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1996
FLUVIAL GEOMORPHIC ASSESSMENT OF THE CARSON RIVER WITH IMPLICATIONS FOR RIVER MANAGEMENT

FLUVIAL GEOMORPHIC ASSESSMENT of the CARSON RIVER:

IMPLICATIONS FOR MANAGEMENT OF A CHANGING RIVER

FINAL REPORT

June 6, 1997

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NOTE TO READERS:

This report was originally submitted in December of 1996, prior to the New Year's Flood of January 1997. It should be noted in reading this document that the conclusions and recommendations stated in this report are based on observations which were made previous to the geomorphically significant flood event. The physical state of much of the observed areas has been significantly altered. In many reaches and subreaches, physical change resulting from these floods has been so significant as to render some recommendations inappropriate. Where such changes have been observed by local land managers, their opinions as to the appropriateness of recommendations should be observed. However, in our opinion, while site specific and short term recommendations may be less appropriate following the flood, general and long-term management considerations are still appropriate and relevant on a watershed scale.

EXECUTIVE SUMMARY

A long history of attempts to control the Carson River for beneficial uses, particularly those related to agriculture, have resulted in widespread instability of the system. Rapidly expanding populations in Douglas County, Carson City, and Lyon County have brought instability issues to the forefront due to the apparent increase in damages to property from regularly occurring flood events. Recognizing that previous river management strategies have in many instances failed to provide a solution for river stability and its value as a multiple-use resource, the Western Nevada Resource Conservation and Development Area coordinated funding for this report which details a fluvial geomorphic investigation of 110 river miles. It is believed that a better understanding of river behavior will guide future efforts related to improving current conditions.

This report is intended for an audience with some technical understanding of rivers. Basic fluvial geomorphic principles are described with reference to specific areas of the river to familiarize the reader with these concepts. A discussion of natural channel stability and how human activities affect stability is central to the report. Notable human influences on river stability on the Carson River include levee construction, channelization, diversions and ditches, and grazing. The report then summarizes the findings drawn from detailed site assessments at over 65 locations along the river corridor. Overall channel stability by reach, planform issues, capacity, sediment supply, and vegetative condition are explored. Detailed site assessments are included in report Appendices, including hydrologic, hydraulic, and channel type analyses. These detailed assessments are intended for a technical audience who may be involved in permitting, design, management, or restoration activities.

Recommendations and options for the enhancement of river stability are presented. System-wide recommendations are covered first, including protection of property and infrastructure, engineering control, aided natural recovery, riparian management, flow management, diversion practices, and levee removal or setbacks. Additional recommendations include the need for study follow-up as the river continues to change through time and increasing the staffing and training budgets of local management agencies. Detailed recommendations by reach are found in Appendix A. Basic engineering practices for river work are briefly reviewed to illustrate the technical nature and needs of modern and professional river projects. Finally, reaches of river are prioritized for river recovery actions based on overall assessment of the corridor.

General conclusions drawn by include a number of overlapping issues which point to the need for coordinated river management. Chief among these is our conclusion that the great majority of the river is in a state of geomorphic transition, and that further changes in channel geometry and planform can be expected. These changes may proceed incrementally as average and moderate flood events occur, or rapidly during large flood events. From a geomorphic perspective, these changes are necessary for the river to achieve a state of natural stability. However, development along the river corridor has created a situation where many of these changes may pose problems, as they may threaten infrastructure and property through river migration and flooding. Further, dewatering of the river through irrigation withdrawals may be an irrevocable river condition which may impair natural recovery even if a number of other beneficial strategies are pursued. Therein lies the greatest challenge for those interested in managing the river for multiple uses, as conflicting objectives must be sorted and a unified plan for river management adopted.

INTRODUCTION

History

Channel instability along the Carson River likely dates back to the first extensive use of the river by industrialized settlers for irrigation and mining related activities. In combination with a geographic setting which regularly delivers large magnitude floods, river instability appears to have been the prevailing condition for many decades. A history of flooding along the Carson River indicates floods have been altering channel alignments and stability every five to twenty-five years (Nevada Division of Water Planning, 1996), since the turn of the century. Attempts to control the river in the aftermath of floods appear to have provided most of the impetus and funding for major channel projects which have subsequently had major implications for river stability. Of prominence are actions taken following the 1955 and 1963 floods, which included significant channelization and levee construction along the river corridor.

Generally, the stability of the Carson River can be described as poor. This condition is manifested by miles and miles of eroding banks, a large potential and in-channel sediment supply, and a degraded riparian corridor. One apparent trend of the river in previously channelized reaches is an increase in channel width and sinuosity, which is providing headaches for those who live adjacent to the river or are maintaining diversions and ditches. Efforts made to manipulate the river in the last several decades appear to be short-lived, with many projects failing within years of installation.

Against this background, this study and subsequent report was conceived. Inter-Fluve, Inc., in association with JBR Resources, Inc., was hired in October of 1996 by the WNRC&D to meet multiple objectives surrounding the current state of river instability. Due to the magnitude of the field work involved and a rapid turn-around time for the report, the Project Team partnered with a number of government agency personnel to accomplish the field inventory. Over 20 different personnel, mostly with the USDA Natural Resource Conservation Service, were enlisted for the project. In addition to assistance provided, the collaborative field inventory was intended to expose the relevant agency personnel to fluvial geomorphic concepts and state-of-the-art river project design concepts.

Project Goals

The intent of conducting a Fluvial Geomorphic Analysis of the Carson River is to provide governing agencies, landowners, and other interest groups with the information necessary to educate involved parties and proceed with selection and implementation of projects which will enhance river health and reduce channel and bank instability. Following responses to the Request for Proposals, three major objectives were identified during meetings with resource personnel who are actively involved with the management of the Carson River. These objectives, listed below, were included as contractual requirements in Inter-Fluve's Work Plan.

1. Develop a qualitative (and quantitative, where possible) understanding of river behavior and geomorphic condition and how it may relate to specific reaches' stability and implications for stabilization projects.
2. Prepare a tool to educate river users and managers concerning appropriate strategies for river management. This includes presenting possible, realistic best management practices (BMPs) and potential stabilization strategies focusing first on High Priority reaches, and then on Moderate to Low Priority reaches.
3. Compile a report based upon all observations made in the field that relate to the river corridor's physical condition. In addition to those identified in the first two objectives (above), this may include observations on flooding dynamics and land use, floodplain function, water quality and condition of existing river stabilization efforts.

In summary, the intent of this project is to compile information and recommendations that will act as a platform for intelligent interim land use decision making, active management, and a base level geomorphic study for future river analysis projects.

GEOMORPHIC PROCESSES ON THE CARSON RIVER

Channel Stability - A Geomorphic Perspective

Even in a natural and undisturbed condition, river behavior is complicated. A number of physical variables, interacting in response to one another, dictate how a river behaves through time. Because of all of the interlinkages, changes in one or more of these variables will result in changes in others. On the Carson River, many of the river behaviors observed fit well within what might be predicted from a purely scientific investigation. Our observations of the Carson River were generally framed within the context of river stability. In other words, we assessed and observed the river's behavior within the context of whether reaches appeared stable or unstable. We then offer possible explanations for these assessments. Therefore, it is worthwhile to briefly visit geomorphologists' definitions of stability, and the specific variables which account for it.

The term *stability* is essentially a measure of the degree to which these variables are in balance. The concept of stability is generally equated with *dynamic equilibrium*, an expression often used in the context of fluvial geomorphology. A system in dynamic equilibrium is one in which all variables are closely balanced, but which still exhibits change in local attributes or the location of these attributes. For example, a *stable* stream, one in dynamic equilibrium, may exhibit gradual bank erosion at outside bends and corresponding accretion at point bars. As the channel migrates, vegetation becomes established on bars which form at an elevation which closely corresponds to adjacent floodplain elevations. In dynamic equilibrium, the volume of material in point bars, the area of eroding banks, and the area of vegetated floodplain remain relatively constant over time, though they may change in location. In addition, a host of channel characteristics remain fairly constant. For example, as one section of river becomes longer due to migration of a meander bend, an adjacent section of river may decrease its length such that the overall stream form and grade (physical characteristics) remain constant for a given reach. Again, this balance is a benchmark of stability.

The physical characteristics of a stream channel can be generally defined as the form and profile of that channel. The form refers to the shape in map view, or planform, while the profile refers to the change in bed elevation over distance, or grade. The particular planform and profile of a channel are related to the erosional and depositional processes of the system. These processes are in turn influenced by the discharge and sediment supply (load and particle size) inputs to the channel. In other words, at any point in the channel, the form and profile are largely determined by the sediment supply and volume of water in the channel. In a stable channel system, these erosional and depositional forces are balanced, such that the gross planform and slope are relatively constant over time. In an unstable system, or one that is not in equilibrium, either erosional forces or depositional processes may exceed the system's ability to adjust to these without significant changes in the form and profile of the channel.

Sediment supply, which includes both volume and particle size, and discharge are the two primary variables which determine channel characteristics. In a stable system the channel evolves over time with physical characteristics which transport the available sediment such that the inputs to the system equal the outputs. Much of the sediment is transported during discrete high flow events, though finer materials are transported continually during low flows as well. Any significant change to the sediment supply input can quickly or gradually destabilize a channel and set in motion a migration of instability. When sediment supply exceeds the systems ability to transport it, deposition occurs and excesses accumulate in the channel in the form of bars. As bars become large relative to the channel, the channel shifts laterally and/or upward (aggradation), resulting in increased stresses on channel banks. A classic example of this process can be observed on the East Fork in Reach E-6 (see Figures 1a-c for Reach locations) at the locations of 3 failed diversion and grade control structures. In each of these cases, when the structure failed, sediment stored upstream of the structure became readily available for transport and was deposited immediately downstream of the failed structures. The result in each case was localized aggradation, lateral expansion of the channel, and rapid bank erosion leading to further sediment supply increases in a downstream direction.

In addition to discharge and sediment supply (sediment load and particle size), which are the *independent variables* determining channel form and grade, there are five additional variables which are related to these. Channel width, depth, slope, roughness, and velocity are inter-related *dependent variables* which adjust simultaneously to accommodate the sediment supply and discharge of the system, in order to maintain or move towards dynamic equilibrium. In a relatively stable system, minor changes in one independent variable are compensated for by minor changes in some or all other dependent variables, generally tending towards mutual adjustment and equilibrium rather than toward instability. For example, if a local bank collapse produces a temporary increase in sediment load at a point, the width, depth, slope, roughness, and velocity of the channel may all adjust to compensate. Viewed in this context, significant changes to planform or grade within a stable system should only be apparent on the scale of hundreds to thousands of years (Knighton, 1984).

In the context of dynamic equilibrium, an unstable system can be defined as one in which one or more variables are significantly out of balance, such that responses of other variables are extreme and exhibit rapid rates of change, on the scale of years or decades. Such instability rarely occurs in natural systems

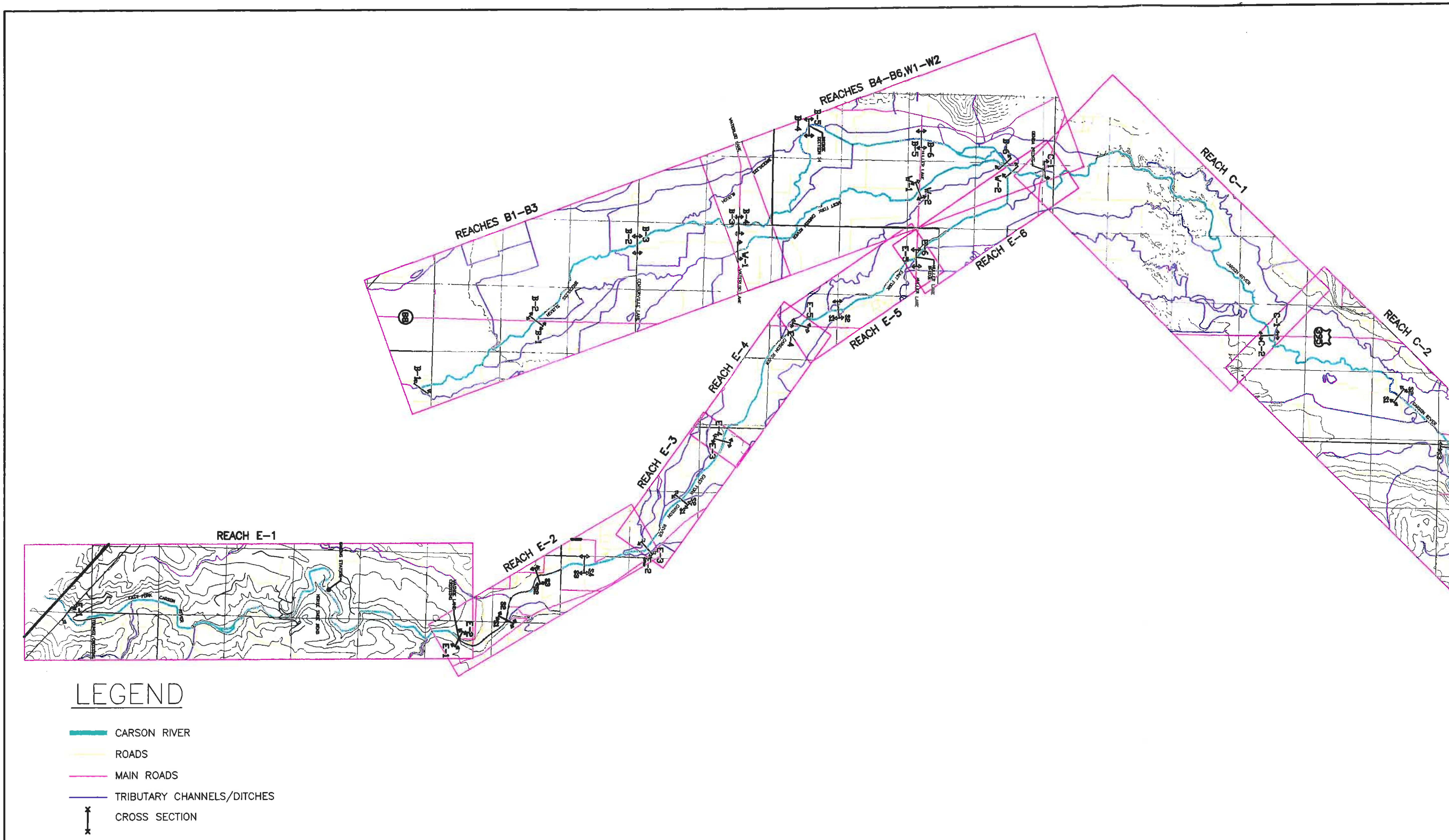


FIGURE 1a. REACH LOCATIONS
REACHES E1-E6,B1-B6,W1-W2,C1-C2

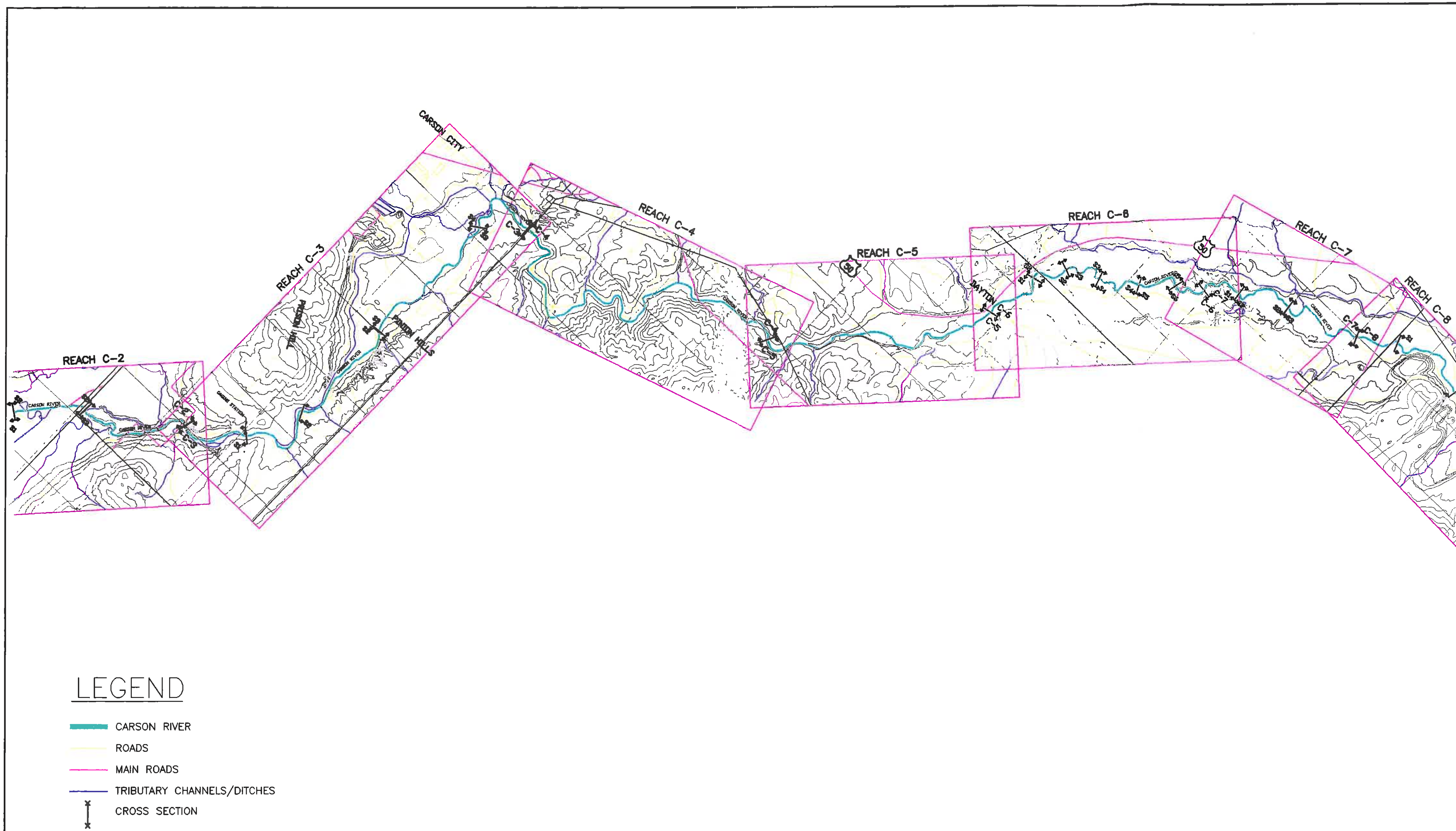
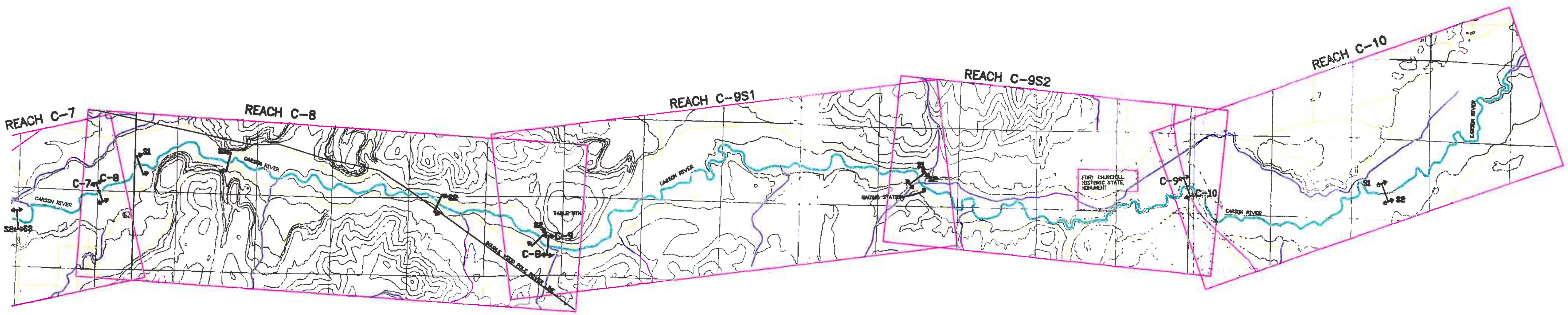


FIGURE 1b. REACH LOCATIONS
REACHES C2–C8



LEGEND

- CARSON RIVER
- ROADS
- MAIN ROADS
- TRIBUTARY CHANNELS/DITCHES
- CROSS SECTION

FIGURE 1c. REACH LOCATIONS
REACHES C7–C10

APPOX. SCALE: 1" = 7500'

NORTH

without catastrophic events. Rapid rates of change and instability in channels are far more often associated with human-induced changes or constraints of the seven variables affecting channel form and grade. Land use practices, channel manipulations, or bank alteration projects can all significantly impact one or more variables. As one or more variables are affected beyond the scope of natural process and dynamic equilibrium, an infinite number of possible responses may occur among combinations of adjustments in these variables. Furthermore, prediction of the extent of these responses is virtually impossible beyond a very general sense. Unstable channels, therefore, are those which are responding to imbalances in the system and include a wide variety of conditions between stable and those initial conditions of instability.

In summary, a stream channel can be generally described in the context of its planform and profile. These general characteristics are determined largely by the interaction of eight variables: discharge, sediment supply, both volume and particle size, channel width, channel depth, channel roughness, channel slope, and velocity of flow. Discharge and sediment supply are the independent variables to which the remaining five dependent variables respond. In a natural, stable system, these variables can be considered to be in a state of dynamic equilibrium, where all are adjusting to minor changes in the others and all adjustments tend towards stability. Significant changes to any of these variables can result in an imbalance among the variables, resulting in instability. Furthermore, any actions and projects which act to inhibit the range of responses of any of these variables may lead to excessive responses in other variables.

Common examples of human actions in the Carson River watershed which alter one or more variables, and their possible responses, are outlined in the following sections.

Human Interference in Geomorphic Process

Human interference in geomorphic processes includes any activities which affect any of the variables discussed previously. These activities include both adjacent land use practices, which may indirectly affect the channel, and change or control of these processes. Virtually all human activities adjacent to or within a channel affect these variables. However, the extent of such activities, in addition to natural channel attributes, determines the need for and capacity of the channel to adjust. Furthermore, while one activity may induce only moderate or minimal channel responses, these responses may move the system closer to the threshold between stability and instability, thereby increasing the likelihood that additional activities or manipulations will create conditions of instability.

Channelization

Channelization has been a significant feature of much of the recent history of the Carson River. The most significant channelization of the Carson River took place under the auspices of the Bureau of Reclamation (BOR) in 1965. A rough estimate of river miles channelized by the BOR is 70 miles of the 110 inventoried. This strategy relied mostly on reducing channel sinuosity, confining areas of multiple channels to a single channel, addition of rip rap to channel banks and diversions, channel relocation, and the expansion of the new channels' cross-sectional area. All told, approximately 1 million cubic yards of gravel was moved in the channel and 36,000 cubic yards was installed covering 3 miles of bank (BOR, 1965). This was accomplished by dozing straight channels and piling the excavated material along the banks to form levees (discussed below) in an effort to increase flood conveyance and to reduce the floodplain area that the channel occupies.

Channelization often results in channel instability because it severely impacts both channel planform and grade. These impacts necessarily result in an imbalance among the variables which determine the channel's physical characteristics. The response is invariably an extreme adjustment in some combination of variables. Because channelization minimizes the length of stream between two points, the slope is increased (slope is a ratio of stream length to change in elevation). Additionally, the channel depth must increase at some point to accommodate the change in slope. The unavoidable effects of channelization, therefore, are an increase in channel slope and channel depth, both of which act to increase channel velocities and associated forces (scour and tractive force).

The most common response to channelization is increased erosion of the channel bed, generally in an upstream direction (headcutting), resulting in incision. From this point, there is an infinite number of combinations of channel responses which act to move toward balance among variables. Erosion will generally exceed deposition until the channel reaches a balance between the sediment supply (from bed and bank erosion as well as upstream sources) and the stream's ability to move sediment. Channel instability associated with channelization also affects upstream and downstream reaches. Downstream reaches are generally affected by excess sediment supply resulting from bed and bank erosion in and below the channelized reach. Upstream reaches are generally affected by headcutting processes migrating upstream from the channelized reach. The most heavily channelized portions of the Carson River system are on the East Fork. The majority of the East Fork in reaches E-2 through E-6 have been channelized and all show extreme channel capacities indicative of incision (see Appendix A).

Levees

Levees are constructed berms adjacent to the channel which act to confine overbank flows which would otherwise disperse on a floodplain. Levee construction on the Carson River occurred simultaneously with channelization projects conducted in 1952 and 1953 and by the BOR in 1965 and were implemented to protect floodplain areas from overbank flows. Approximately 70 miles of Carson River system have or have had levees along their banks. Additionally, many areas where channel work has been performed exhibit spoil piles or berms along the river bank where excavated material was deposited. Any of these which are continuous and act to raise the elevation of the floodplain adjacent to the river are, for the purposes of this report, considered levees as defined above.

In a stable channel without levees, relatively frequent flows (approximately 2-year flows) overtop channel banks and inundate the floodplain, thereby dispersing stream energy. The fundamental effect of levees is to increase channel depth, thereby containing greater than the historic bankfull flows. With an increase in depth comes an increase in the velocity and erosional forces of a river. Consequently, the primary effect of levees are extreme channel depths during floods. In some areas of the Carson River, the combination of channel incision, related to channelization, and levee construction has resulted in channel depths up to 20 feet where previous natural channel depths may have been less than 5 feet.

In addition to incision in reaches confined by levees, upstream and downstream effects of levee construction may include downstream sediment excesses, resulting from bed and bank erosion, and upstream incision due to headcut migration. Furthermore, levees reduce the frequency of floodplain inundation, thereby limiting floodplain energy dispersal and sediment storage and the potential for productive riparian zones.

Diversions

The Carson River valley from the Nevada State line to Lahonton Reservoir has a long history of agricultural land use, most of which has relied on irrigation withdrawals using river diversions (CDWR, 1991). Diversion structures exist throughout the length of the Carson River and its tributary forks. All diversion structures withdraw water from the river, and in some reaches during the fall season as much of 100 percent of the flow is taken, with downstream irrigation withdrawals being dependent on upstream return flow. The effects of flow withdrawals on water supply is discussed in subsequent sections. The majority of diversion structures are permanent structures, while "push-up structures" are constructed on an annual basis from riverbed materials.

All diversion structures, whether permanent or push-up structures, create a distinct break in natural channel slope. In order to effectively divert water from the channel during irrigation season, the elevation of the water surface is generally elevated at the point of diversion. This effectively reduces the water surface slope upstream, thereby reducing velocity and creating a "backwater" area. This local reduction in slope and velocity causes aggradation upstream of the structure, as the potential for sediment transport is reduced. Local aggradation raises the streambed elevation, forcing the stream to migrate laterally or become braided. In either scenario, greater pressure is put on streambanks and bank erosion is the common response. Virtually all of the diversion structures observed on the Carson River showed evidence of aggradation upstream of the structure. In a few instances, the current or recent aggradation is within the previously incised channel and does not represent prehistoric floodplain access.

Due to the accumulation of sediment upstream of a diversion, the channel downstream of the structure may have a reduced sediment load. Theoretically, this reduction of bedload can result in bed erosion because material transported from below the structure is not replaced by material moving downstream from upstream of the structure. Without exception, the permanent diversion structures observed along the Carson River showed aggradation upstream of the structure and incision below the structure. Because the majority of these structures occur in reaches which have also been channelized and/or leveed, it is impossible to determine whether incision below the structure results from channelization, from sediment transport interruptions associated with diversion structures, or from a combination of both. However, since incision generally migrates upstream rather than downstream, it is probable that channelization has played a greater role than the diversion structures in observed incision. An exception to this supposition may be in Reaches C8 and C9 (See Appendix A) where there is no apparent history of channelization and channel enlargement below diversion structures is prominent.

In many instances, permanent diversion structures may be acting to prevent headcutting upstream of the diversion. This is particularly evident in Reach C-9, where channel capacity below the diversion structures indicates incision (containing the 50-year discharge), while channel capacity upstream of the structures are probably more in keeping with historic, natural conditions (containing the 1- to 5-year discharge). In these instances, and assuming that diversion structures are not in part responsible for incision, diversion structures may be checking headcuts and promoting stream stability for as much as 2,000 feet upstream of the structure. These potentially stabilizing qualities, however, should be balanced with the potential for instability associated with aggradation and the disruption of sediment transport continuity, as evidenced above the majority of diversion structures in the East Fork reaches.

In contrast to permanent diversion structures, the push-up diversions which require annual repair and construction do not act as beneficial grade controls. In fact, such structures may create high potential for instability for a number of reasons. First, the structures create a sharp break in channel slope which may create a knickpoint. Second, construction of these structures requires significant disturbance of the bed armor layer which otherwise inhibits bed erosion. When a dozer pushes bed materials to form a diversion, it removes the bed armor layer and frees up bed materials for relatively easy transport, leading to excess sediment downstream and local scour. And third, the aggradation upstream of a diversion, due to backwatering effects, creates an additional sediment source for high flow events which cause push-up structures to fail on a regular basis.

Grazing and Loss of Riparian Vegetation

The Carson River watershed has a long history of grazing and agricultural use. With the exception of more developed areas along the East Fork, the vast majority of the land uses adjacent to the Carson River are grazing and irrigated pasture lands. Both of these practices have resulted in limited or absent riparian corridors throughout the drainage. In many instances, riparian vegetation has been actively eliminated and a combination of land use, flow depletions, and incised channels have limited the areas capacity for riparian regeneration. Grazing can impact riparian vegetation through both browsing and trampling. Grazing of succulent shoots and sprouts reduce or eliminate young growth and regeneration, while grazing of mature vegetation inhibits further growth and reduces survival potential. Additionally, channel changes can occur from loss of riparian vegetation associated with preceding instability and incision. Incision generally drains high water tables and forces additional vegetation changes, thus initiating a progression of riparian vegetation loss.

Reach C-2 illustrates the impacts of grazing well. In subreach C-2 S-2, grazing has been eliminated and there is a thick, vigorous riparian corridor along this channelized reach, despite historic channel modifications which created a channel alignment through areas which may not have originally had riparian vegetation. Immediately downstream, in S-3, there is a long history of grazing riparian areas. Riparian vegetation is virtually absent, and that which does exist is heavily browsed and of a uniform age class with no signs of regeneration. Comparison of these two reaches, neither of which have had any other land use in recent history, reveals the importance of riparian vegetation to bank stability and resulting channel stability. In S-2, banks are stable and the channel is stable, while in S-3 banks are unstable and the channel is unstable.

Loss of riparian vegetation, and a riparian corridor, is also important from a channel stability perspective. As evidenced in Reach C-2 S-2, even when a channel is radically modified by channelization, the associated bank instability and channel instability can often be offset when a healthy riparian corridor is allowed to establish. Riparian vegetation is perhaps the most important factor determining bank stability. Riparian vegetation root systems hold soils together and in place and reduce flow velocities along channel margins, thereby reducing erosional forces on the banks. In this manner, riparian vegetation can significantly reduce sediment inputs to the system from bank erosion. As discussed previously, sediment inputs are one of two key independent variables which determine channel form and grade. When riparian vegetation is absent or reduced, bank erosion becomes more prevalent and leads to increases in sediment supply, which, in turn, can lead to channel instability.

Irrigation Withdrawals

All reaches of the Carson River, from the Reach E2 and W1 to the confluence of the East and West Forks, and from the confluence to Lahontan Reservoir, are affected by irrigation withdrawals. Irrigation withdrawals deplete the discharge of the river, primarily during the low flow periods of summer and fall. While withdrawals have little or no effect on discharge during runoff periods, the flows which have the greatest effect on channel morphology ("channel forming flows"), they can significantly affect the moisture regime of the system during the growth periods of riparian complexes.

From a channel stability perspective, irrigation withdrawals may be significantly affecting the Carson River by reducing the potential for riparian vegetation regeneration and the potential for maintenance of existing vegetation. Flow diversions withdraw much of the water available to the Carson River channels and thereby reduce the moisture available to bars and banks by lowering the water surface and the local water table. Furthermore, these flow reductions, in some instances, isolate the channel banks from the active channel by minimizing that area which carries water during low flow periods. The majority of bars on the Carson River are unvegetated and show little signs of riparian revegetation.

In a stable, natural system, vegetation on bars along channel fringes grows readily, stabilizing the bars. This is important to channel stability because it reduces the sediment source available for transport. A vegetated bar is far less likely to erode than an unvegetated bar. Many bar forms along the Carson showed evidence of riparian seedlings. However, the majority of these sprouts are apparently not living long enough to become established. This is likely due to both the limited availability of moisture, reduced by irrigation withdrawals, and the availability of sediment in the channel from upstream unvegetated bars and eroding banks which may be burying seedlings on an annual basis during periods of sediment transport.

Carson Geomorphology - Summary

Virtually every mile of the Carson River system has been affected by human activities, which range from the direct effects of channel manipulations and in-channel structures to the indirect effects of land use activities and irrigation withdrawals. Furthermore, those few areas which have not been directly affected, are indirectly affected by upstream or downstream instability and imbalances. As discussed above, these human activities lead to channel instability through a wide variety of interacting processes. Generally speaking, these activities have affected one or more of the variables which, when balanced, encourage stability in the system. In some cases, one or more variables has been greatly distorted, instigating drastic responses in other variables. In other instances, one or more variables has been controlled or limited, necessitating greater responses in the remaining variables and thereby inducing instability. Furthermore, localized instability has migrated either upstream, in the form of headcuts, or downstream, in the form of sediment supply excess. The interaction of localized instability with further imbalances superimposed on these from either upstream or downstream instability has exaggerated both channel problems and the complications associated with alleviating these problems.

In effect, the sum total of human activities, both those which have thrown the system out of balance and those which have been implemented in an effort to control problems and imbalances, has resulted in a river system in which the entire length is susceptible to complicated problems and responses. As river engineers have realized over and again, attempts to control a complicated natural system are hopeful at best, and often create a series of channel responses which represent greater problems than those which existed previously. In previous sections, human activities and the river's responses to these have been discussed. Listed below are summaries of the existing physical characteristics and processes affecting the Carson River, from a geomorphic perspective.

Channel Stability Summary

Appendix A - Reach Summaries, includes detailed descriptions of channel stability and reach maps illustrating channel stability. Throughout the East Fork and Carson River sections which are classified as moderately unstable to extremely unstable, the channel is actively changing. It is important to note that because of the complexities of river responses to instability discussed previously, the end product of these changes cannot be predicted. While some sections may be classified as moderately unstable, their current condition may be progressing toward either greater instability or greater stability, depending on the inputs they receive from upstream and the extent of human influences.

Table 1 summarizes the stability assessments, as determined by field investigations, of all reaches of the Carson River. As this table shows,

TABLE 1

Carson River Stability By Reach				
Reach	Reach Length	Subreach	Subreach Length	Stability
E-1	48,695			stable
E-2	18,655	S1, S2	9,505	stable
		S3, S4	9,150	mod. unstable
E-3	10,600	S1, S2		mod. unstable
E-4	11,720	S1	7,110	mod. unstable
		S2	4,610	unstable
E-5	11,210	S1	3,400	ext. unstable
		S2	7,810	unstable
E-6	13,825			mod. unstable
B-1	11,940			not evaluated
B-2	11,345			stable
B-3	9,200			mod. unstable
B-4	13,675			stable
B-5	9,235			stable
B-6	7,790			stable
W-1	18,165			stable
W-2	8,535			mod. unstable
C-1	31,675	S1	1,450	stable
		S1	30,220	mod. unstable
C-2	31,525	S1	15,460	mod. unstable
		S2	6,000	stable
		S3	10,065	unstable
C-3	42,125	S1	5,630	mod. unstable
			7,360	not evaluated
		S2	8,965	very stable
		S3	20,170	stable
C-4	34,485			very stable
C-5	20,285		8,775	not evaluated
		S1	7,695	stable
		S2	3,815	mod. unstable
C-6	22,525	S1	4,935	stable
		S2	3,115	mod. stable
		S3,S4	8,130	unstable
		S5	3,595	mod. unstable
		S6	2,750	ext. unstable
C-7	16,465	S1	3,630	mod. unstable
		S2	5,130	unstable
		S3	7,705	stable
C-8	37,545	S1,S2	36,730	unstable
		S2	815	stable
C-9	35,385	S1	32,575	unstable
		S1	2,810	mod. unstable
	25,795	S2	25,795	unstable
C-10	37,580	S1	23,460	mod. unstable
		S2	14,120	stable

channel stability varies greatly over the project area, though there are long sections with consistent stability ratings. The greatest variability in stability ratings occurs on the East Fork, in reaches E-4 through E-5, and on the Carson River in reaches C-5 through C-7. These areas also coincide with the greatest areas of development and infrastructure, indicating that channel geomorphic process are more likely to be affected on a local level where adjacent development impacts the channel. On the East Fork below Reach E-1, there are approximately 1.8 miles of stable channel, 7.7 miles of moderately unstable channel, and 3 miles of unstable and extremely unstable channel. With the exception of reach E-6, which is classified as moderately unstable, instability increases downstream through the East Fork. On the West Fork and Brockliss Ditch reaches, approximately 11.4 miles of channel are classified as stable, and 3.4 miles as moderately unstable.

On the main stem of the Carson River above Brunswick Canyon (Reaches C-1 through C-3), approximately 6.9 miles of channel are stable, 9.7 miles are moderately unstable, and 1.9 miles are unstable. The lesser degree of instability in this section of river, as compared to the East Fork, is likely due to a lesser degree of channel manipulation and the virtual absence of channelized reaches. Below Brunswick Canyon, in reaches C-5 through C-10, there are approximately 7.3 miles of stable channel, 7.1 miles of moderately unstable channel, and 21 miles of unstable and extremely unstable channel. 1.7 miles were not assessed for stability due to access constraints. As on the East Fork, extensive channel instability appears to be associated with significant channelization projects, particularly in the vicinity of the town of Dayton.

Channel Planform

Channel planform is one of two primary channel characteristics which result from the sediment supply and discharge of a river system, the other being channel grade, or slope. Channel planform is the product of the physical processes and interaction of physical variables which define a channel and is largely interactive with channel slope. In the Carson River system, channel planform has been most significantly affected by channelization projects and by increased sediment supply. The effects of channelization are discussed above and include channel incision, increased sediment transport, and increased sediment supply to downstream reaches.

While channelization has directly altered the planform of the Carson River, other processes can affect planform indirectly. These processes include sediment transport and bank stabilization projects. In a stable system, a channel's planform and cross-sectional characteristics are balanced to transport the average volume of material input to the system. Any changes to this volume can lead to planform changes. For example, if sediment supply is increased due to excess bank erosion upstream, the channel may be unable to transport all of this material, leading to in-channel deposition. This accumulation of material reduces the cross-sectional area of the channel, which responds by widening or migrating laterally. This migration is a planform response to changes in sediment supply.

Planform changes occur in a direction which offers the least resistance (softest banks) or where erosional forces are greatest (along outside bends), and in response to changes of other channel variables. These shifts in channel location or shape are often undesirable, when considering the location of development, infrastructure, or loss of property. The common response to such changes is to harden the banks in these locations to inhibit further migration. Examples of such efforts are the barbs installed in reach E3 and the recent work done immediately above the Muller Lane bridge in E5. While such projects may effectively restrict migration at a point, it should be kept in mind, that in the context of dynamic equilibrium, restriction of certain channel responses at a point will likely act to exaggerate other responses at that point, or transfer those processes to another location.

Channel Capacity

Channel capacity refers to the amount of water, expressed as discharge, that a channel is able to convey at a given cross-section. This discharge is often expressed as a recurrence interval, e.g., a five-year discharge, which implies that the flow which is equaled or exceeded on average once in five years will be contained within the channel. Channel capacity is determined by a combination of channel cross-sectional area, channel slope, and channel roughness. Channel capacities for surveyed cross-sections are described in detail in Appendix A - Reach Summaries and in Appendix B - Hydrology and Hydraulics.

In most natural, stable systems, channel capacity is roughly the 1- to 3-year discharge. In other words, flows which have a return interval greater than 1 to 3 years, will overtop the channel banks and access the floodplain, thereby dispersing flow energy on the floodplain. With very few exceptions, all surveyed cross-sections on the East Fork and the Carson River showed evidence of channel capacity exceeding that of a stable, natural channel. On the East Fork, which has been almost entirely channelized and largely leveed from Broken Dam to the confluence with the West Fork, the channel contains between the 50- and 100-year discharges. The only exception to this is in Reach E2 where one cross-section shows overbank flows on one side at a 2-year discharge, though the other bank contains flows greater than the 25-year discharge. On the Carson River above Brunswick Canyon (Reaches C-2 and C3), channel capacities range from containing the 2- to 10-year flows within both banks at a section, and containing from 5- to 50-year flows by one bank while the other bank is breached at lesser flows because it is at a lower elevation.

Below the canyon, in reaches C-5 through C-8, channel capacities are significantly greater, indicating greater enlargement and incision than reaches above the canyon. In these reaches all flows less than the 5-year discharge are contained at all sections. The majority of sections contain between the 10- and 50-year discharges within both banks. In the lower reaches of the Carson River, C9 and C10, there is a wide range of channel capacities. With the exception of those sections nearest Lahonton Reservoir, the Carson River channel contains flows between the 5- and 100-year discharge within both banks. In those reaches at the bottom of the study area (above Lahonton Reservoir), channel capacity is limited to the 1.25-year flow on both banks.

In summary, virtually every section surveyed on the Carson River and its tributary Forks indicates an enlarged and/or incised channel relative to historic conditions. In addition to being an indicator of instability, such channel characteristics can also lead to instability, particularly for downstream reaches. Because higher discharges are contained within the channel, flow energy is not dispersed across a floodplain, resulting in increased bed shear, scour, and bank shear forces. These erosional forces increase as a function of channel depth and flow velocity.

The consequence of increased channel capacity and resultant erosional forces include increased bed and bank instability and increased sediment supply to downstream reaches. The potential channel responses to increases in sediment supply, in the context of channel stability, are discussed in subsequent sections.

Sediment Supply

Indicators of sediment supply excesses were common throughout the Carson River system and included areas of aggradation, "blown out" reaches, and large unvegetated bar forms. Furthermore, sources of excess sediment were also prevalent, and included continuous unstable banks, incised channel reaches, and unvegetated bar forms which were out of proportion to the channel size. The two most probable initial sources of sediment are channelization projects which lead to erosion of the channel bed (incision) and loss of stabilizing bank vegetation which leads to increased bank erosion. In both cases, initial sediment supply excesses can lead to instability which then maintains excesses in sediment supply through lateral migration and bank erosion. In this manner, initial sediment problems can lead to long term instability.

Indicators of channel incision were prevalent throughout the Carson basin, except at local grade controls which were primarily diversion structures. However, few, if any, locations showed evidence of active downcutting or headcutting. Channel grade in virtually all reaches was considered relatively stable or aggrading. Numerous aggrading reaches were observed. For example, in E-3, aggradation is apparent in the form of mid-channel bars, with steep drops on the downstream faces, and recent new channel development along the historic channel margins. This and other areas of current aggradation are likely associated with excess sediment supply from eroding banks. The majority of reaches throughout the Carson basin have significant areas of unstable banks which continue to contribute to sediment supply problems.

Vegetation

The majority of reaches along the Carson showed evidence of degraded or absent vegetation on its banks, bars and floodplains. This degradation can be explained by a combination of factors and processes including: channel incision (due to channelization), which lowers the water table relative to the banks and floodplain irrigation withdrawals, which limit moisture during summer and fall growing seasons, grazing, which damages existing vegetation and reduces regeneration, and entrenched channels which result in excessive scour and deposition and limit regeneration within the channel margins.

Supplemental information regarding the status of vegetation in the Carson River basin includes existing conditions and a summary of reproductive biology of cottonwoods in Appendix C - Cottonwood Regeneration.

RECOMMENDATIONS TO ENHANCE RIVER HEALTH AND REDUCE INSTABILITY

General

The recommendations contained in this section of the report are general in nature. More specific recommendations, on a reach by reach basis, are found in Appendix A, Reach Summaries. Given the vast scale of channel instability, which extends from the California/Nevada state line to the Lahontan Dam, there is not a single set of best management practices or engineering prescriptions that will have application throughout. The instability is related as much to current land uses as it is to an intricate and long history of past uses. In addition to the geographical scale of the problem, those affected by the river have not yet coalesced around a common theme for its management. For example, while some view the river as a potential wildlife and recreational corridor, others see the river simply as a conduit for water to be used for irrigation. Still others see the river as a problem directly affecting their lives by threatening their homes with floods or eroding away their land. While an ideal solution for river management would include all perspectives equally, it is not certain that all interests will be easily accommodated. The recommendations found here attempt to address as many interests as possible, and provide a foundation for future planning.

Before addressing system-wide and specific reach recommendations, it is also important to recognize that the Carson River, in its current condition, is not a good candidate for active "restoration" in the purest sense of the word. Channel restoration requires the recovery of a system to a natural state, complete with functional ecosystems. Unfortunately, the historic uses visited upon the river, combined with the development along its margins and current uses, likely precludes a river restored to an historic pristine state. Instead, efforts should be focused on aiding natural recovery processes, reducing current impacts, managing for future river changes, and improving the condition of unstable reaches where possible.

System-Wide Recommendations

There is always the temptation to implement projects with high visibility or on properties where the project proponents' skill in obtaining funding is good. In contrast, in unstable river systems, the most practical approach for river recovery is often to work from the top of the watershed downstream. This implies that to change the behavior of the river downstream, improvements must first be made upstream. This geographic priority does not always coincide with those who have immediate interests downstream. A coordinated Carson River management scheme will need to balance these conflicting interests.

Property and Infrastructure Protection

While not necessarily a channel recovery strategy, protection of infrastructure at risk is generally recognized as a first priority in unstable systems. These fall into two categories: 1) those related to threat via channel migration and, 2) threat of flooding. It appears as though some reaches of the Carson experience significant lateral movement even during moderate magnitude floods. These areas should receive immediate attention given the relatively high annual risk of experiencing a moderate magnitude flood. The loss of homes, roads, bridges, utilities etc., represent a great cost to a community, and warrant high cost solutions.

In terms of flooding, these risks are more difficult to identify due to the relative infrequency of the 100-year magnitude flood. However, given the history of recent channel changes, in conjunction with an increasingly urbanized floodplain, this is clearly an area in need of more intensive investigation. Anecdotal evidence and field observations suggest that many areas of the Carson River's natural floodplain are being or have been developed and are affected by less than the 100-year flood. Given the built-in errors in modeled 100-year floodplain estimates, the local communities may need to assess their comfort level when ground is developed at elevations near the predicted flood elevation. In light of the above, the following general recommendations are made:

- Conduct a risk assessment to identify private and public infrastructure at risk.
- Develop river stabilization or stress alleviating schemes for areas where significant private or public infrastructure is threatened by river migration.
- Re-assess the current zoning regulations regarding future development in flood prone areas. Insure this assessment relates to an accurate and current 100-year floodplain delineation.

Regarding infrastructure protection, bear in mind that engineered solutions should focus only on at-risk infrastructure at first; the costs escalate rapidly for these solutions when their area of application increases. Also, as with all river projects, the impacts of the stabilization or floodplain management/development schemes on the hydrologic and geomorphic behavior of the river should be fully analyzed prior to implementation. Many areas suffer increasing flood depth after development because of the accumulating effect of elevated structures or roads removing the effective floodplain area. *All* stabilization schemes should follow the following best practices:

- A complete assessment of the possible effects on upstream and downstream river stability from project implementation.
- Professionally designed and engineered treatments with clearly identified factors of safety and design criteria.

- The use of treatments which will also provide benefits for fish and wildlife.
- Identification of likely failure scenarios and the anticipated costs for long-term maintenance.
- Professionally installed treatments.

Engineering Control of the River Corridor

On a conceptual level, one could consider engineering projects to promote river stability everywhere instability was identified. Between the categories of Moderately Unstable and Extremely Unstable, our inventory identified 54 miles of channel that could be considered in a large river corridor project. Clearly, this would be a massive undertaking. The 1965 BOR levee and channelization work is a recent historical example of projects of this scale. The legacy of increased channel instability resulting from this project should give the community and its river managers pause. It may be wrong to assume that the engineering world can develop a scheme which will provide the long-term benefits the Carson River community is seeking. The economics of attempting to mechanically control a river, which on a large process scale, is in a state of geomorphic transition, should be carefully considered. These issues are addressed below.

Large river control engineering works are phenomenally expensive for the following reasons:

1. Rivers are complicated and powerful systems. Engineered solutions in these environments require extensive feasibility assessments to ascertain possible solutions.
2. Once feasible solutions are identified, engineering practice requires designers to consider worst case failure scenarios under extreme flood events. This leads to rigorous design which ultimately requires very expensive construction practices and materials. For relatively straight-forward bank stabilization in rivers the size of the Carson, $200 to $300 per running foot for engineering and installation is not uncommon.
3. Liability is of great concern in river engineering practice, particularly where infrastructure may be potentially threatened. A large scale river engineering project will require that the designers undertake substantial risk, which frequently translates into higher costs in design.
4. Treating one piece of an unstable river is very risky, since upstream and downstream instability can negatively affect the performance of an installed engineered project. Therefore, a total engineering control scenario requires stabilization of the upstream and downstream areas. This quickly compounds costs as the river is "buttoned up" from top to bottom.
5. The costs of annual maintenance of large river engineering projects can be high, and require a constant supply of money. Recall that financial

resources were not available for community maintenance of the 1965 BOR levees (Piper, pers. com.), contributing to their future failure in many locations.

To stabilize the Carson River system, one would need to: 1) consider both lateral and vertical control measures, 2) the influence of a large in-channel sediment supply and the efficient transport of that supply downstream and, 3) the effects of large floods, which the Sierra drainages are very capable of producing. Further, there could be legitimate questions regarding the viability of attempting to control a river which is perceived to be in a state of geomorphic transition. Overcoming geologic processes on a river the size of the Carson would be no trivial matter.

Aided Natural Recovery Options

Natural Recovery Process

Earlier in this report the geographic scale of instability on the Carson River was identified. The problems with reliance upon large scale engineering projects were discussed above. Therefore, natural recovery, or aided natural recovery options, become much more attractive, since in principal, direct costs are not high. However, the natural recovery options are not without some problems of their own. They relate to both natural process and human interference in that process. These issues are explored in greater detail below.

Left completely alone for many years, the Carson River will adjust to a more stable channel type. This could include the recovery of the original or some other equilibrium base level through aggradation, and the development of a functional floodplain and stable banks. However, it can not be predicted with any certainty just how long this would take, nor whether such a strategy is consistent with the local political and social climate and current uses.

Based on field evaluations and simple hydraulic analysis (see Appendix A and B), it is our belief that the river is expressing a trend towards widening its currently entrenched active channel and the development of incipient floodplain surfaces. Currently, the active channel has excess capacity and very little available floodplain for frequent as well as moderate magnitude floods. Excess capacity in this case (an entrenched channel) means that flood flow energy (represented by scour and sediment transport capability) remains high and promotes an unstable environment. Left unchecked, it is logical that the channel will continue to gain width until the sediment supply exceeds the ability to transport it. While a stable channel may evolve from this channel width, it is not guaranteed. For example, a braided river channel, in this system, is unstable but may remain at a relatively constant active channel width for long periods of time.

Aided Recovery- Vegetative Management

While the trend of the river appears to be a in active channel width and the development of incipient floodplain surfaces, other vital components of natural recovery of a stable channel appear to be missing. Of particular note is the absence of regenerating riparian vegetation on incipient floodplain surfaces (terraces, large alternate bars and point bars). Without vegetation to stabilize the forming floodplain surfaces, these features appear to be regularly obliterated by moderate magnitude floods. Until vegetation can gain a foothold, the river will likely remain unstable at any channel width.

The absence of significant in-channel vegetation, a key to long-term stability, is likely linked to two factors: 1) inadequate growing season flows and, 2) the scouring and depositional processes of the river during floods. While the latter is partly related to the active channel width and depth, the former is a result of irrigation withdrawals. Without adequate low flows during the growing season, natural recovery may not be a possibility. In theory, this situation can be changed by allowing more flows down the channel in the stressful summer months, making a natural recovery scenario viable. However, due to the long history of litigation concerning Carson River flows, the acquisition of flows for channel stability needs could prove to be a battle of great proportion.

Aided Recovery - Additional Options

Additional options are available to assist natural recovery, though at this time, many strategies raise as many questions as they might address. For example, installing grade control structures on the East Fork may prove to be a viable alternative for promoting floodplain formation and/or restoration, with added benefits for channel stability. However, such an approach would clearly be an attempt to assert control over one independent variable (slope) with an expectation that this would promote a balance between the other variables. Because of the interactive feedback loops between the variables controlling river behavior, it may be risky to assume that there would not be some other unanticipated negative impact of the treatment. In this case, if the grade were raised to promote aggradation, downstream reaches may become more erosive due to the reduction in sediment supply. The point being made is that possible solutions for the Carson River, even on the conceptual level, will not be simple. Detailed feasibility assessments will be necessary before confidence can be placed in these types of solutions.

Other possible solutions to aide natural recovery are discussed in following sections, including: riparian management, water flow management, improvement of diversion structures, and alterations of existing channel geometry.

Riparian Management

Natural channel recovery can also be promoted by BMP's. If summer low flows were not a limiting factor, efforts to manage the corridor for an increase in the amount of woody riparian and herbaceous vegetation would help the system recover. While some BMP's are very straightforward, such as the adjustment of grazing or agricultural practices so as not to limit full riparian potential, others are not so simple. For example, a conceptually attractive idea is to physically re-plant the river corridor with desirable species. While a well-thought out plan may have some local benefit, there is no precedent for a riparian planting program on the scale of the study area and there is the possibility that other channel instability problems could overwhelm the planting efforts. Such efforts, if undertaken, should be viewed as experimental and tested in small areas before a larger program is instituted.

Any riparian planting program should consider the following:

- A professionally conceived and implemented program with many treatment types to be run as a pilot program, with consistent monitoring and reporting. Lack of survival, as well as successes, should be related to specific site conditions so that future efforts can build upon past experience.
- The program should address areas with most potential to respond favorably or resist further degradation.
- Chances of success will increase with the level of funding that can be committed to design, acquisition of quality plant materials, and installation.
- Consideration should be given to utilize existing irrigation networks to provide supplemental watering during stress period and surplus water in wet years to get the right plants established in the right places.
- Some mechanical work on the channel may aid the chances of planted species survival. This may include bank re-sloping for revegetation stabilization, bank removal to create a channel of appropriate width, and/or energy dissipation structures.

BMP's in the corridor should focus on:

- improvement of riparian health, including age and species diversity, and
- an increase in riparian zone width

Low-Flow Withdrawals

If our observation that summer low flows are limiting riparian plant recruitment and survival in the channel is accurate, augmenting these flows is a logical step to improve the situation. However, due to the political ramifications of any such scheme, further study is absolutely warranted. There have been a number of studies in the greater east side Sierra region (Taylor 1982, Kondolf 1989, Smith et al 1990, Stromberg 1994, 1991) and other arid regions (Stromberg and Patten 1993, Rood and Mahoney 1990) which have investigated the relationship between flow withdrawals and riparian health. Using similar methods, a sound scientific investigation should be conducted on the Carson River so that the conclusions drawn have unbiased weight.

Short of augmenting summer low flows, the only other options for increasing low flows would be improved irrigation efficiency or a reservoir system. Though this report's scope did not include investigation in these areas, it is assumed or known that many of these strategies have already been promoted in the area. It is recognized that water use in the basin will not be easily changed and may be untenable as a solution to promote river stability. If this is a political reality, it also must be acknowledged that the options for natural recovery may be greatly limited.

Diversion Structures

In a previous section observations were presented relating to the irrigation diversion structures and effects on channel geomorphology. Previous investigations, as well as this one, have noted the negative impacts of both diversion dam failures and permanent diversion structures on channel stability. Of particular note are diversion structures on the East Fork, which have been the subject of discussion for over 20 years (Carson Valley Conservation District 1976, SCS 1981). When functioning, loose rock (push-up) diversions, because of their single purpose (diversion of flows during the irrigation season) cause many problems such as bank erosion downstream, weakening of the bed downstream due to heavy equipment entry into the channel, and the creation of scour holes downstream. When they fail, they have negative impacts on channel sediment supply and local slope.

Conceptually, we recommend that loose rock diversion structures be replaced with more permanent diversion structures or pumping galleries, in conjunction with the consolidation of diversion points to eliminate unnecessary structures. These recommendations are not new; they have been promoted since 1976 (Carson Valley Conservation District 1976, SCS 1981). It is assumed that these recommendations have not been acted upon due to the costs associated with implementation. For example, in 1980 dollars, installing a permanent diversion (and associated channel work necessary for long-term stability) at the Cottonwood Diversion was estimated to cost $1,000,000 (SCS 1980); for the reach between Muller Lane and Genoa Lane (Reach E-6, this report), $1,300,000 was estimated in 1976 dollars (Carson Valley Conservation District 1976). Today, these projects would have significantly higher price tags, and they do not include replacement of numerous other loose rock diversions on the East Fork. A gross estimate for replacement of all loose rock structures on the East Fork could easily reach $15-25 million.

In addition to the East Fork diversion structures, a number of loose rock diversions may be in need of permanent replacement on the Carson River, including: Dayton Town Diversion, Ricci Diversion, Quilici Diversion, and the Minor Diversion. Of these the Dayton Town Diversion and the Ricci Diversion are likely having the greatest impact on natural river function (see Appendix A). Unfortunately, these two diversions are also the largest on the Carson in terms of total top width and fall over the structures.

Additional considerations for diversion include changes to the existing permanent structures, of which there are several on the East Fork and Carson mainstem. While structure failure during floods is one of the larger impacts of the loose rock diversions, aggradation behind the permanent structures may also be related to local channel instability and greater channel dynamics. As slopes decline with aggradation, the channels have a tendency to further widen due to the change of timing and location of hydraulic forces. Conceptually, if the existing permanent structures could be re-engineered to allow for greater bedload transport during moderate and frequent high flow events, overall sediment transport continuity on the river may be improved. Replacement with pumping systems would allow for natural river function without the negative effects of diversion structures. The benefits of improved sediment transport may be difficult to quantify, though allowing the river the "freedom" to move bedload downstream in as natural a manner as possible is consistent with aided natural recovery options.

Channel Capacity

Given that the majority of the study area's channel can generally be described as entrenched and with excess flow capacity (relative to natural systems where flows approximating the 2-year return interval flow are just contained in a bankfull condition), options which allow flood flows overbank should be considered. Options which promoted this should be considered as aided natural recovery strategies. Implementing these strategies could involve several approaches in combination or singly, including:

- removal of levees deemed unnecessary for control of flood flows which might otherwise threaten infrastructure;
- elevation of channel grade with structures to raise frequent flood elevations to the historic floodplain elevations and;
- large earthwork projects which would selectively lower overbank areas to elevations which would flood more frequently.

Selective Levee Removal

Regarding levee removal, extensive feasibility assessments would be necessary to demonstrate that alterations would not negatively affect existing infrastructure. In addition, socio-political problems may arise from local land owners who have come to expect that the historic floodplain surfaces are not flood prone areas. For example, farming of the floodplain areas would have to work with natural cycles of flooding and ground saturation, which may be different from desired planting and ground preparation schedules. A potential benefit of encouraging overbank flooding includes the well documented benefits to farmers, including improvements of soil fertility and groundwater recharge during floods. Further, it is possible that a local land owners channel instability problems will be reduced by dissipating flood energy over a floodplain rather than concentrating them in the channel. Indeed, much of the channel instability identified is likely related to the influence of the levees during flood flows. Given the potential benefits of levee removal, we recommend:

- Levee removal programs should be investigated as part of an aided natural recovery strategy for the river.
- As a companion to or part of the same feasibility study, a flood hazard evaluation should be completed for areas where urban encroachment on the floodplain is taking place.
- The initial implementation should be considered a pilot program, and may best be located in an area where floodplain development (housing, etc.) is not currently an issue.
- The program should be scientifically evaluated and professionally designed; in particular, existing condition and post-treatment water surface elevation models should be constructed and then evaluated against actual flows.

An issue related to flood hazard and the levees is levee condition. Currently, land is being developed based on the protection afforded by the levees. However, the history of levee maintenance is spotty at best, and it is possible that many levees are not sufficient to withstand large floods. While flood hazard analysis is beyond the scope of this report, the public has demonstrated demand for more and more heavily engineered river structures when they experience flood damage. Strategies including aided natural recovery are not popular in the immediacy of a flood event or soon thereafter. Addressing potential flooding problems before they occur will give river managers greater flexibility in implementing longer range strategies.

Grade Control Structures

The entire discussion of grade control is framed by discussions surrounding aggrading or degrading reaches of the Carson River. While our investigation of this issue is qualitative, some reaches have been more formally investigated (Lidstone and Anderson 1993 and USGS, Carson City Nevada, 1996, report in review). The latter study has investigated bridge pier undermining in the Carson Valley. To date, it is unclear whether either the East or West Forks and the Carson mainstem are still incising their beds system wide. Evidence from bridge piers and some diversion structures (East Fork) does suggest that local scour and deposition cycles are occurring, though no information to date has been presented to suggest a larger pattern of bed degradation.

Grade control structures have some history on the East Fork. As early as 1976, investigators (Carson Valley Cons. District, 1976) reported three grade stabilization structures on the verge of failure between Muller Lane and Genoa Bridge (Reach E-6). It is not known when these structures were installed, though our 1996 inventory confirmed predictions of impending failure. Given these examples, a strategy to raise channel grade should proceed with caution, if at all. Our investigation did not suggest that the channel bed was still incising in this area, an observation also confirmed by another group of investigators (Lidstone and Anderson 1993; see also E-5 and E-6 in Reach Summaries, Appendix A). In contrast, this reach may be in a state of aggradation. Therefore, there would need to be a compelling argument made for accelerating the rate of aggradation. One potentially good argument would be to hasten the more regular deliveries of flood flows to the historic floodplain, though development surrounding the East Fork may preclude this option due to increased flood hazards.

Outside of irrigation diversion dams, grade control structures do not appear to have been part of Carson River mainstem strategies. In general, we do not recommend further investigation of this strategy in this area for the following reasons:

- To have a significant effect on the tens of miles of channel, a large number of structures would be necessary. Each structure would be very expensive to design, install and maintain.
- It is not clear that such a strategy is the most appropriate for the Carson River from a fluvial geomorphic perspective.

In our opinion, grade control structures are only warranted if a significant need can be demonstrated and funding is available. With the possible exception of bridge protection, we did not identify areas of significant need based on a qualitative examination.

Additional Recommendations

Study Follow-up and Analysis

A great deal of information was collected as part of this investigation, much of which can be subjected to closer examination. Further effort may benefit decision making on the part of the river managers as they contemplate river projects. For example, while we have provided at-a-section hydraulics and compiled a great deal of channel geometry and condition data, exploring further linkages between channel geometry, hydrology, and hydraulics may lead to enhanced understanding of current channel condition and how it may continue to change through time. At a minimum, we recommend:

- Surveyed cross-sections and photo points should be replicated on at least a biannual basis in areas of concern, or the whole river, if time and funding allows. This will provide a better picture of river processes and facilitate future feasibility assessments for individual projects. Monitoring can be accomplished by local resource agencies.

  The validation or re-assessment of channel behavior trends explored in this report will be important for management decisions made at some future time. For example, periodic aerial photography can be an important tool in monitoring channel changes and lead to changes in river management strategies.

Design Criteria for Channel and Bank Stabilization Projects

Increase Training of Agency Personnel and Expertise Acquisition

An important observation is that most of the channel stabilization work we observed in the project area had either failed, was in disrepair, or of questionable integrity in the face of larger floods. The exception to this observation was some work undertaken be private individuals with outside consulting services and some of the recent emergency work (i.e. above the Muller Lane Bridge). Better conceived and implemented work may be possible if <u>*all*</u> river projects are subjected to state of the art river channel design criteria. It became apparent to us that the number of projects in the area exceed the capacities of government agency personnel trained in the specialty area of river mechanics. As a consequence, some projects do not appear to meet standards generally considered to be baseline in the private sector. This is compounded by the fact the scale and magnitude of river instability on the Carson demands exceptionally designed projects.

We strongly recommend that local agency river mangers, engineers and regulatory personnel consider the following:

- Invest in specialty training for those involved with river management. Training should focus on geomorphology, design, engineering, and project implementation. Weaknesses in any of these areas will be reflected in installed projects. Emphasis should be placed on emerging and specialty techniques for management of severe erosion and stability problems. Given the urbanizing growth in the area and potential conflicts with the river, upgrading all capabilities in these areas should be considered a top priority for local governments.
- A good case can be made for local agencies hiring of more staff trained in hydraulics, engineering, river management and channel recovery. The need is clearly there, though agency budgets may not be able to accommodate them at this time. None-the-less, agency staffing boils down

to priorities and political will. All avenues should be explored for increasing agency staffs with these skills.

- An alternative to increasing agency staffing levels is to rely on private sector firms for needed expertise. Our experience suggests that this can provide needed and timely assistance, but should also coincide with increased training for agency specialists who will ultimately be involved in letting and administering contracts.

Basic Design and Engineering Standard Practices For Channel Work

A thorough discussion of design and engineering practices for modern channel stabilization work is not within the scope of this report. However, this knowledge can be gained through investments in training for those individuals with need. Briefly, we offer some standard considerations for high intensity projects (for a rough guide, we consider a high intensity project one that exceeds $50,000 in design and construction costs):

- Thorough hydrologic assessment is critical for all projects. Limits in gage information and the complex hydrology of the Carson River make at a site assessments of hydrology difficult. For example, the hydrology compiled for this report (Appendix B) took a fair amount of analysis and is still based on a number of assumptions that limit its applications. While adequate for our purposes, a more thorough examination of a wide range of site flows is necessary for good projects.
- Site-by site examination of channel behavior is also critical. While this report provides reach level analysis which can be extended to individual sites, designers and engineers must always consider specific site anomalies, opportunities, and problems.
- Detailed projects require detailed project site maps. Digital terrain maps with appropriate resolution should be considered essential to every project. Sometimes appropriate resolution is 0.05 feet, as in the case of channel slope in flat reaches.
- Water surface modeling should be part of every detailed project. While at-a-section hydraulic analysis is useful for preliminary design work, pre- and post-project step-backwater models should be considered standard. In FEMA designated floodplains and some county regulations, these are frequently required, though many times they are inexplicably overlooked.
- Sediment transport investigations, such as scour and deposition models are frequently needed. On the Carson River, analysis of existing and proposed sediment transport dynamics is essential. Short of full transport models, other avenues exist.
- Analysis of geotechnical site conditions should be required when bank stabilization schemes are contemplated. Frequently overlooked, failure to identify geotechnical modes of failure, and how to protect against them, can easily lead to project failure.

- Analysis of construction material suitability is also critical. Examination of scour depth, bed and bank shear stress, and velocity leads designers to various construction materials (rock sizes, geotextile and erosion blankets, plant materials, etc.) which are suitable. Frequently, factors of safety play a part in material selection.
- Quality installation of projects can not be underrated in project success. Even the tightest designed projects can fail with poor installation. All contracts for work should include quality assessment and control mechanisms. This is congruent with the need for very detailed and explicit technical specifications for all projects.
- Project monitoring after installation is one of the most overlooked standard practices across the country and in the Carson River area. Without examination of failures and successes, the best strategies for river stabilization do not emerge. There is no reason that design or concept failures should be repeated on a regular basis.

Land Planning and River Corridor Management

The efforts of the local agencies and groups focused on the better management of the Carson River are commendable and should be acknowledged. However, grass roots efforts for river management are in the inception stage, as the public has not coalesced around a common vision for the river. Important tools in promoting changes in river management can be found in land planning in the river corridors. Many ideas contained here are controversial, and are not always easily digested by the greater public. None-the-less, we offer the following recommendations:

- Enforce all county and community obligations for inclusion in the Federal Flood Insurance Program under FEMA. These relate to development in flood prone areas. While easily said, our experience suggests that local political and other opposition is present in rapidly developing areas. Conflicting pressures from developer interests and local long-term landowner resistance to zoning or perceived "takings" is usually high. However, regulations are regulations, and should be enforced. It may be fruitful to re-visit existing county regulations to ensure that community protection is adequate. This relieves pressure on local agencies to respond to threats to infrastructure by reducing the number of developments in the path of the river.

- The Carson River communities should consider setting aside "no development" corridors in the potential migration path of the river. This strategy may ultimately be the most cost effective method for containing long-term costs associated with stabilization of the river. We have identified some of the most unstable areas of the river in areas of heavy development. For undeveloped areas, the cross-road between the path to development or persistence of agricultural ground is in the future at current rates of community growth. Undeveloped areas make the most logical candidates to establish river corridors where the river is free to adjust its boundaries under an aided natural recovery strategy.

Regarding river corridor management, other communities with similar problems have investigated acquisition of river park corridors through outright purchase, tax incentives on easements, purchase of development rights, and land trades. The particulars of such programs can be exhaustive. However, from a geomorphic perspective, we have predicted further channel instability and change that may be driven by processes larger than can be easily addressed with public works projects. Looked at another way, is river instability a problem if no one is directly impacted by it? River management strategies increase, and costs decrease when the river has more freedom to adjust itself to geomorphic dynamics.

PRIORITY REACHES

General

Priority reaches are discussed from two perspectives. First, we recommend that the protection of infrastructure take place as the number one priority. Second, after infrastructure priorities are addressed, river managers have a wide range of choices and opportunities for work in individual reaches. Beyond potential aided natural recovery options discussed previously, the option of active channel restoration and implementation of BMP's are also available strategies. All strategies may in fact be implemented simultaneously on varying levels of intensity. It is recommended that in addition to previous sections of this report and the following discussion, that the Reach Summaries, found in Appendix A, be carefully reviewed to identify the full suite of options available.

Potential river strategies are presented on a reach by reach basis in Appendix A, Reach Summaries. In these summaries, the land management recommendations usually do not include full channel restoration options for several reasons. First, any reach specific restoration option must consider the state of upstream reaches; until it is known whether these reaches will be stabilized, discussion of restoration activities downstream are premature. Secondly, we were unable to identify even marginally feasible activities which would not incur major expenses. Until an identified funding source emerges to contemplate large scale channel recovery projects, specific recommendations are premature. However, in following sections, we do prioritize reaches for large scale recovery projects to provide a starting point should the area river managers some day acquire necessary funding.

Reaches Amenable to Active Restoration

The following reaches should be considered priority reaches for any active restoration projects.

Reaches E-2 through E-6

With the exception of E-2, S1 and S2, Reaches E-2 through E-6 are moderately unstable to extremely unstable. These reaches should be considered a high priority based on the following:

1. They are relatively high in the watershed; actions taken here will begin to address instability problems downstream.
2. These reaches are in areas of the greatest current or potential development.

The central strategy for these reaches should be to reduce the delivery sediment to the Carson River. Given the East Fork's tendency to gain width, recovery activities would likely involve increasing channel width and the construction of a floodplain which is inundated on a bi-annual basis. These efforts would involve a great deal of earth moving and stabilization of the new channel fringes, among other activities.

Reaches C-1 through C-3, S1

C-1, C-2 and C-3 S1 are characterized by unstable banks and general trend of channel meandering and enlargement. Large scale recovery of these reaches would involve strategies outlined for E-2 through E-6. With the exception of upper C-1, C-1 through C-3 reaches are in a relatively undeveloped area where a number of historic meander scars are present. The migrating and incised character of these reaches suggest that they will continue to be a major source of sediment until the channel has widened and developed a new vegetated floodplain surface. It may be possible to reconstruct these reaches such that this process is accelerated. Any such effort would require an extensive feasibility assessment.

Reach C-6

Much of C-6 is in relatively undeveloped area and may therefore be a good candidate area for strategic bank stabilization and channel geometry reconfigurations. However, total recovery of C-6 would still be a major undertaking due to: some severe channel instability, mixed land ownership, and geomorphic activity suggesting a channel in a long-term transition state. Lower intensity approaches include selective bank stabilization and construction of high flow terraces and floodplains in the upper subreaches. Subreaches lower down on C-6 have potentially gained adequate flood prone width though still have very actively eroding banks. Strategies to stabilize selected banks and the enhancement of flood prone area could also prove feasible here. Detailed opportunities should be investigated with a feasibility assessment.

Other Reaches

Subsections of Reaches C-7, C-8, and C-9 could also conceptually be restored with significant effort. These reaches do not have as much priority due to their position low in the watershed. It may be many years before these can be addressed if upstream reaches' instability is first addressed. General recommendations are, therefore, limited to land management BMPs including riparian grazing management where appropriate.

Protection of Infrastructure

Bridges

A separate USGS study is investigating scour at bridges in the project area; it is assumed that its finding may direct the need for bridge improvements to enhance their engineered stability. In brief, the geomorphic condition of the river may be jeopardizing several of the bridges in the project area, including: the Lutheran Bridge, Highway 88 Bridge, Genoa Bridge and Cradlebaugh. These are evaluated below:

- Lutheran Bridge. Potential failure of the downstream Burnell irrigation diversion dam could promote local bed incision which may result in pier scour, though the bridge currently appears in good shape.
- Highway 88 Bridge. Pier footings are exposed on the bridge currently, suggesting recent (post bridge installment) local base level instability. It is unclear whether the bed is still degrading in this area, though upstream and downstream instability is high, warranting investigation of bridge safety during large floods.
- Muller Lane Bridge. Emergency work in the Spring of 1995 included the installation of flow deflectors on the left upstream bank. Channel instability is locally high, and combined with an apparently undersized bridge (does not appear to convey flows even as large as experienced in 1996) and exposed pier footings, suggests that the river may prove to be unpredictable in this area, possibly resulting in further pier and abutment scour and threats to overall stability.
- Genoa Bridge. This bridge appears to be undersized, and given the large in-channel sediment supply upstream, there could be future problems with local aggradation and abutment scour during large floods. All Genoa Lane bridges crossing the Carson and Brockliss are particularly at risk if considering the potential for significant channel shifts above these bridges.
- Cradlebaugh Bridge. Local evidence suggests base level lowering, including the observation of exposed pier footings.

Homes

Several homes along the study area appear to be at risk from further channel migration and/or flood flows. While more complete assessments of flood hazards related to channel instability may be necessary, we offer the following observations by reach (see relevant Reach Summary, Appendix A, for more detailed accounts):

- W-2. In the area of the confluence of the East and West Forks, the potential for channel shifts and backwater problems may be threatening nearby homes.
- C-1. At the head of C-1, one home in the Willow Bend area appears vulnerable to channel migration. Apparently the land owner is aware of this problem, though no action has been taken to date.
- C-5. In S1, the construction of a push-up diversion dam threatens the left bank and home adjacent to the channel. It is highly recommended that this dam be removed prior to 1997 runoff.
- C-6. In S1, a trailer park on the left bank is close enough to the river that there is the possibility that the river could migrate into this area. Though bank stability and channel condition is relatively good in this reach, the river's unpredictability may warrant a future examination of this area.
- C-7. In both of S1 and S2 several homes on the left bank appear vulnerable either to river migration into them and/or flood threats.

Other Infrastructure

All rock push-up diversions can be considered infrastructure at risk, and have been discussed previously. Efforts to replace these with permanent structures will be very expensive, but useful from the perspective of those maintaining them as well as general river stability.

In Reach C-6, the Cardelli Diversion on the left bank of the State Park is at risk and will be lost without stabilization. In addition to the ditch, the park camping and road facilities are also at some risk to channel migration. These areas are discussed in greater depth in the C-6 Reach Summary (Appendix A).

Some sections of road in the project area may be at risk, particularly near the previously identified bridge locations. In addition to these, a section of road on the left bank of C-7 may be at risk, though evidence of active erosion on this bank is not present. This may be a lower priority than other identified infrastructure, but is noted here so that a more careful investigation can be made and that upstream instability is high.

Miscellaneous out-buildings and fence lines, usually associated with farming or ranching activities, were noted to be in close proximity to actively eroding channel banks. While this may be of some concern, the perceived value of these items was not high, and likely do not warrant expensive fixes to protect them.

Levees throughout the project area, if they are serving some legitimate flood protection service, need to be inspected. In general, their state of repair was good to poor. Recall that in a previous discussion, levee removal may be part of channel recovery options. If they serve little purpose, their eventual failure only adds to the already abundant supply of sediment in the system.