type as the Drainage Design Manual suggests. If the sediment supply change, as represented by the difference in the sediment transport rates, is to be utilized as a valid design parameter then a new relationship between channel slope reduction and basin development will have to be formulated. This new relationship should use a sediment reduction factor as a major component and place less influence upon channel geometry.

This study was undertaken using field data which are unique to Pima County, Arizona. Caution should be exercised when using the results of this study in areas which have different soil and precipitation conditions. In order to provide a measure of transferability to the results of this study, a sediment gradation envelope curve was developed and is shown in Figure 61. The average d-50 for this envelope was 1.35 mm. As a general rule of thumb, if applying the study results to an area having a higher sediment size distribution, the slope adjustments should be less severe than predicted here. This, of course, gives only an indication of the slope adjustments, for many factors influence the change of channel slope.



AVERAGE d_{50} = 1.35 mm
SEDIMENT SIZE ENVELOPE

Figure 61.
Sediment Gradation Curve

The results of this study should be useful when comparing a natural channel to a designed or constructed channel for the density of 1 R.A.C. This study shows that development in a basin where channels do not closely adhere to natural channel stability constraints will produce undesirable effects, ranging from reduced channel capacity to excessive channel maintenance. If a channel were constructed in a basin which had densities of 1 R.A.C., the slope which would yield a stable reach would be about one percent. The urban basin channel would exhibit a slope adjustment of approximately 66 percent. A natural basin, which had a grade control structure installed as a part of development would show a slope adjustment of about 70 percent. The expected final slope for a channel in this type of basin is about 1.3 percent.

The slope is the most important design criteria for producing a stable channel. A channel has the ability to function efficiently if it is constructed too wide or narrow, but this is possible only if the channel had a suitable slope when initially designed. This is the stable slope.

From studies of the few sites which had densities above 1 R.A.C., a general conclusion was reached (based upon findings for the 1 R.A.C. densities) that such channels will have more channel stability problems than low-density natural channels. More care and attention must be given to design of such channels because they will react or adjust at a rapid rate in responce to the effects of development. It is possible for major adjustments to occur during a single flow event.

LIST OF SYMBOLS

Sc	Stable Design Slope Clear Water Equation.
n	Manning´s Roughness Coefficient.
q	Flow per Unit Width (2 year flow value).
Seu	Stable Equilibrium Slope After Urbanization.
Sn	Natural Slope or Existing Stable Slope.
nu	Manning´s Roughness Coefficient Urbanized Conditions.
nn	Manning´s Roughness Coefficient Natural Conditions.
Qwu	2-Year Peak Discharge After Urbanization.
Qwn	2-Year Peak Discharge Before Urbanization.
Tu	2-Year Top Width Urbanized.
Tn	2-Year Top Width Natural.
R	Reduction Factor For Sediment Supply.
c	Sediment Concentration Percent By Weight

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