5.0 EQUILIBRIUM SLOPE AND FUTURE CONDITIONS ASSESSMENT

A change in bed material size, continued narrowing, and channel bed incision all indicate that this channel is currently not stable, and that it will continue to evolve. For this study, channels described as 'stable' are those in which 1) the bed material is mobile during channel forming flows, but the sediment size is not changing, 2) supply of sediment is relatively steady, 3) general channel dimensions (e.g., width and depth) and slope are not changing significantly, and 4) the channel pattern remains constant over time. The systematic migration of a meander bend is still considered a stable channel even though the dimensions and location of the floodplain are constantly changing in this environment. This section assesses both the stability of the current slope and the measured grain sizes of the gravel layer. From this information, future conditions of channel pattern, slope and width were estimated. For purposes of this study, the equilibrium slope is defined and calculated using two methods: 1) the slope that transports the incoming sediment supply without any scour or fill on the channel bed, and 2) the slope required for the initiation of incipient motion of the current bed material.

5.1 Equilibrium Slope and Width Analysis

5.1.1 Historical Slopes

Current and historic channel slopes were determined using photometric and field measured cross section data in the HEC-RAS model. Results of this exercise show that slope has varied through time (Table 17), but that many transport zones now have slightly lower slopes or similar slopes to those from the 1960's.

Table 17: Summary of average water surface slopes from HEC-RAS at 5,000 cfs, San Acacia Reach (1962-1999).

Transport Zone	1962	1972	1992	1997	1999
1	0.00096	0.00089	0.00085	0.00074	0.00077
2	0.00107	0.00079	0.00107	0.00103	0.00092
3	0.00058	0.00043	0.00032	0.00031	0.00065
4	0.00109	0.00095	0.00125	0.00107	0.00093
5	0.00083	0.00090	0.00084	0.00067	0.00061
6	0.00080	0.00079	0.00078	0.00080	0.00091
7	0.00140	0.00146	0.00123	0.00133	0.00099
8	0.00101	0.00097	0.00064	0.00083	0.000700

5.1.2 Equilibrium Bed Slope based on Sediment Size

The channel bed slope stability analyses based on sediment size, found that the current channel slopes are close to equilibrium with the gravel-sized sediment, but not at equilibrium with sand-sized sediment. Four sediment transport models, Schoklitsch (1932), Meyer-Peter & Muller (1948), Lane (1955), and Shields (1936), estimated 'stable' slopes based on channel conditions from the 1999 survey data. Schoklitsch's model incorporates grain size and width with discharge to obtain the stable channel slope. The Meyer-Peter & Muller method combines discharge with bed roughness (Manning's 'n' variable) and grain size, but also adds in channel depth. Lane's model uses the critical tractive force along with channel depth to determine slope, while Shields' model uses the Reynolds number with shear velocity and particle size. The analysis for the sand sizes was performed at a discharge of 3,000 cfs, since this is the estimated effective discharge, while a flow of 5,000 cfs, or bankfull discharge was used for the gravel data (Channel Forming Flow Section 4.2). Since zone 5 is transitional, stable slope estimates were not calculated. Slopes were not calculated for the gravel data in zone 8 either, since no gravel data was collected. Results for sand sized sediment (Table 18) show that the current channel slopes are all greater than the estimated stable slopes, while estimated slopes for gravel are similar to the current slopes. Hence, these data indicate that the sand layer is not stable with the current channel slope, but with the increase in sediment size to gravel, the current bed slopes are stable.

Table 18: Computed stable bed slopes for sand and gravel sized sediment for San Acacia reach.

Zone	Shoklitsch (1932)	MPM (1948)	Lane (1955)	Shields (1936)	Average of all Models	Water Surface Slope
Slopes for Sand Sized Particles						
1	0.00008	0.00024	0.00034	0.00002	0.00017	0.00077
2	0.00009	0.00040	0.00037	0.00002	0.00022	0.00092
3	0.00010	0.00041	0.00038	0.00002	0.00023	0.00065
4	0.00012	0.00049	0.00043	0.00002	0.00027	0.00093
5	N/A	N/A	N/A	N/A	N/A	N/A
6	0.00010	0.00043	0.00053	0.00003	0.00027	0.00091
7	0.00007	0.00033	0.00039	0.00002	0.00020	0.00099
8	0.00009	0.00041	0.00040	0.00002	0.00023	0.00070
Slopes for Gravel Sized Particles						
1	0.00121	0.00400	0.00073	0.00094	0.00172	0.00086
2	0.00128	0.00347	0.00059	0.00078	0.00153	0.00076
3	0.00089	0.00302	0.00039	0.00049	0.00120	0.00074
4	0.00140	0.00351	0.00068	0.00094	0.00163	0.00119
5	N/A	N/A	N/A	N/A	N/A	N/A
6	0.00182	0.00419	0.00056	0.00095	0.00188	0.00101
7	0.00388	0.00807	0.00148	0.00185	0.00382	0.00092
8	N/A	N/A	N/A	N/A	N/A	N/A

5.1.3 Estimated Equilibrium Slope and Width based on Sediment Supply

The equilibrium slope and width, estimated using a sediment analysis model indicated that the channel will generally continue to narrow and steepen. Sediment supply and current channel conditions were used in SAM (U.S. Army Corps of Engineers' SAM-Hydraulic Design Package for Channels, 1998), a model developed to estimate stream power and the associated channel characteristics such as width and Energy Grade slope (EG slope) based on supply of sediment. Energy grade slope is a combination of water surface slope with velocity head ($velocity^2/2*gravity$). The sand load was estimated in Section 4.6 – Sand Load from Upstream Sources, at approximately 12,700 tons/day for a 5,000 cfs spring flow (Figure 22), while the current channel conditions are summarized in Table 16, Section 4.8 – Sediment Routing. Results from SAM include the estimated stable channel width and estimated stable Energy Grade Slope. The estimated stable channel width results indicate that most of the channel will continue to narrow (Table 19). With the exception of transport zones 6 and 7, the estimated stable EG slopes are generally steeper than the current EG slopes (Table 19). Zones 6 and 7 have EG slopes steeper than the estimated EG slopes from SAM. These results indicate that Zones 6 and 7 which still have channel features most similar to historic conditions have a significant potential to lose both energy (EG slope) and width, while the other zones will likely continue to only narrow.

Table 19: Computed stable width and EG slopes for the current channel conditions and sediment supply for flows of 5,000 cfs: San Acacia Reach.

Transport Zone	EG Slope (ft/ft)	Width (ft)		Est. Stable Width (ft)	Est. Stable EG Slope
1	0.00084	180		140	0.00098
2	0.00059	230		150	0.00096
3	0.00087	280		155	0.00089
4	0.00061	280		160	0.00091
5	0.00066	230		160	0.00091
6	0.00105	410		150	0.00081
7	0.00093	730		165	0.00075
8	0.00061	150		160	0.00085

5.1.4 Summary of Equilibrium Slopes and Widths from Sediment Transport Models

Bed slope analyses indicated that the current channel bed slopes are stable for the current channel that is gravel bedded, while the SAM analysis indicates that the channel will continue to narrow and increase in velocity to transport the current sand load. The historic slope data (Table 17) indicate that, in general, bed slopes have decreased since 1962, averaging about a 20% change. The stable bed slope assessments based on sediment size found that the current slopes are close to equilibrium for the gravel-sized sediment. The predicted bed slopes for sand were significantly shallower than the current slopes, indicating that sand sized sediment is not the stable sediment size in this reach. Current channel conditions compared with the SAM results showed that only two zones had unstable EG slopes, while most zones would continue to narrow. Combining the bed slope analyses with the SAM results and historic trends indicates that although the bed slope is stable, the dimensions of the channel which have continuously changed over time will likely continue their trends toward a narrower, deeper channel with a faster velocity.

5.2 Stable Sediment Sizes

The gravel sizes measured in the first 4 miles (zones 1-4) downstream from San Acacia diversion dam are mobile when the flow approaches the channel forming discharge of 5,000 cfs (Table 20), however, the gravel sizes found in the remainder of the reach are not necessarily mobile at this flow. The flow needed to induce sediment mobility for the grains in the gravel layer was estimated using Yang's sediment transport model (1984) for gravel. Yang's model uses unit stream power to estimate sediment transport capacity. The measured d_{84} for each zone was used to represent the armored surface condition. Zone 5 is transitional, therefore no calculations were performed; also, no calculations were performed in zone 8 due to lack of data for the gravel layer.

Results from Yang's model indicated that grain sizes present in zones 1-4 are mobile near the channel forming discharge, but further downstream in zones 6-7, the current gravel sizes are not mobile. In zones 1 and 2, flows near 5,000 cfs, the channel forming/bankfull discharge, are estimated to transport the d_{84} particle size (Table 20). These data indicate that the gravel is stable for the current channel form in zones 1 & 2. Gravel in zones 3 and 4 can be transported with much lower flows, indicating that the current sediment sizes may not stable, and that smaller flows can initiate sediment transport. In zones 6 and 7, the discharge necessary to initiate sediment transport is significantly higher than the channel forming discharge, indicating that the gravel currently present is not likely transported by the current hydraulic conditions in the river. The source of the gravels in zones 6 and 7 is likely from adjacent hillslopes, nearby arroyos and are relic fluvial deposits. Although the gravel measured in zones 1-3 may also be from these local sources, its systematic decreased in size suggests that it was likely transported from upstream sources.

Table 20: Grain sizes present, estimated sizes of grain mobile during a 5,000 cfs discharge and the specific discharge required to mobilize the current grains on the channel bed in the San Acacia Reach.

Transport Zone	Measured d_{84} Grain Size (mm)	Estimated Grain Size Mobile (mm)	Discharge for Grain Mobility (cfs)
1	51	32 to 64	4,800
2	41	16 to 32	5,600
3	13	16 to 32	3,700
4	93	32 to 64*	~3,000 for 64 mm*
5	91	not calculated	not calculated
6	41	8 to 16	22,500
7	56	2 to 4	greater than 35,000
8	none measured	not calculated	not calculated

*Yang's model is not designed for grain sizes larger than 64 mm (very coarse gravel) therefore this model cannot accurately estimate the mobilizing discharge for the d_{84} present in zone 4.

5.3 Future Conditions - No Action Scenario

Data indicates that sub-reaches 1 and 2 have channel patterns and characteristics that are stable, while sub-reaches 3 and 4 have potential for continued channel evolution. The future conditions analysis focuses on three dominant channel features: 1) channel pattern, 2) bed material/grain size, 3) channel width and 4) channel bed elevation. Although each sub-reach is assessed individually, evolution in one sub-reach could affect the future condition results for another sub-reach, which will be summarized in the last section. The current sediment supply and discharge patterns are used in this assessment.

5.3.1 Future Conditions of Sub-Reach 1

Channel features such as channel patterns and grain sizes have not changed recently in sub-reach 1 and appear to be relatively stable. Sub-reach 1 is a straight channel with a gravel bed, intermittently covered by thin sand deposits. This channel is physically confined by railroad tracks and by tall terraces, and therefore cannot readily widen or flood. Although channel bed grain sizes could change in the future, the change from a sand bed to a gravel bed is complete. With a channel bed composed of gravel sized sediment, bed degradation is expected to decrease in the future, since the gravel bed is able to form armor layers resistant to erosion. Due to a decrease in incision, channel slope values are also expected to stabilize. Although the SAM analysis indicated that this sub-reach could still narrow, the historic analysis of channel width indicates width is stabilizing. In summary, significant changes in this sub-reach are not expected in the future.

5.3.2 Future Conditions of Sub-Reach 2

Although meandering channels, such as sub-reach 2, typically migrate across their floodplains, channel characteristics such as width, depth and slope should remain constant, which is the trend expected for future conditions in sub-reach 2. Sub-reach 2 is a slightly meandering channel with a gravel bed that is intermittently covered by a thin layer of sand sized sediment. Unlike sub-reach 1, this channel is likely to slowly erode the confining banks (terraces and levee walls) and slowly migrate from its current location, due to its meandering channel pattern. However, channel characteristics such as width and depth are not expected to change significantly due to channel migration. Although the SAM results indicated a significantly narrower channel for the future, the current channel width appears to be stabilizing. As with sub-reach 1, the channel bed has already converted to gravel, which will likely inhibit future degradation, and hence stabilize channel slope. Although some conditions in sub-reach 2 may change, for example, specific channel location, the hydraulic properties of the channel are considered stable.

5.3.3 Future Conditions of Sub-Reach 3

The morphology of sub-reach 3 is expected to continue converting to a slightly meandering channel, which will be a channel that is narrower, deeper, and less steep. Current sub-reach 3 morphology conditions are: 1) zone 4 has already converted to slightly meandering channel, 2) zone 5 is in the process of converting, and 3) zones 6 and 7 are still dominated by a low-flow braided morphology, but prominent thalwegs have developed recently in portions of these zones. The development of a prominent thalweg may suggest that conversion to a single-threaded, meandering channel has already begun. Channel characteristics from sub-reach 2, an established meandering section of river, were used as a guide for extrapolating future morphology conditions in sub-reach 3; specifically, channel width and period of meander bends from sub-reach 2 were extrapolated to sub-reach 3. The July 1999 cross section data were physically modified to reflect the dominant morphology features in sub-reach 2: 1) the sand layer was removed to the depth of the current gravel deposits; 2) a meandering channel pattern was incorporated; and 3) the channel width was decreased to approximately 250 ft. Channel characteristics for these modified cross sections were estimated using the HEC-RAS model and then averaged. With the emerging gravel bed and a change in channel pattern to meandering, physical channel attributes are expected to changed dramatically: channel width will decrease by at least half, while doubling the channel depth. Although the bed slope is expected to decrease (due to the increased channel length of the meandering channel), the water velocity is still expected to increase due to the reduced channel area as predicted in the SAM results.

Table 21: Average future conditions for sub-reach 3, based on a slightly meandering, gravel bedded channel, San Acacia Reach.

	Width (ft)	Depth (ft)	Area (ft^2)	Velocity (ft/sec)	Mean Bed Slope (ft/ft)
Current Conditions	640	2.5	1600	3.7	0.00092
Future Estimated Conditions	250	5.0	1250	4.0	0.00082

Using the modified channel characteristics, a stable grain size analysis found that although the median gravel sizes currently found in sub-reach 3 are likely mobile, the channel armoring bed material (d_{84} sediment size) was not. Yang's gravel sediment transport model

(1984) estimated the potential mobility of particle sizes found in the current gravel deposits in sub-reach 3. The channel forming flow of 5,000 cfs, and the estimated future channel characteristics (Table 21) were used in the analysis. The particle size most likely to form an armor layer, the d_{84}, is estimated to be approximately 40 mm (Table 20) in sub-reach 3, while the median particle size (d_{50}) was 16 mm. The sediment transport model indicated that the current median particle size is mobile; however, the current d_{84} particle size is not mobile. These data suggest that the channel forming flow will erode the sand layer and create an armored gravel layer. Since armor layers naturally impede bed erosion, the rate of degradation in this reach will likely decrease or even stop as the gravel layer is 're-worked' by high flows.

5.3.4 Future Conditions of Sub-Reach 4

Sub-reach 4, a straight, narrow, deep channel has not changed much since 1972 (Table 11), except in elevation, which is expected to stabilize in the near future. Moderately tall terraces confine the channel and sufficiently contain channel forming flows. The SAM model results indicate that channel width is stable; the channel bed contains little gravel. The one notable feature that is changing in this sub-reach is the area at the Arroyo de la Parida confluence. Due to a major channel modification prior to the 1960's, the arroyo flows through an abandoned reach of the Rio Grande before joining the current Rio Grande channel. Since the 1960's, the larger sediments (i.e., gravel) transported by the arroyo were deposited in the abandoned channel, and not in the current channel. However, in recent years (post 2000), the arroyo has filled in the abandoned channel and is now transporting its total load to the current Rio Grande channel. These arroyo sediments are now deposited in the Rio Grande, creating a sediment fan that extends across the river. The fan is composed mostly of gravel and cobble sized sediment, some of which is being transported downstream by the Rio Grande. The fan is approximately 3 feet taller than the former channel height measured in 1999. The fan is expected to persist long-term and is already creating a point of stable channel bed elevation in the Rio Grande. With a stable bed point, channel degradation upstream of the arroyo is expected to decrease or even stop.

Sediment sizes in this sub-reach are changing rapidly due to the supply of coarse material from Arroyo de la Parida. The sediment fan is creating two features in the Rio Grande: a backwater/pool upstream of the fan, and a gravel bed downstream of the fan. The extent of the upstream backwater area is presently unrealized; however, by extrapolating the current stable channel slope upstream of the confluence (Figure 27), the backwater affects of the fan may reach the sub-reach 3 boundary. In this 1.5 miles, the slope is decreased, and a modest amount of finer sediments are expected to be deposited and to be retained long-term. Downstream of the fan, the sediment size is expected to increase to at least gravel size. The development of a stable-channel elevation and the deposition of gravel in the lower section of the sub-reach are expected to hinder channel incision. Hence, degradation rates in sub-reach 4 are expected to decrease or even cease due to the re-connection of Arroyo de la Parida to the Rio Grande.

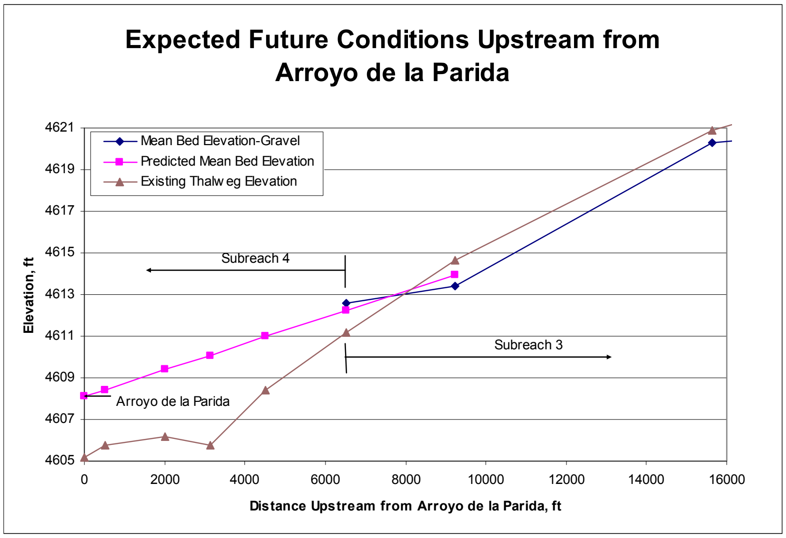

Figure 27: Future elevation conditions of Sub-Reach 4, Rio Grande – San Acacia Reach.

5.3.5 Summary of Future Conditions

The Rio Grande in the San Acacia Reach has undergone several major geomorphic changes in the recent past, however the evolution is not complete; future conditions analysis indicates that channel pattern changes will continue, the emergence of a gravel bed will extend downstream of it's present location, and that with these changes, channel elevation may become more stable. Channel pattern is stable in sub-reach 1 due mostly to its high confinement. However, sub-reaches 2 and the upstream portion of 3 have recently converted to a slightly meandering channel pattern. The remainder of sub-reach 3 appears to be preparing to convert to a single-threaded meandering channel, which will be the most dramatic change to the current channel features present in the reach. Channel pattern in sub-reach 4 appears stable, as in sub-reach 1. The emergence of a gravel bed, which began in the late 1980's at the diversion dam has migrated about 4 miles downstream (upstream portion of sub-reach 3) and is expected to connect with the Arroyo de la Parida fan in the future. As a result of Arroyo de la Parida reconnecting to the Rio Grande and the emergence of a protective gravel layer throughout the whole reach, the rate of degradation is expected to subside if not cease altogether.