Dry Creek Bank Erosion Management Plan

Roseville, California

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1. Introduction and Problem Statement

Dry Creek flows through the middle of the City of Roseville, Placer County (**Figure 1**) within a deeply incised channel. Extensive bank erosion occurred in the mid to late 1990s along public and private properties leading to emergency bank repairs and many sites in an unstable condition. Many individual landowners have acted on their own to protect their property while others are seeking assistance with design, permitting and funding from the City and other agencies.

During the same period, environmental regulation and permitting of bank protection projects have become more restrictive since the listing of Chinook salmon and steelhead trout as threatened species. This has led to the consideration of softer "bioengineered" designs that incorporate native vegetation plantings into hard structures such as riprap and gabions to improve the ecological habitat. The City of Roseville successfully constructed such a project along Dry Creek in Royer Park in 1999 with funding and planning assistance from the California Department of Water Resources (DWR) Urban Creeks Program and the Dry Creek Conservancy (DCC), a local non-profit organization promoting resource conservation and restoration in the Dry Creek Watershed. Based upon the success of the Royer Park project, DWR has provided the City and DCC a new grant to develop an erosion management plan for the lower reach of Dry Creek.

The present work has been developed for the City of Roseville and DCC by Restoration Resources, Inc. The project includes an engineering and geomorphology study document, as well as the construction of a set of bioengineered bank protection projects at three previously selected locations within the project reach.

2. Objectives and Methods

The objectives of the Dry Creek Bank Erosion Management Plan are to:

- Develop a reach-specific bank protection planning and design process that leads to designs that optimize site and local reach stability, while incorporating relevant ecological features;
- Enumerate a variety of bank protection designs that address local bank stability factors and long-term and short-term geomorphic processes;
- Address the long-term stability of Dry Creek channel through consideration of the effects land use development has on channel stability;
- Conduct field surveys to determine the areas of immediate near-term and long-term project needs and develop a bank stability rating criteria specific to Dry Creek project reach; and
- Develop environmental enhancement features that address the habitat needs of local sensitive wildlife species and can be incorporated in future erosion control management.

This document describes the rationale for a recommended management plan approach to bank erosion in Dry Creek, including scientific and engineering research and techniques for designing and constructing bank protection projects. The work involved to complete this document used the following methods.

The hydrology and geomorphology of Dry Creek was characterized from existing information, including historical aerial photographs, FEMA flood study, engineering studies, maps, and hydraulic modeling provided by the City of Roseville Public Works Department and other sources. Prior work on restoration

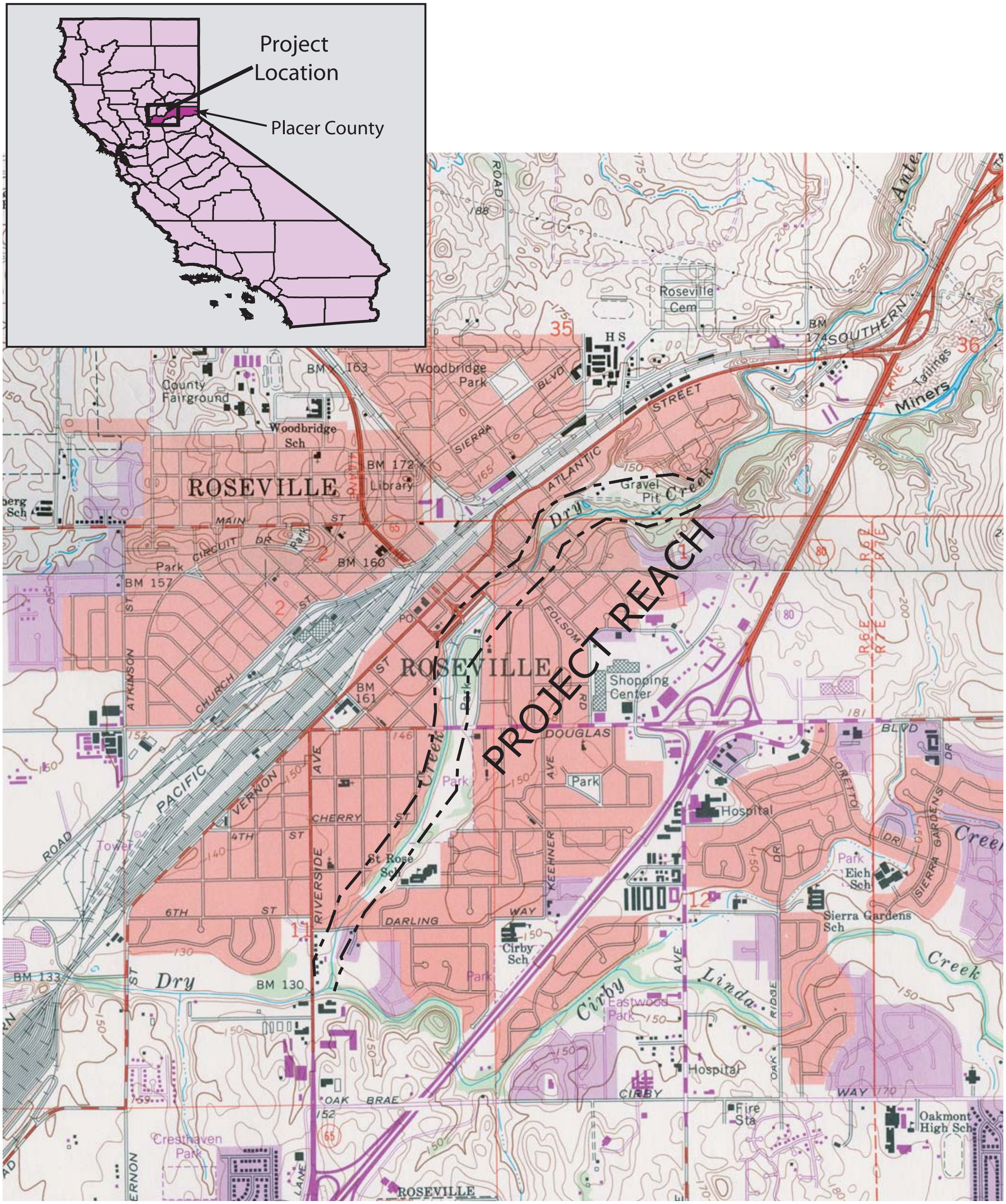

Figure 1: Site location map for the Dry Creek - Roseville Project. Source: 1967 USGS Topographic Map (Roseville and Citrus Heights Quads). Scale: 1:24000.

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design and fisheries improvements by Swanson Hydrology & Geomorphology on Secret Ravine, Miners Ravine, Robla Creek and wetlands in the Dry Creek Watershed was also incorporated.

Fieldwork was conducted to document channel stability factors for rating all banks in the project reach, to map new erosion sites, and to identify existing erosion control structures and their condition. The in-field data collection included a longitudinal profile survey of the streambed, cross-sectional surveys at the FEMA stations, a Rosgen-type channel stability assessment, and a qualitative bank protection assessment.

The longitudinal profile survey was conducted using an automatic level and rod to record elevation changes and a tape to measure channel distance along the stream centerline. City of Roseville benchmarks were used to establish and check elevations along the length of the project reach. The 1987 FEMA flood plain cross sections were resurveyed with special attention paid to the channel shape between the stream banks. This data was previously absent from the FEMA sections because aerial photography does not detect bed shape beneath the water surface. The survey was carried out using an electronic total station and prism. Temporary benchmarks set by the long profile survey crew were used to establish elevation at each section. City of Roseville benchmarks were tied in to confirm the previous survey. The current cross section elevation data was then used to update the 1987 FEMA HEC-RAS model to include current channel conditions[1]. The 2002 HEC-RAS model was rerun to determine the stream flow velocities at various stages, and to assess the general hydraulic forces and the frequency of their occurrence within the existing channel. **Appendix A** plots the water velocity and sheer stresses associated with the bankfull, 10-year and 100-year flows. The hydraulic modeling provided additional information for our assessment of the geomorphic stability and can be used in the future to predict the hydraulic impact of proposed bank protection structures.

The channel stability survey adopted a modified Rosgen (1994) technique that documents channel bank materials, channel geometry, vegetation density, rooting depth, and recent activity for resolving an erosion hazard rating; this technique is useful for planning future needs. The channel erosion sites were mapped on a recent aerial photograph and dimensions were estimated in the field. Rosgen method is based on the assumption that the ability of a stream bank to resist erosion is primarily determined by seven components.

- The ratio of streambank height to bankfull stage,
- The ratio of riparian vegetation rooting depth to streambank height,
- The degree of rooting density,
- The composition of streambank materials,
- Streambank angle,
- Bank material stratigraphy and presence of soil lenses, and
- Bank surface protection afforded by debris and vegetation

In order to complete the channel stability assessment, reach length, flow distribution, erodibility, bankfull width, two-times bankfull width, bank height, bankfull height, sinuosity, bank angle, percent bank face protected, percent root density, rooting depth from top of bank, bank material particle size, bank material sorting, bank soil stratification, streambed material, and stream gradient were measured in the field. Each field parameter was determined for homogeneous stream and bank segments (reaches). Bank parameters were determined for left and right banks (looking downstream) separately to determine the final index values for each stream reach. Based on these assumptions and observations made in the field, the bank erosion potential is assessed for each of the criteria included in **Table 1**.

[1] Swanson Hydrology possesses the 2002 HEC-RAS model for the subject reach and future decisions to conduct specific restoration projects should utilize HEC-RAS simulations to anticipate the future response of the system to specific changes.

Table 1: Bank Erodibility Hazard Rating Guide (adapted from Rosgen, 1996)

Bank Erosion Potential												
Criteria	**Very Low**		**Low**		**Moderate**		**High**		**Very High**		**Extreme**	
	Value	Index	Value	Index	Value	Index	Value	Index	Value	Index	Value	Index
Bank Height / Bankfull Height	1-1.1	1-1.9	1.1-1.19	2-3.9	1.2-1.5	4-5.9	1.6-2	6-7.9	2.1-2.8	8-9	> 2.8	10
Root Depth / Bank Height	1-0.9	1-1.9	0.89-0.5	2-3.9	0.49-0.3	4-5.9	0.29-0.15	6-7.9	0.14-.05	8-9	< 0.05	10
Root Density (%)	80-100	1-1.9	55-79	2-3.9	30-54	4-5.9	15-29	6-7.9	5-14	8-9	< 5	10
Bank Angle (Degrees)	0-20	1-1.9	21-60	2-3.9	61-80	4-5.9	81-90	6-7.9	91-119	8-9	> 119	10
Surface Protection (%)	80-100	1-1.9	55-79	2-3.9	30-54	4-5.9	15-29	6-7.9	10-15	8-9	< 10	10
Totals		5-9.5		10-19.5		20-29.5		30-39.5		40–45		46-50
Additional Adjustments and Considerations Bank Materials: Bedrock - Bank erosion potential always very low Boulder - Bank erosion potential low Cobble - Decrease by one category unless mixture of gravel/sand is over 50%, then no adjustment Gravel - Adjust values up by 5-10 points depending on composition of sand Sand - Adjust values up by 5-10 points Silt/Clay - No adjustment Stratification: Adjustment of 5-10 points (upward) depending on position of unstable layers in relation to bankfull stage												

Following the initial field channel stability survey and identification of erosion and bank protection sites by the project geomorphologist, the project engineer performed a field survey to verify documentation and add essential engineering data. The channel stability assessment conclusions were amended and improved, where necessary. Existing bank protection within the subject reach was assessed and rated for effectiveness. The existing geomorphic and hydrologic conditions were then applied to each specific erosion site to estimate causes of failure and potential feasible solutions.

The field data were reduced and analyzed in light of technical literature regarding geomorphic stability, bioengineering techniques, geotechnical stability, and accepted engineering practices. The analysis determined a range of possible "bio-engineered" bank treatments based upon the level of site constraints within the context of a coordinated treatment plan. A planning process was devised to develop a site-specific bank protection design, yet still within the context of the localized reach and overall conditions in Dry Creek. Channel stability factors discovered in the geomorphic analysis were incorporated in the design process, as well as the placement of specific environmental features.

3. BANK EROSION PROCESS

To link the process of erosion and sediment deposition to channel morphology and the magnitude and frequency of floods, it is useful to identify three stages or separate channels within the river. The smallest is the "low flow" channel, which carries flow over 99 percent of the time and contains most of the aquatic habitat in a given stream system. The next channel is often termed the "bankfull" channel and reflects those flows that move sediment and occur often enough to influence the channel width and shape in a fundamental way. It is also concurrent with the elevation at which a new flood plain is formed; flood plain in geomorphology is defined as a low flat area or bench occurring adjacent to the channel and receiving fine sediment deposition in the present climate. The bankfull channel is also concurrent with the flow that carries the most sediment over time, which is a reason why bankfull flow has a great influence on channel form. The largest channel is often called the "flood" channel and contains flows up to the point where channel capacity is exceeded and spills out onto the valley floor (or flat). This channel is bounded by terraces, which in geomorphology are defined as "abandoned" flood plain surfaces by virtue of the fact that the channel bed has incised and these terraces are no longer subject to frequent flooding and fine sediment deposition. The incision of a channel into a valley floor can be caused by climatic change and/or by human land use (i.e. channel straightening, reduction in sediment supply, levee construction, flow confinement, urbanization).

Stream bank erosion is a natural process of alluvial streams, which flow within the unconsolidated and recently deposited sediments underlying a valley floor. Research on alluvial streams indicates that the natural tendency of channels is to meander in an attempt to minimize the variation in energy expenditure in the downstream direction. In other words, the stream would prefer to take a longer path if the rate of energy loss to heat and kinetic energy was more evenly distributed along the entire reach. Meandering streams move across their valley floors through erosion of the outer bank and aggradation on the inner bank (point bar), as sediment is transported down valley. Areas contained within the zone of meandering, or meander belt, are susceptible to erosion. As will be discussed below, there are many factors that affect the resistance of banks to erosion (the effect of vegetation being a primary one) and the opposing hydraulic force driving erosion, including the tendency of the stream to create channel geometry (width and depth) and pattern that reflects the balance of flow and sediment transport.

At a basic level, bank erosion occurs when the hydraulic force of flow undermines the lower portion of the bank, leading to upper bank failure by mass wasting (slump, block fall, or debris slide). Many erosion failures occur on the recession of large floods when the upper bank is saturated and long duration flows impinge and erode the lower bank. Sometimes erosion occurs during moderate or small floods, indicating that the progression of undermining the bank toe has been ongoing or that erosion of the channel bed has occurred through migration of a headcut or knickpoint along the bed. In any case, the factors affecting lower bank erosion are a primary concern in designing bank protection, because it is the location of maximum hydraulic force and the lower bank stability will dictate upper bank stability.

3.1 Lower Bank Stability

The lower stream bank area generally encompasses the lower third of the overall bank height. From the lowest point in the streambed (thalweg or flow line), the lower third of the bank is saturated and exposed to flow in most years. The resistance of the lower bank to erosion is dictated by the nature of its geologic materials and the degree to which they are cohesive or lithified. Clay rich sediments tend to be more cohesive than sandy sediments or coarse gravels and cobbles; in some cases circulation of groundwater can cement sediments with calcium carbonate or silica precipitates and increase their resistance. Stratification can be very important as lenses of erodible sand may be wedged between layers of cohesive silts and lead to block failures of the lower bank once the sand is eroded out.

The natural tendency of the Dry Creek project reach is to maintain a meander pattern and dissipate the energy of water transport over a much longer channel than currently exists. Hydraulic force on stream banks can be extenuated by meandering processes and by irregularities in channel width along the stream that cause backwater and eddying. Once this happens, the focused flow path toward a stream bank possesses a helical motion or spiral flow that is in the direction normal, or perpendicular, to the primary flow. The outer bank is the focus of hydraulic force and the point where bank erosion naturally occurs. The inner bank is in most cases an area of sediment deposition, termed a point bar. This flow pattern results in excessive energy focused at the channel bank and can induce localized erosion and undercutting of the bank material.

In an incised stream channel, the hydraulics of flow is less organized, especially if the stream has been artificially straightened and deepened. If the natural historic tendency of the entrenched stream is to meander, then it will first attempt to erode its streambed and banks to establish a flatter gradient and the meandering pattern. This process creates constrictions and expansions in the width of the flood channel, resulting in discontinuities in hydraulic force and sediment transport. As flows increase during the rising limb of a flood, the constrictions can become backwater controls and lead to loss of sediment transport capacity and deposition of coarse bedload in a mid-channel bar upstream of the constriction. As flow declines, the backwater control dissipates, but the pile of deposited coarse bedload occupies the channel and flow has to move around the obstruction. Because hydraulic forces are increased over and around the bedload, it usually can erode less resistant lower banks and lead to widening; the widening above a constriction creates an even greater discontinuity and eddying, where flow currents impinge at direct angles to the banks. Until the channel reaches a stable profile grade and channel width and the original meander belt is restored, this process will continue.

Flood plain reclamation practices often involve deepening and straightening stream channels, which increases bank height above natural height. The height of the bank is an important factor as it dictates the upper bank mass and the degree to which hydraulic force exerted on the channel bank will increase as discharge in the stream increases. Steep, high banks are generally less stable than low, flat banks, regardless of the resistance of bank materials. This results in an entrenched or incised channel and limits overbank flow onto the flood plain during a flood. Overbank flow when storm runoff is able to access its flood plain will decrease flow depth both within the channel and on the flood plain and dissipate the hydraulic force in the channel. In urbanized areas, efforts are made to contain the flood flows within the channel, thus exponentially increasing the hydraulic force to erode and transport sediment from the stream channel itself. Shear stress is the critical force necessary to mobilize sediment and erode the streambed; the greater the shear stress, the larger the particle size the flow is capable of entraining.

$$t_w = g^* R^* s$$

where t_w= erosive force of water
g = is specific weight of water
R = is the hydraulic radius (cross sectional area of flow/ wetted perimeter))
s = is the energy slope approximated by the slope of the channel bed

Based on the above equation for shear stress (Du Boy's 1879), a steeper channel will exert greater erosive force on the streambed given the same discharge. In addition, hydraulic radius is also directly proportional to the erosive capability of the water. The compounded impacts of both channel confinement and incision exacerbate channel erosion of the lower bank and oversteepen the upper banks, eventually leading to upper bank failure.

Urbanized channels such as Dry Creek contain other hydraulic controls, including bridges, pipeline, flood plain fill areas, bank protection structures and road crossings that affect sediment transport continuity and hydraulic forces during floods. These infrastructure features often cause local channel adjustments in streambed profile, but are susceptible to erosional damage due to long term channel bed lowering, or degradation, and to scour damage, or the short term lowering of the bed during a flood event.

A very important factor in lower bank stability is the topographic stability of the streambed. Incised streams can experience bed degradation as the channel profile adjusts to restore a flatter gradient. The rate of erosion depends upon the frequency of erosive flood events and the erosional resistance of the bed material. Often, the bed is lowered through a process of "headcutting", or upstream migration of a steep drop in the streambed profile. Headcuts or knickpoints migrate upstream as flow spills over the steepened section into a plunge pool. Knickpoints can immediately lower the bed profile by several feet during a flood, leading to immediate lower bank erosion and loss of upper bank stability. An examination of a detailed topographic survey of the channel bed can estimate the location of headcuts and their rate of upstream migration.

Vegetation plays an important role in lower bank stability. Vegetation cover can be variable in an incised channel or one that has experience channel bed degradation. In some cases, the lower banks are too steep and composed of instable material to be suitable for vegetation establishment. Woody riparian plants species such as willow (*salix spp*) and alder are naturally adapted to the lower banks and scour zone of streams. These plants and other woody riparian species rely on fresh mineral soils deposits for germination and usually move into recently disturbed areas of the stream or flood plain. Riparian species contain significant root depths and strength, and once established significantly increase the stability of a bank. Vegetation uptakes water from the soil, enhancing natural drainage and producing an organic layer at the surface of the soil. This layer will reduce potential for erosion by protecting the soil from direct erosive forces such as rainfall and flowing water. Vegetation can also dampen the extreme temperatures experienced by exposed soils, such as freeze/thaw or direct sunlight. Exposed soils will also weather at an accelerated rate, decreasing bank stability. In addition to providing soil cohesion and bank stability, vegetation provides shelter for insects and animals, decreases water temperatures by creating shade, and is a necessary component for streamside ecological function. The natural and physical benefit of bank vegetation is significant, and any future restoration efforts should include riparian recovery wherever possible.

3.2 Upper Bank Stability

Upper bank stability is primarily dependent upon the buttressing effect of the lower bank, the geotechnical properties of the bank materials and the rooting strength provided by riparian trees. In cases where the lower bank has been eroded, the ability of the upper bank to stay intact is a function of the internal angle of friction and the degree of cohesiveness. These factors depend upon the origin of materials, but in general a clay loam will have greater strength than well-sorted sand. In the stream environment the resistance of the upper bank can be decreased by saturation, which will increase mass and can reduce the internal angle of friction. Saturated pore pressure can reduce the cohesiveness of certain clays in the cases where clays have shrink swell behavior.

The primary forces causing and resisting bank failure are common to most failure mechanisms. The force of gravity exerted on the mass of the bank materials (*weight*, W) is the major force causing slope failure, while the *shear strength* of the bank's materials (including vegetation) determines the ability of a slope to resist this force. Failure occurs when the weight of the bank materials overcomes the composite *shear strength* of a slope. The weight can be resolved into two components. The down-slope component, or *shear force* (W sin a), acts to shear the soil along a potential failure plane, while the *normal force* (W cos a) acts perpendicular to the failure plane, compressing the bank materials to create *normal stress* (σ). **Figure 2** is a schematic of these basic components, depicting their actions on a simplified slope comprised of uniform material. As discussed above, Dry Creek's banks typically consist of multiple material constituents, each with its own inherent properties and associated failure mechanisms.

The *shear force* is resisted by the *shear strength* (τ_f) of a slope, which is a measure of the constituent materials' ability to resist failure. The *shear strength* of a material is a function of the applied *normal stress* and two strength parameters: *internal angle of friction* (Φ) and *cohesion* (c). None of these parameters is fixed for a given soil, but each is dependent on the conditions found within the bank at a given time. Applied *normal stress* works to increase inter-granular friction within bank materials to develop increased *shear strength*. This *normal stress* can be counteracted by the presence of *pore water pressure* (u), as the buoyant force exerted by *pore water pressur*e on the individual soil particles directly reduces the stabilizing forces developed by the *normal stress*. The *internal angle of friction* is a function of the soil's particle size distribution, shape, mineral constituents, and material properties. *Cohesion* is a soil parameter used to describe electrostatic attraction between mineral and water ions. The cohesion of

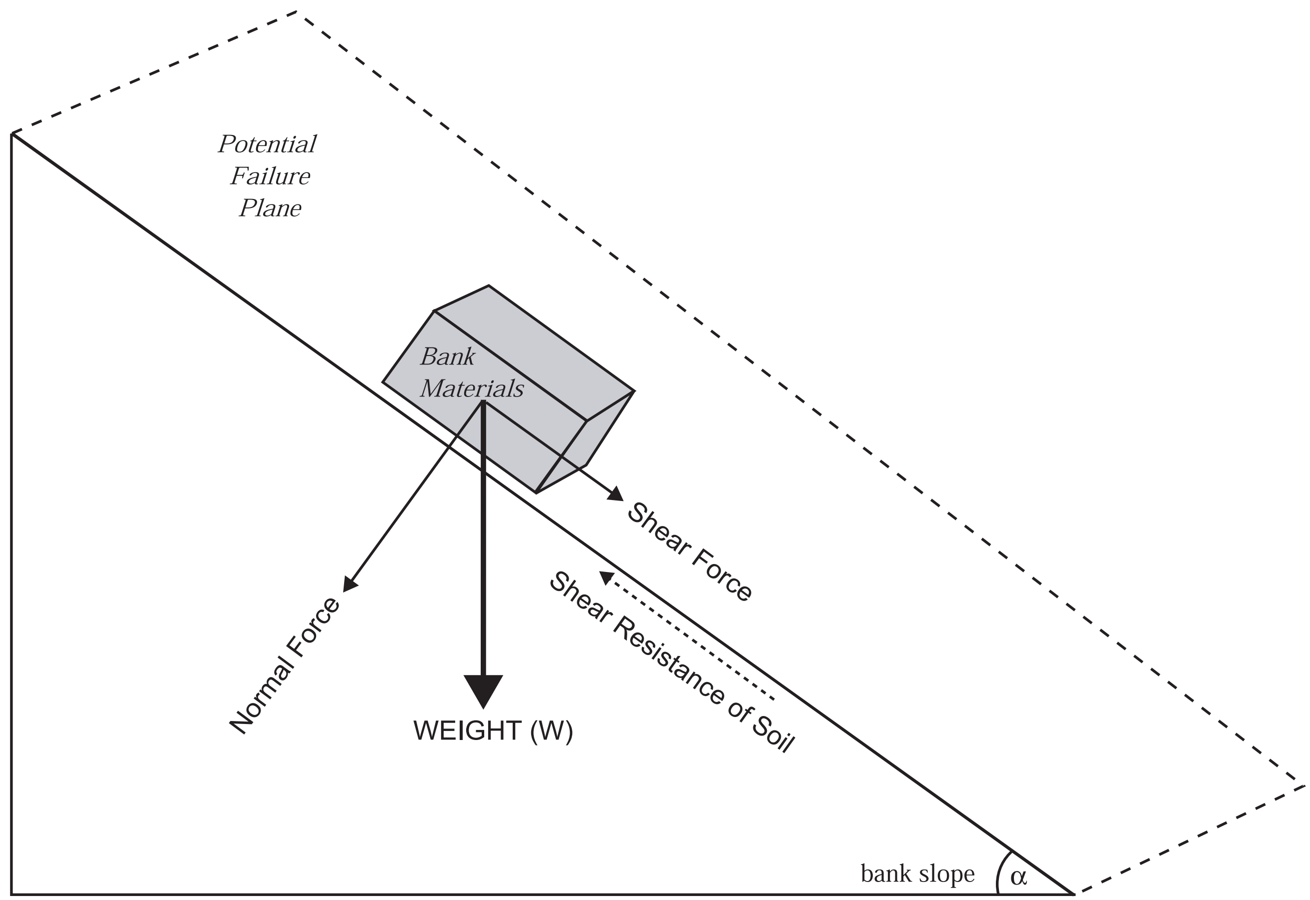

Figure 2: The force of gravity exerted on the mass of the bank's materials (weight, W) is the major force causing slope failure. The weight force can be resolved into two components. The down-slope component of the weight, or shear force (W sin α), acts to shear the soil along a potential failure plane, while the normal force (W cos α) acts perpendicular to the failure plane, compressing the bank materials to create normal stress (σ). The shear strength of a bank's materials (including vegetation), determines the ability of a slope to resist shear forces.

the soil has a strong contribution toward the soil's resistance to failure and is highly dependent upon the amount of clay present and the grain size distribution of the material.

The interaction of the above described soil parameters and their individual contributions to a bank's strength properties is demonstrated by the Coulomb equation (Craig, 1998).

$$\tau_f = c' + (\sigma - u) \tan \phi$$

Based on the above equation, *shear str*ength (τ_f) at a given location will increase directly with increases in *normal stre*ss (σ), *cohesio*n (c) or *internal angle of friction* (ϕ), but will decrease in response to increases in *pore water pressure* (u). An understanding of the above relations and their effect on failure mechanisms is critical to the selection of an appropriate bank protection strategy.

As in the lower bank, vegetation can play an important role in upper bank stability. Root systems of large trees and smaller plants increase the cohesive strength of soils. A key factor in overall bank stability is the rooting depth of vegetation and the percentage of vegetation cover. When erosional forces on the lower bank are able to work below the rooting zone, the rate of erosion can be greatly accelerated. This can lead to rapid change in channel location and morphology, sometimes referred to as a threshold change. This rapid change is often characteristic of incised channels where channel bed degradation and headcut migration is active; the lower bank is rapidly eroded under to root zone and the upper bank fails in blocks of root-bounded soils.

3.3 The Effects of Urbanization

Urbanization in and around streams and their drainage basins can fundamentally change the physical condition of the stream and the hydraulic forces and geomorphic processes at play and can have several potential effects on stream channel stability and bank erosion. As mentioned above, land reclamation often involves deepening and straightening of the channel into an unnatural geometry and pattern. This can lead to incision and bank erosion as the stream attempts to re-establish its former profile grade and channel morphology. Urbanization also converts watershed areas from irregular surfaces of soil and vegetation with runoff to rainfall ratios between 0.4 and 0.6 into hardscape (pavement and roofs) with little absorption and runoff to rainfall ratios of 0.8 to 1.0.

Urban landscapes also have very efficient drainage systems, which collect and transport runoff to the stream faster than what occurs naturally. In terms of the impact on channel morphology, urbanization tends to increase the duration of flows effective in the bankfull range and therefore increase the erosion and sediment transport work done. In simple terms, if the 1.5-year recurrence peak flow is an average bankfull channel flow and channel bankfull channel width and depth are proportional to drainage area, then urbanization has the effect of increasing flow at the 1.5-year recurrence interval and the effective width and depth of the bankfull channel. Because alluvial channel width is proportional to the meander wavelength and radius of curvature, changes in bankfull flow can translate into an expansion of meander loop dimensions and meander belt width. Some research has shown dramatic channel changes with as little as 17% conversion of watershed area to urban cover (Dunne and Leopold 1978).

Historically, placer mining was a common practice during the gold rush in the Dry Creek Watershed and often involved dredging the valley alluvial sediments, diverting the stream through sluice channels and flushing spoils downstream. This activity changed channel morphology and the depth of soils on the valley floor, leading to the higher and less cohesive banks of today.

4. RELATIONSHIP OF GEOMORPHIC PROCESSES TO AQUATIC AND RIPARIAN HABITAT

Aquatic and riparian habitat quality of a stream system is directly related to the geomorphic, hydrologic, and hydraulic processes acting on it. The width of the channel, variability of the flood plain, sediment supply and sorting mechanisms, and hydrologic setting all act to define the type of riparian species that can grow and reproduce, the abundance and species richness of aquatic macroinvertebrates, and the fish species assemblage present in the reach of interest. Conversely, the abundance, distribution, and age structure of the riparian vegetation community can have a profound impact on local channel morphology (e.g. – meander pattern, pool and riffle formation, etc) and sediment supply and sorting characteristics. The presence of large woody material or geologic controls (e.g. – bedrock outcrops, boulders, etc) dictates pool development, the quality of riffle habitat, and gravel/sand sorting occurring at the tail of pools. Stream banks that are stabilized by mature riparian vegetation provide escape cover for fish by allowing the formation of undercut banks that do not increase the risk of bank failure.

The Dry Creek Watershed currently provides spawning and rearing habitat for federally protected steelhead and fall-run Chinook salmon. Adult fall-run Chinook salmon migrate upstream from July to December to spawn and complete their life cycle. Spawning occurs from early October to late December with young emerging and out-migrating to the ocean from January to June. The exact timing of adult migration, spawning, emergence, and out-migration greatly depends upon the streamflow conditions for any given year. If fall rains arrive late, spawning may be delayed and in some cases will not occur at all if low flow migration barriers occur between the ocean and spawning grounds in headwater tributaries such as Dry Creek. Chinook salmon have been found to be more abundant in Dry Creek than steelhead since the freshwater portion of their life-cycle is completed within a single wet season and the juveniles do not over-summer in Dry Creek nor its headwater tributaries, such as Miners and Secret Ravines. Summer rearing habitat has been found to be limiting in the lower gradient reaches of Dry Creek, Secret Ravine and Miners Ravine due to high water temperatures and predation from introduced warm water species (Titus, 2001).

Steelhead enter streams and rivers to prepare for migration to spawning grounds as soon as streamflow is adequate to allow passage over potential barriers. This typically occurs in November or December, depending upon the frequency and magnitude of late fall storms. Migration to spawning grounds typically begins in December and can last well into May if late spring storms provide adequate flow to negotiate potential passage barriers. Following spawning and emergence young steelhead spend 1 to 2 years in freshwater streams before heading to the ocean as smolts. The amount of time spent in freshwater depends primarily on food availability and metabolic rates. Each of these factors is highly dependent upon water temperature. As water temperature increases, fish become more active and require more food to support higher metabolic rates. Higher water temperatures allow for more primary and secondary productivity and make more food available to fish. The result is a delicate balance between food availability, water temperature, growth rates, and metabolic rates. This life cycle makes juvenile steelhead very susceptible to land use impacts that affect the quality and quantity of available rearing habitat.

For both Chinook salmon and steelhead, the quality of streambed habitat for early life stages can become seriously disrupted by an influx of fine sediments. Coarse substrate and redds can be buried by influxes of fine sediments that move along the bed, even during summer low flow periods. The degree to which substrate is buried by fine sediment is known as embeddedness. Fine sediment can clog redds, reduce water circulation and kill or force early emergence of sac fry, thereby decreasing the chances of survival. Fine sediment can also significantly reduce rearing habitat and places to hide, known as escape cover, by burying cobble and boulder areas on the streambed. In the Dry Creek Watershed, the presence of excessive fine sediment due to bank erosion and resuspension of historic mining debris has had a significant impact on the success of spawning and the survival of emerging juveniles. This has been exacerbated by the lack of roughness elements, such as large woody material, that creates the hydraulic variability necessary to create pockets of high quality spawning habitat and development of rearing habitat.

The reach of Dry Creek that is the focus of this report meets the habitat needs of Chinook salmon and steelhead in different ways. Chinook salmon are able to use this reach of Dry Creek to complete their entire life cycle. Limited spawning and winter rearing habitat is available to support fish, though the reach is primarily used as a migratory corridor to reach better habitat found in Secret Ravine and Miners Ravine. This reach is potentially very productive and the spawning and rearing habitat for Chinook salmon can be developed and improved through implementation of more geomorphic and hydraulic variability. This could include bank stabilization projects that integrate large woody material and other roughness elements, planting of riparian vegetation, and reduction of fine sediment supply. Steelhead appear only to use this reach as a migratory corridor to reach better juvenile rearing habitat in Secret Ravine. It is not clear whether or not steelhead spawn through this reach. If any spawning does occur juvenile steelhead do not likely survive because of poor rearing habitat (i.e. – high summer water temperatures, predation from warm water fishes). Due to cumulative impacts and introduced predators, steelhead restoration on the mainstem of Dry Creek is not likely to happen. Instead, improvements should be focused on removing potential low flow barriers so steelhead can reach spawning and rearing habitat in the upper watershed.

5. DRY CREEK WATERSHED AND PROJECT SETTING

5.1 Geography and Geology

Dry Creek drains a 57 mi^2 basin from Auburn to Cirby Creek in Roseville (JMM Engineers 1992) (**Figure 1**). The City of Roseville is situated within an area where several tributary stream confluences occur. Dry Creek begins at the Secret Ravine and Antelope Creek confluence near Atlantic Avenue. These streams originate just south of the City of Auburn and flow southward roughly parallel to Interstate 80. Miners and Strap Ravine flow west towards Roseville from the Auburn Folsom Road area. Linda and Cirby Creek drain areas east and southeast of Roseville beyond the Sacramento / Placer County lines.

The Antelope and Secret Ravine Creek Watersheds flow within narrow alluvial valleys underlain by resistant granitic rocks and bounded by ridges of younger volcaniclastic rocks of the Merhton Formation. Miners Ravine Creek flows within a flatter granitic landscape with abundant alluvial and decomposed granite filled valleys before entering a deep canyon bounded by hillslopes of Merhton Formation. Linda and Cirby Creek flow within hilly terrain underlain by old alluvial fan deposits and hardpan soils.

The Dry Creek Bank Erosion Management Plan project reach is 1.7 miles long, situated within the City of Roseville between the Adelante High School site and Riverside Drive. Four bridges cross the project reach at Folsom, Royer Park, Douglas and Darling Boulevard. Sanitary sewer lines and storm drains occur in many places along the stream banks and there are two locations where sanitary sewer lines cross the channel and form prominent grade controls (**Figure 3A**).

Dry Creek flows through numerous privately owned lands with residential and commercial uses. Some commercial buildings and parking lots are situated at the top of the bank. Publicly owned parklands (Royer and Saugstad Parks) or vacant parcels of various ownerships bound other reaches.

5.2 Climate and Hydrology

The climate of a watershed will have a strong influence on its hydrology. The Dry Creek drainage basin experiences a Mediterranean climate with warm dry conditions between April and October and wet and mild weather between November and March. Average rainfall is 22 inches per year with most occurring during the peak rain months of December through March.

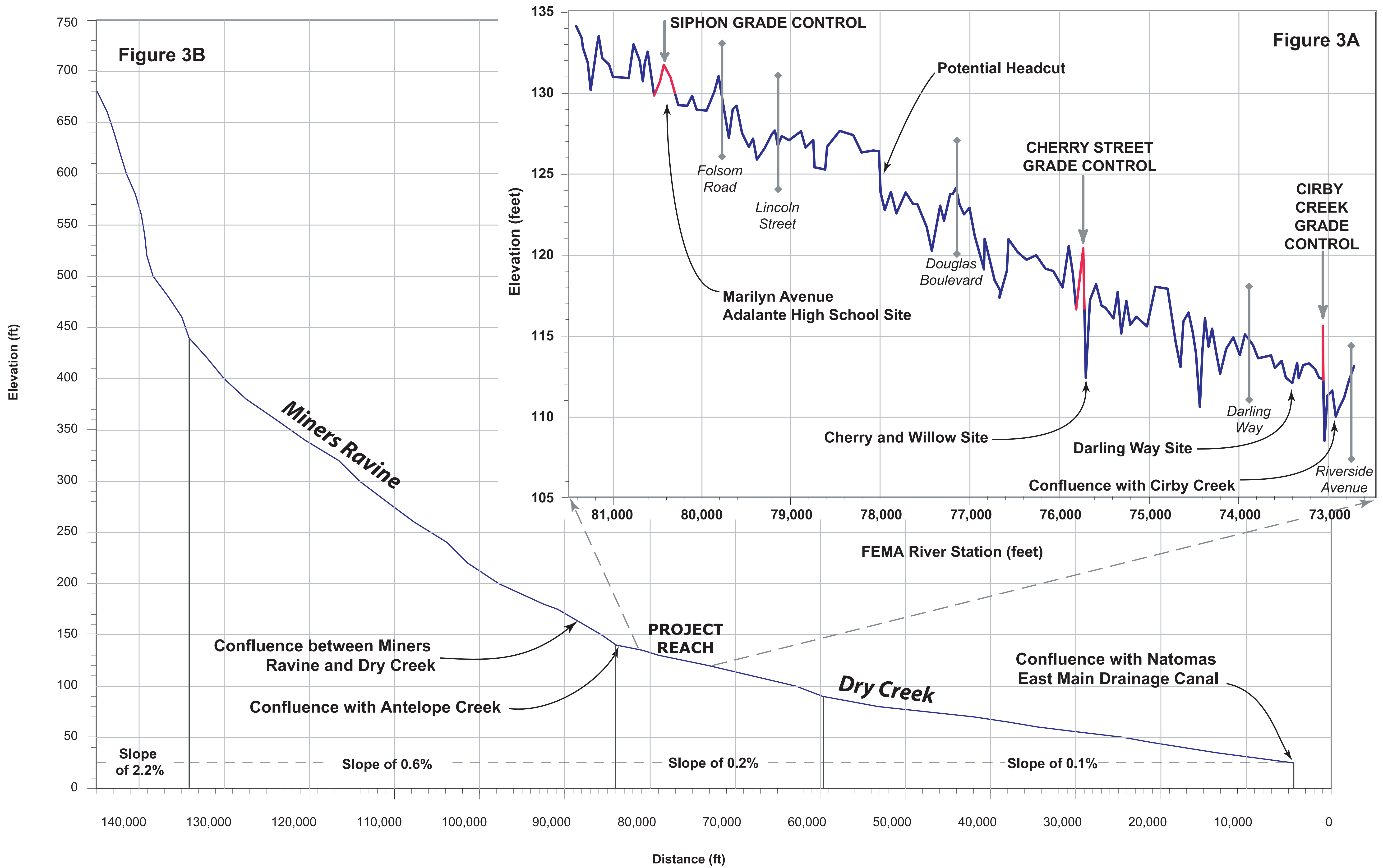

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Figure 3: Longitudinal profile from headwaters of Secret Ravine to the confluence of Dry Creek and the Natomas East Main Drainage Canal. Note that the project reach is located in the transitional reach. Inset is the detailed longitudinal profile of the project reach as surveyed by SH&G in May 2002, adjusted to match FEMA hydraulic model river stationing. Bridge locations are shown by gray vertical lines.

Minimal stream flow records exist for the subject reach. Over 40 years of data has been collected by the US Geologic Survey (USGS) stream gage station (#11447300) located on Dry Creek at Vernon Street, downstream of the confluence of Dry and Cirby Creeks. The complexity of hydrologic routing and the relatively similar watershed area of Cirby Creek renders the data inapplicable for the purposes of this project. However, using the regional hydrologic analysis conducted by Montgomery Engineering (1989) of the Dry Creek Watershed, we have estimated the flow frequency of various storm events based upon the drainage area of the subject reach (**Table 2**).

Table 2. Flood frequency analysis based on Montgomery Engineering 1989 and FEMA Model 2001.

Recurrence interval (yrs)	Regional Hydrology Equations $Q=a*Area^b$	Subject Reach of Dry Creek Peak Flow (cfs)	FEMA Flood Discharge Estimates (cfs)
2	$Q_2 = 109A^{0.66}$	1,570	na
10	$Q_{10} = 272A^{0.69}$	4,430	5,403
25	$Q_{25} = 360A^{0.72}$	6,610	na
50	na	na	8,551
100	$Q_{100} = 580A^{0.72}$	10,660	9,726
200	$Q_{200} = 670A^{0.73}$	12,820	na
500	$Q_{500} = 850A^{0.74}$	16,934	na

The regional hydrology curve produced by Montgomery Engineers was determined using historic regional flow records prior to 1989. Since that time, the Dry Creek Watershed has experienced significant urban development. Estimates from Placer County Planning suggest that the Dry Creek Watershed may be nearly 40% urbanized. Urbanization increases the efficiency of water routing from the surrounding watershed to the channel, thus increasing the peak discharge and decreasing the time the peak of the runoff takes to reach the stream channel. Therefore, the current peak flows are most likely slightly greater than those estimated in 1989. The response of the channel to these hydrologic changes has resulted in an increase in the size and capacity of the low flow channel. The measurable increases in the frequency of the channel forming flow in the lower reaches of Dry Creek in Roseville have contributed to the channel incision observed today.

5.3 Geomorphology

The length of a stream within its watershed can be separated into three distinct geomorphic zones. The steep channels and hillsides in the upper watershed, termed the "zone of erosion or depletion," are subject to net erosion because flow is too swift to allow for significant storage of sediment. The middle portion of a watershed is the transitional reach where the stream flows within a sloping, alluvium-filled valley and temporarily stores sediment that is later transported during subsequent flows. Over a number of years the sediment load coming into a transitional reach is equal to that going out. The lower watershed area, where the stream meets its "base" level (such as a delta or the ocean), is the zone of net deposition. The subject reach of Dry Creek is located in the transitional zone of the watershed, poised just downstream of the confluence of two fairly similar sized subwatersheds, Miners Ravine and Antelope Creek. The slope of the Dry Creek reach through the City of Roseville is relatively less than that of the upper watersheds draining the Sierra Nevada foothills and possesses all the physical characteristics (slope, sediment load and channel media) of a meandering channel through the alluvial valley floor. From the confluence of Antelope and Secret Ravine, Dry Creek flows within a relatively wide alluvial valley bounded by higher hills. The alluvial valley and the Dry Creek channel have been urbanized and highly modified with large areas of fill in the flood plain, road and bridge crossings and a straightened Dry Creek channel. In some places roads, walls and buildings border the channel and constrict the stream's morphology.

The longitudinal profile from the headwaters of Secret Ravine to the confluence of Dry Creek and Natomas East Main Drain (**Figure 3B)**, illustrates that the subject reach is located just downstream of a distinct break in the elevation gradient (i.e. the transitional zone). Following large sediment mobilization during the Placer Mining era, the subject reach was inundated with as much as 20 feet of sand and silt. Initially following the transport and deposition of this large amount of sediment, the subject reach of Dry Creek was most likely a braided channel, occupying many small channels within the unconfined hydraulic mining debris. As settlement of the City of Roseville occurred, levees were built and flow paths were enhanced in order contain floods and reclaim flood plain areas.

The longitudinal profile of the subject reach is enlarged in **Figure 3A** and illustrates that the streambed exhibits a naturalistic deep pool and shallow riffle profile with significant grade controls at Siphon, Cherry Street and Cirby Creek. As mentioned above, channel incision can be the physical result of a headcut migrating upstream. Based on the reach specific longitudinal profile (**Figure 3A**), a headcut may be present at Royer Park (FEMA station 78,000), as indicated by the steep channel gradient in this location. The detailed longitudinal profile can be used to determine the gradient and relative location of future restoration and bank stabilization sites.

The natural plan form of the river provides information concerning the stable form of the channel. The primary factors controlling the channel pattern are slope, discharge and bed material. There are no aerial photographs or historical maps created prior to the development of the City of Roseville and its encroachment onto Dry Creek's borders. By 1940, urban development had already begun to encroach on the river's flood plain and meander bends, forcing the active channel into a much straighter morphology than it would naturally occupy. The prominent meander patterns can be observed in **Figure 4,** suggesting the form of the natural channel meander of Dry Creek following hydraulic mining. The southern portion of the City of Roseville has been developed within the meander belt and the modern flood plain. The mapping of the natural meander belt illustrates the susceptibility of the local stream banks to erosion as Dry Creek attempts to reestablish its natural meander pattern. The average channel slope in this location is approximately 0.006. Analysis of the 1940 aerial indicates an average meander length of 2000 feet, a radius of curvature of approximately 480 feet and a channel width of nearly 175 feet. This geometry is consistent with the well-established relationship among meander wavelength, channel width and radius of curvature for a wide array of channel sizes (Leopold, 1994), and also indicates the plan form that Dry Creek is currently attempting to reestablish.

The combination of the recent increase in stream flows due to impervious surfaces and the relative reduction in sediment supply from the surrounding watershed has also had a profound effect on the Dry Creek morphology. Historically, the Dry Creek Watershed had a relatively high sediment load from Pleistocene glaciations, followed by hydraulic mining activities. The recent and rapid urbanization has significantly decreased the sediment supply to the project channel reach of Dry Creek. In some catchments, the reduction in sediment supply from the surrounding watershed shifts the sediment source to the channel itself (Trimble 1997), resulting in dramatic channel incision or increases in width, or both. Many locations within the subject reach have exposed over 20 feet of hydraulic mining debris and show dramatic evidence of accelerated channel incision. Channel incision results in a lowering of the groundwater table that will deleteriously impact the water supply for riparian vegetation. This coupled with the relatively rapid exposure of the newly eroded banks further exacerbates incision rates. Channel enlargement and in stream erosion also degrade the biotic integrity by destroying riparian cover, increasing water temperatures and resulting in a homogenous channel substrate lacking physical complexity and ecological diversity.

Assuming that the cross-sectional channel area of a natural channel is shaped by the 1.5-year flow, urbanization of a watershed would result in channel enlargement to accommodate the increase in discharge for the 1.5-year flow (Leopold 1968). In subject reach of Dry Creek, the channel pattern and width have been laterally stabilized to protect streamside property, thus forcing the channel to change its

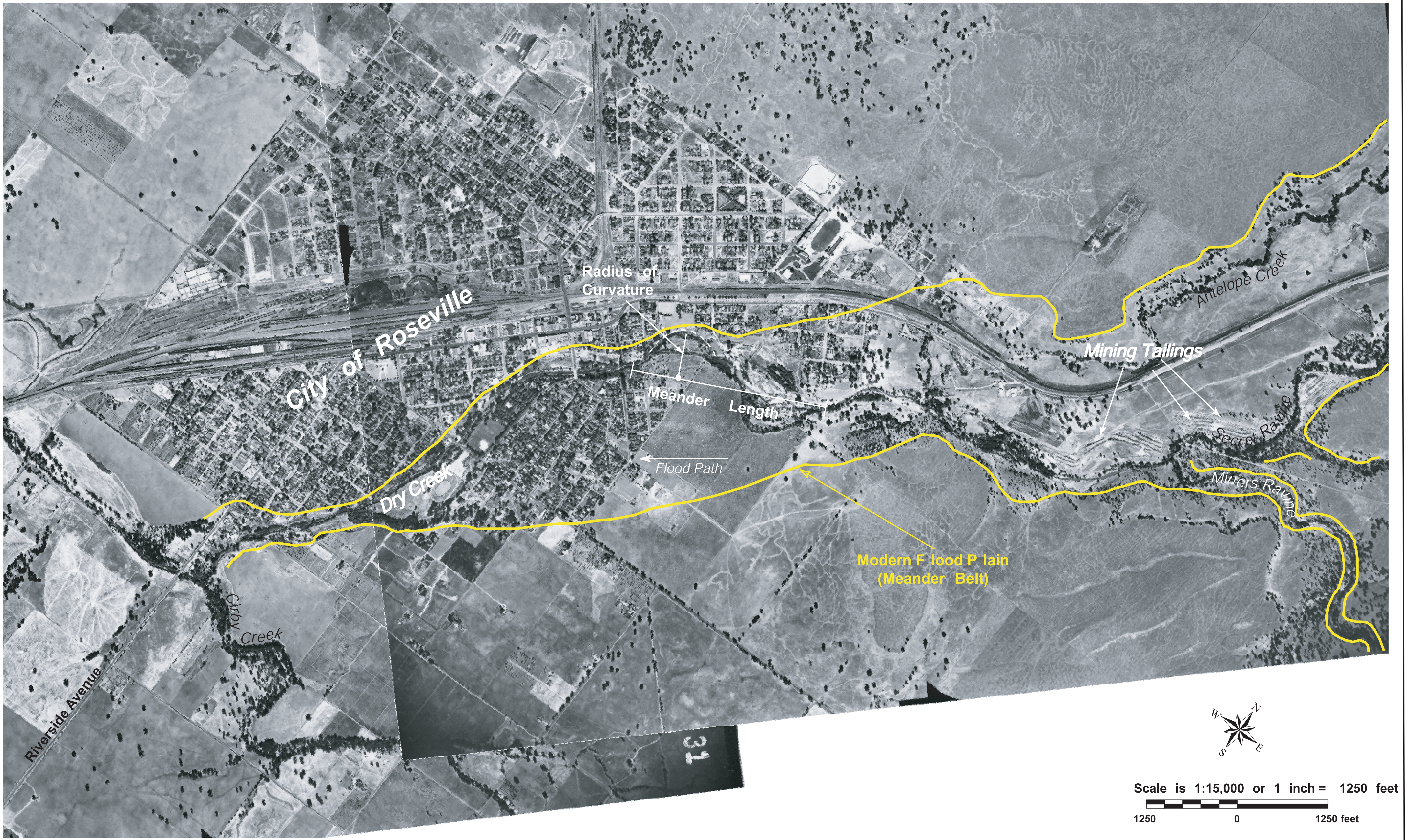

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Figure 4: 1940 aerial of Dry Creek watershed as it flows through the City of Roseville, California.

profile and capacity by incision. From a flood control perspective, channel incision lowers the water surface elevation of a flood event, decreasing the frequency and magnitude of overbank flows. However, channel incision or local scour exposes the banks to further erosion, contributes fine sediment to the channel downstream, and negatively impacts the ecological value of the stream system.

The channel's geometry (width and mean depth) and pattern as measured in the field will generally correlate well with the drainage area in a given geographic region that shares similar climate and geology. The power of analyzing channel geomorphology and channel forming flows lies in the understanding of existing and potential stable channel forms and associated processes. A regional stream geometry analysis has been conducted to determine the local relationship between drainage area and bankfull stream geometry. **Figure 5** is bankfull geometry data collected within the field from the project reach and within other nearby watersheds to determine a regional relationship. Based on the data collected in Dry Creek downstream of the Douglas Blvd crossing and the additional regional data, the bankfull geometry of a watershed with basin area of 57 mi^2 should be on the order of:

Bankfull width ≈ 60 ft
Bankfull depth ≈ 4.0 ft
Bankfull cross-section area ≈ 300 ft^2

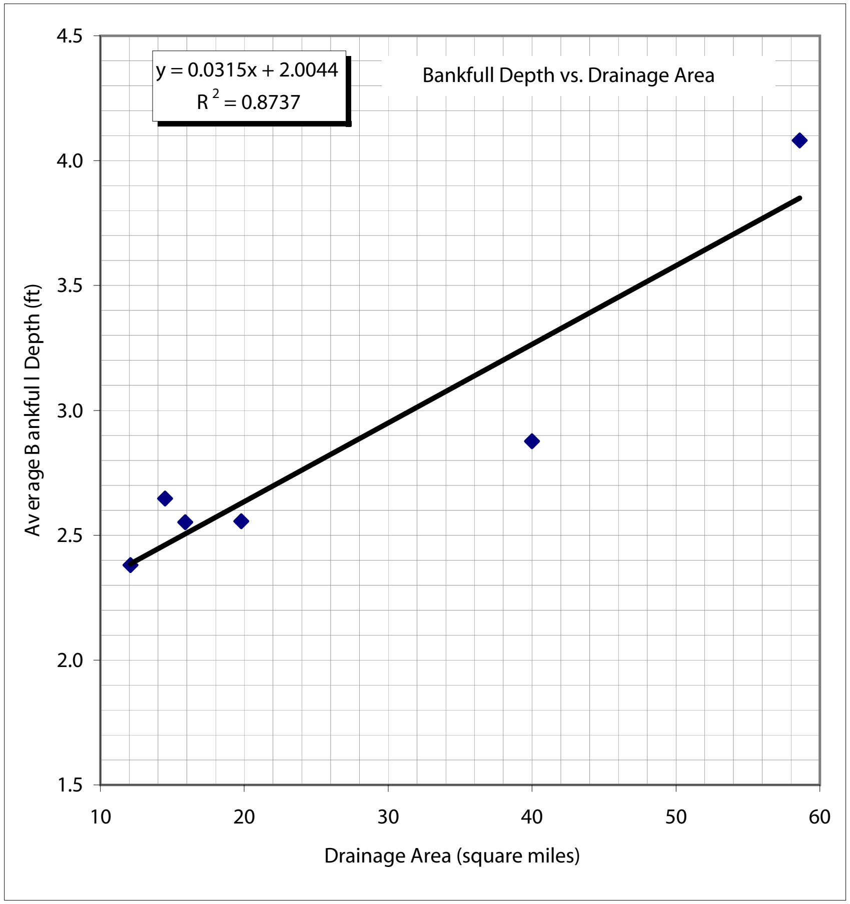
However, in many locations within the subject reach the channel has been significantly incised. Based on the visual observation of seven cross-sections, the low flow channel geometry appears to be significantly larger that what we would anticipate. The low flow channel was identified using the cross-sectional data collected in the field and determined by the shallowest bench within the channel. The shallow bench identified in many locations within the subject reach is assumed to be a remnant terrace deposit, illustrating the significant incision of the channel profile. **Table 3** provides the location and the respective geometry observed and illustrates the significant enlargement of the low flow channel relative to the anticipated bankfull geometry.

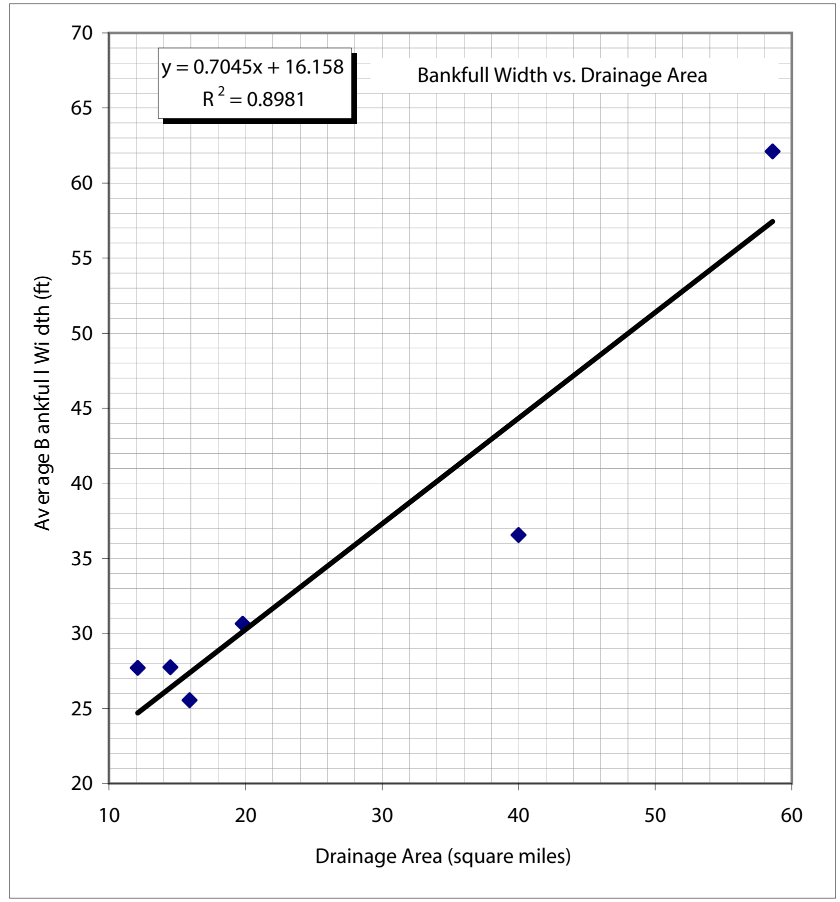
Table 3. Low flow channel indicators from SHG cross-sections were used to sample 7 locations within the subject reach. The respective discharge and channel geometry were provided by revised FEMA HEC-RAS model (Swanson Hydrology 2002).

Cross-section location (FEMA station)	Low flow channel width (ft)	Low flow channel area (ft^2)	Average low flow channel depth (ft)	Bankfull velocity (ft/s)
72982	74	588	7.9	5.1
74898	92	590	6.4	3.6
76150	61	503	8.2	5.0
76871	79	462	5.8	5.4
80434	82	584	7.1	4.3
81379	64	404	6.3	5.0
Low flow channel average	**75**	**521**	**7.0**	**4.7**
Bankfull channel	*60*	*300*	*4.0*	

A comparison of the low flow channel and bankfull geometry illustrates a relatively confined channel width with slight expansion laterally, but an average channel depth and cross-sectional area nearly two times greater than the bankfull flow needs. The significant incision is the result of continual scour at the toe of the lower bank.

The resiliency of Dry Creek can be observed at a number of locations where some space and freedom exists to restore morphological complexity. For example, upstream of the Cherry Street grade control, the low flow channel has developed a meander, which allows for sorting of sediment grain sizes, bar formations, and an increase in the low flow channel length. Recent attempts by the river to restore its





Site	Location	Thalweg Slope (%)	Low water Slope (%)	Bankful Slope (%)	Bankfull Width (ft)	Bankfull Depth (ft)	Drainage Area (sq mi)
Miners Ravine	below Auburn Folsom Rd	0.78	0.48	0.63	27.7	2.38	12.1
Miners Ravine	below Sierra College Blvd	0.30	0.56	0.52	27.8	2.65	14.5
Secret Ravine	above Rocklin Road	0.92	0.90	0.98	25.6	2.55	15.9
Secret Ravine	at Roseville Parkway	0.48	0.45	0.34	30.7	2.56	19.8
Dry Creek	below Miners/Secret confluence	0.77	0.45	0.37	36.6	2.88	40.0
Dry Creek	downstream of Douglas Blvd	0.52	0.23	0.39	62.1	4.08	57.6

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Figure 5: Average bankfull depth and width (feet) as a function of drainage area (square miles) from field data collected in the Dry Creek Watershed in the Central Valley of California. The creeks drain the foothills of the Sierra Nevadas east of Sacramento and are tributary to the Natomas Main Drainage Canal.

meandering characteristic is obvious in locations where the flow pattern is focused preferentially toward one bank, inducing pool scour and bank erosion. The opposing bank experiences sediment deposition and the formation of a point bar, indicative of the process of meander formation. This is especially obvious downstream of Douglas Boulevard, where upstream the channel has been extremely straightened and confined and at Douglas Boulevard the channel widens (**Figure 6**). This is currently a location of sediment aggradation due to channel widening and decrease in slope. Sediment bars are temporarily formed, causing deflection of flow toward the right stream bank (viewing downstream), creating toe scour and pool formation by hydraulic eddies.

5.4 Watershed Land Use History and Effects on Dry Creek

Over the past 150 years, there have been three distinct phases of watershed land use impacts that have significantly altered the natural characteristics of the Dry Creek stream reach through the City of Roseville and are responsible for the unstable channel conditions seen today, including:

- Extensive placer mining of the upper watershed
- Agricultural and urban encroachment of the natural flood plain
- Rapid urbanization of the watershed over the past 40 years.

The timeline presented in **Table 4** summarizes the major climatic or land use changes that have impacted the subject reach of the Dry Creek Watershed. The recent historic climatic and land use changes have resulted in three distinct geologic layers that compose the stream banks of the Dry Creek project reach. Approximately 10,000 years ago during the Pleistocene glacial retreat, streams and rivers draining the Sierra Nevada were much larger, with significantly more water and much greater sediment transport capacities. Large well-rounded cobbles and boulders were mobilized during glacial retreat, a streambed deposit that has been exposed at the base of the Dry Creek channel in many locations (**Figure 3**).

Table 4. Chronology of key climatic and land use changes within Dry Creek Watershed.

Year	Event	Impact to Dry Creek and fluvial valley
10,000 years before present	Pleistocene Glaciation of the Sierra Nevada	Relatively wetter colder climate. Increased sediment delivery and deposition. Flows capable of transporting large sized cobbles (seen at the toe of eroded channel sites).
1,000 years before present	Holocene	Warmer climate, decreased sediment transport capacity, therefore smaller sediment load and grain size deposited in subject reach. Dry Creek most likely contained within a defined meander belt.
1840-1880s	Hydraulic Mining	Miners Ravine and some areas in Secrets Ravine, heavily mined for gold. Large amount of fine material (sand and silt) transported and deposited along subject reach. Exposed debris layers as much as 20 ft thick in some eroded areas. Aggradation during hydraulic mining may have produced a braided stream at the subject reach.
1914	Lincoln Highway	Lincoln Highway crossing at Riverside Avenue constructed. May have constricted channel width and/ or altered channel grade.
1940	Aerial photograph	As explained in **Figure 4** and text. Natural meander belt indicated on figure, flood plain encroachment and channel straightening begins in City limits.
1955	Flood	Major flood event in Northern California.

Year	Event	Impact to Dry Creek and fluvial valley
1956	Aerial photograph	Photo taken the Spring following the December 1955 flood. Significant deposition apparent upstream of the project reach located south of the intersection of Atlantic Ave and I-80. Active aggregate in stream mining evident at this location, altering the grade and sediment transport capacity upstream. The channel width through Roseville has been confined and straightened by the construction of 3-foot bridges along Royer Park and Douglas Blvd bridge, limiting channel meander potential. Development encroachment of the Oak Street parking lot and Veterans Memorial building. Locations of channel bar development through confined reach adjacent to Royer Park.
1960	I-80	Completed.
1970	Development boom and drought	Growth in Roseville area increases to approximately 6% per year. Drought of the 1970's decreased surface water flows and storm events. Channel reach stabilized by riparian vegetation and flood plain encroachment.
1982	Flood	A series of tropical storms roared through the state that month, causing flooding throughout California. In Sacramento, nearly 10 inches of rain fell in an 11-day period.
1986	Development	Up to 10% impervious surfaces and approximately 20% urbanization.
1995	Flood	In 1995, heavy rains in January and March fell on the Sacramento Valley causing widespread localized flooding throughout the state, including Arcade, Morrison, Florin, Unionhouse and Dry Creeks in Sacramento.
1997	Flood	Significant floods in Northern California.
2001	Development	Estimated 18% impervious surfaces and 40% of the watershed urbanized.

Human activities have resulted in significant land use changes within the Dry Creek Watershed over a relatively short time period. The first major human alteration to the Dry Creek stream channel was the extreme increase in sediment loads during placer and hydraulic mining in the 1840s and 1850s. Miners Ravine Watershed contained a substantial deposit of the gold-laden auriferous river gravels and was occupied by numerous mines where the ancient stream channels were dug and mined for gold. The operations involved diversion of flow from the stream into trenches of alluvium from which gold was sorted and sluiced by gravity. These operations significantly enlarged the original channel and flood plains in the mining locations, releasing large volumes of nutrient-poor sand downstream. The organic rich and productive native topsoils historically covering the valley floor were buried by over 20 feet of unconsolidated sand in many locations within the lower watershed of Dry Creek (**Figure 7**). This deep mass of unconsolidated sand is apparent throughout the Sierra Nevada foothills and is currently the material that composes the banks of the stream channels such as Dry Creek.

Shortly following the Gold Rush era foothill towns began to develop. The City of Roseville appears on maps as early as the 1870s and agriculture was prevalent along Dry Creek at the turn of the century due to the adjacent water supply in a relatively arid summer climate. A 1940 aerial photograph shows a number of cultivated fields bordering the subject reach of Dry Creek (**Figure 4**). Agriculture and urban development resulted in the initial channelization of Dry Creek through the City of Roseville, increasing in stream erosion, channel incision and the disconnection of the stream from its natural flood plain. The meander belt of Dry Creek was mapped on the 1940 aerial to indicate the area within which the historic stream formed and abandoned channels. The natural geometry of the subject reach was characterized by significant meander bends with wavelength on the order of 2000 feet, apparent in the few meanders that

Close-up Photo of Site 29R

Photo of Site 29R looking downstream

Figure 6 - Composite Failure

Site 29R is located downstream of the Douglas Boulevard Bridge. A sudden decrease in bed slope, coupled with a wider channel relative to the adjacent reach upstream, allows elevated stream flows to decrease both water depth and velocity in this location. These hydraulic characteristics result in sediment deposition and bar formation on the left side of the channel. The presence of the bar diverts low flows into the exposed, unvegetated bank (shown in the close-up above), causing chronic undercutting at the toe and slab failure of the lower bank. This is a natural response to re-establish a meander, increase channel length, and create geomorphic complexity. The upper bank is composed of loose, sandy hydraulic mining debris and experiences chronic shallow failure. Future bank stabilization at this site will preserve the established meander pattern while providing bioengineering toe protection to reduce bank erosion.

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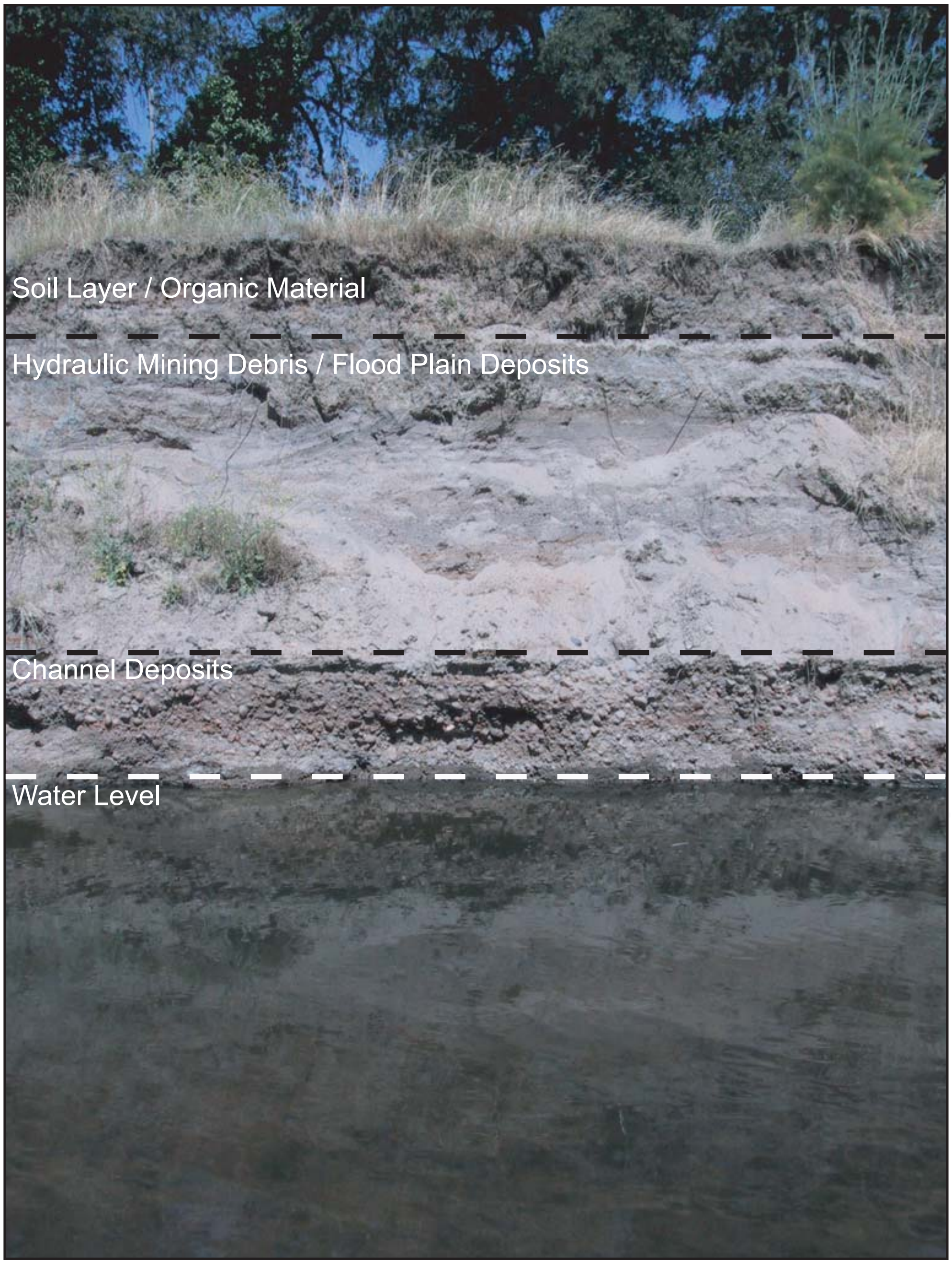

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Figure 7: Photo illustrating the three distinct geologic materials composing the Dry Creek stream banks. (Taken Spring, 2002 at Erosion Site 29R.)

were present in 1940. The modern channel is attempting to restore its natural meander pattern, and thus is susceptible to significant bank erosion within the historic meander belt.

The rapid urbanization of the surrounding watershed over the past 30 years has maintained the channelized nature of the Dry Creek reach, in addition to increasing the duration and magnitude of flood flows as a result of impervious surfaces and storm sewer systems. The significant urban development boom in the Roseville area and surrounding watershed began in the early 1970s and continues today, where urbanization rates have been on the order of 4% per year (Montgomery Engineering, 1992). Development of a watershed significantly increases impervious surfaces (roads, parking lots, roofs, etc), reduces vegetative cover, compacts soil, reduces areas of depression storage ,and dramatically increases the rate of delivery and total volume of storm runoff. The hydrologic effect of converting land cover from grassy hillslopes to hundreds of acres of impervious pavement and efficient storm drain systems has been dramatic. The seasonal hydrograph of an urbanized stream displays increased peak flows due to more efficient delivery of water to the channel. Prior to development, channels were formed and sized by the 2-year flood. Estimates suggest that 10 to 20 percent watershed imperviousness may increase the discharge of the 1.5-yr flow as much two to three times (Hammer 1972). Neller (1989) conducted a historical analysis of urban catchment morphology of 15 channels in New South Wales and found nearly a four-fold increase in channel size to accommodate the increased discharges. While this is a general relationship, the magnitude of the response of the channel to urbanization will be highly variable and sensitive to watershed context and water conveyance characteristics of the developed areas. The combination of increased flows and the disconnection of the river from its flood plain exacerbate the problem of channel incision. Flows that naturally would exceed the capacity of the bankfull channel, three to five-year flows and above, are now contained within the channel, increasing the erosive capacity of storm runoff events (Neller 1989). According to Andy Marrow of Placer County Flood Control Agency, the Placer County General Plan is perhaps 90% complete and using these estimates, 18% of the subject watershed for this study is currently covered with impervious surfaces. Dunne & Leopold (1992) have suggested that the impacts of urbanization are not limited to the extent of impervious surfaces. Channel removal and routing to gutters, storm drains and culverts also significantly increase the frequency and magnitude of storm volumes. Therefore, an estimated 18% impervious surface cover can be interpreted as approximately 40% urbanization of the subject watershed (Dunne & Leopold, 1978).

Collectively, the land use changes have resulted in the following existing conditions observed within Dry Creek:

- Stream banks are composed primarily of unconsolidated, highly erodible sands as a result of hydraulic mining.
- The loss of natural meander patterns due to channelization has increased water velocities and erosive power, shortened the overall stream length, and steepened the gradient.
- Storm runoff magnitudes have been significantly increased due to urban development and increases in impervious surfaces. In addition, the natural channel forming flow (1.5-yr recurrence interval) is a larger discharge, increasing the sediment transport and erosive capacity of storm flows within the channel.
- The need for flood protection has increased the size and discharge capacity of the stream channel and limited the natural process of overbank flow. The larger channel has also contributed to the increased erosive power of higher flows and the resulting bank erosion and streambed incision.

6. RESULTS OF FIELD SURVEY

The field surveys consisted of channel stability assessment; individual sites exhibiting excessive bank erosion or past bank protection efforts were identified and cataloged. The channel stability assessment was conducted for the entire project reach and has been indicated on the GIS maps provided as **Figures 8A-8G**. Also mapped on **Figures 8A-8G** are the channel erosion sites mapped on a recent aerial

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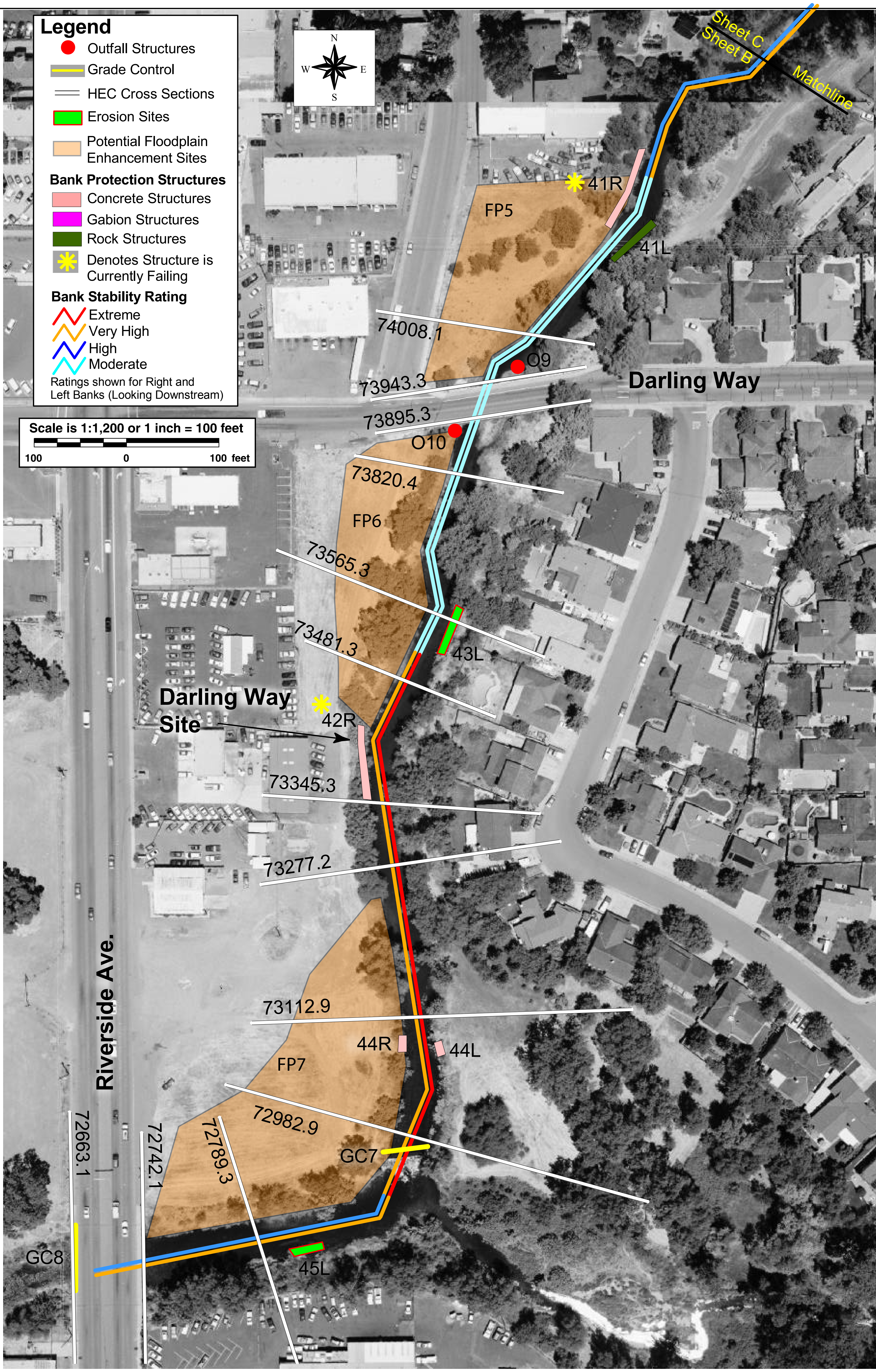

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Dry Creek Urban Stream Restoration Project

City of Roseville
Placer County, CA

Basemap

Figure 8-B

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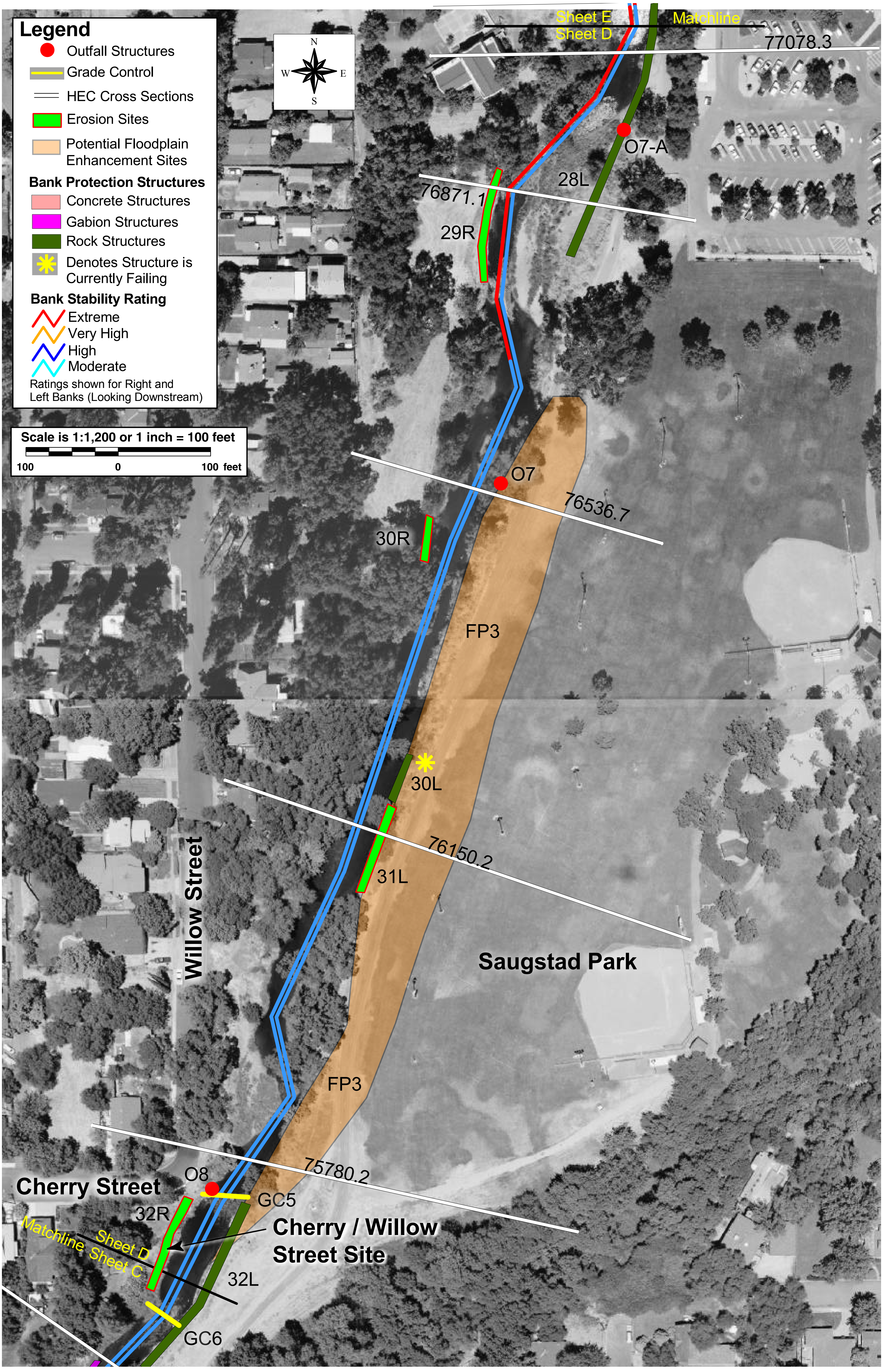
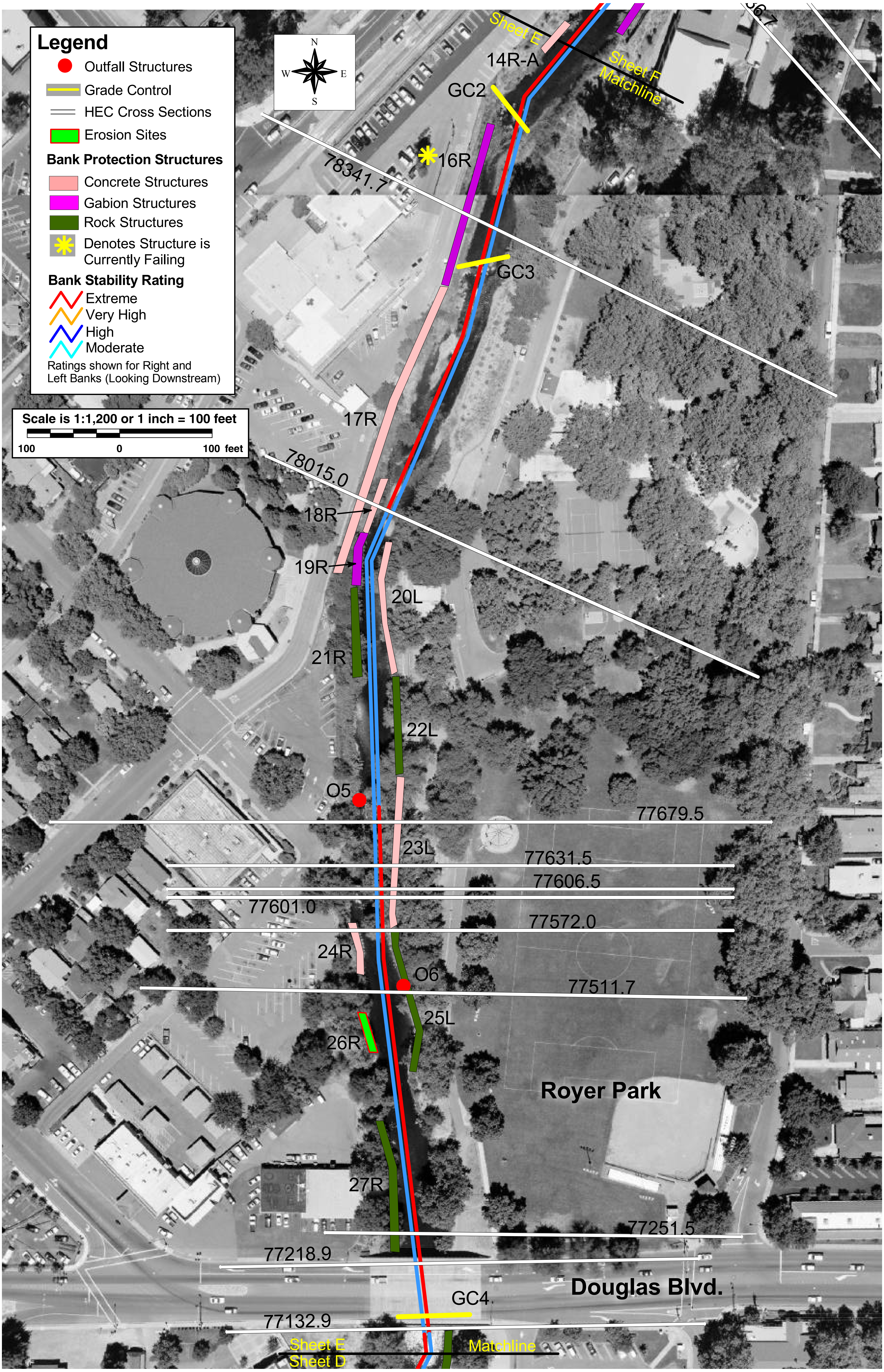


Swanson Hydrology & Geomorphology 115 Limekiln Street, Santa Cruz, CA Tel: 831-427-0288 Fax: 831-427-0472	Dry Creek Urban Stream Restoration Project	City of Roseville Placer County, CA	Basemap	Figure 8-D



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Dry Creek Urban Stream Restoration Project	City of Roseville Placer County, CA	Basemap	Figure 8-E

Figure 8-F

Basemap

City of Roseville
Placer County, CA

Dry Creek Urban Stream
Restoration Project

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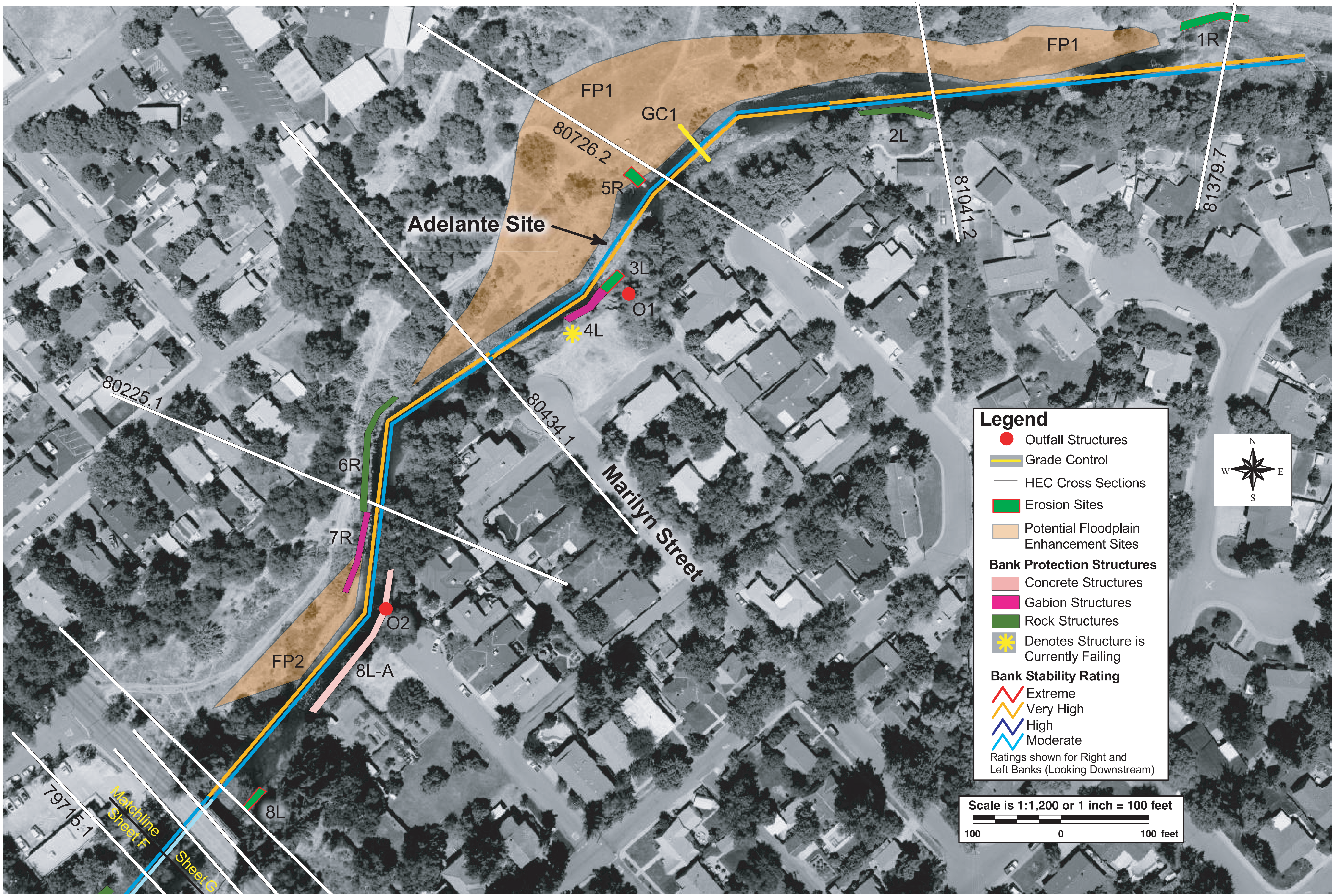

Figure 8-G

Basemap

City of Roseville
Placer County, CA

Dry Creek Urban Stream
Restoration Project

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photograph and whose dimensions were estimated in the field. **Table 5** presents the detailed information gathered at each of the existing untreated erosion sites, and **Table 6** presents similar data for sites where previous bank stabilization efforts have been performed. The complete inventory of bank failure and existing bank protection sites is included as **Appendix B** (presented in digital format). The inventory provides photographs of each site, summarizes the observations made at each of the primary erosion sites, classifies the type of erosion, and hypothesizes as to the primary cause and mechanism. We also identify our opinion of the ideal channel geometric structure, given all existing constraints, and indicate why any previous stabilization efforts may have failed. Below we provide background concerning the primary mechanisms of bank failure observed in Dry Creek, prior to reviewing the details of the channel stability assessment and the bank erosion survey.

Table 5: Erosion Sites without Stabilization Efforts (7% Total Bank Distance)

Site #	Length (ft)	Height (ft)	Angle (degrees)	Material Type	Veg Type	Veg Coverage (%)
01R	72	8	70	SA/GR		0
03L	32	20	90	SA	GRS	5
08L	27	6	80	SA	GRS	10
11R	12	N/A	N/A	SA	GRS/TR	40
26R	70	10	70	SA	TR	10
29R	223	15	70	SA	GRS	10
30R	81	10	80	SA	GRS	5
31L	108	15	85	SA	GRS	40
32R	100	10	60	SA	GRS	60
34L	40	7	70	SA	TR/SH	60
35L	66	12	70	SA	AN	30
36R	105	15	80	SA	AN/BB	60
37L	117	15	60	SA	AN/GRS	30
38L	77	15	80	SA/GR	GRS	10
43L	150	15	80	SA/SI	GRS/SH	30
45L	47	20	80	SA	BB/AN	60

CC = Concrete	RSP = Rock Slope Protection	BO = Boulders	TR=TREES
CO = Cobble	ASPH = Asphalt	SA = Sand	GRS=GRASS
SI = Silt	AN=ANNUALS	GR = Gravel	SH=SHRUBS
BB = Black Berry Bush	WD=WOOD		

See Appendix B for a complete description of all sites.

Understanding how and why a slope or stream bank has failed are essential to the selection of an appropriate bank protection strategy. The particular mechanism or mode of failure is a result of the applied load, the properties of the bank material, the slope geometry and the influence of water. The base deposit present in the stream banks of Dry Creek is poorly sorted, fairly well consolidated channel deposits, with grain sizes ranging from silt and clay to large well-rounded cobbles (**Figure 7**). This deposit is indicative of the high-energy hydrologic environment following the last glacial maximum

Table 6: Erosion Sites with Stabilization Efforts

	Site #	Length (ft)	Height (ft)	Angle (º)	Material Type	Veg Type	% Veg Coverage	Treatment Type
Stable Sites (19% of Total Bank Distance)	02L	110	15	50	RIP RAP	BB	60	RIP RAP
	04L	57	8	80	CO		0	GABION
	06R	225	15	90	METAL		0	CRIB W/ RSP TOE
	07R	44	12	90	CO		0	GABION
	8L-A	180	15	45	BO	SH	95	CC SLABS
	10R	69	6	60	RSP	GRS	60	RSP
	12L	175	12	90	CO	AN	10	GABION
	13L	50	12	50	SLABS	GRS	30	CC SLAB 6' DIA
	14R	45	20	45	BO		0	RSP
	14R-A	40	16	50	CC	AN	80	SMALL RIP RAP
	15L	224	12	70	CO/BO	AN	30	GABIONS W/ ROCK TOE
	17R	312	10	90	CC/WD	GRS/TR	50	CC WOOD WALL @ TOP
	18R	34	15	70	SLABS	BB	70	CC SLABS
	19R	55	12	60	CO	BB	5	GABION
	20L	270	6	60	CC	TR	60	CC PIECES
	21R	105	10	45	BO	TR	40	SMALL RSP
	22L	54	10	45	BO	BB	5	RSP
	23L	150	12	45	CC	TR	15	CC SLABS
	24R	56	8	45	CC	TR	30	CC SLABS
	25L	206	12	45	BO		0	RSP
	27R	160	12	50	BO	TR	30	RSP
	28L	328	6	30	BO	GRS	20	RSP
	32L	195	15	60	BO		0	RSP
	40L	77	12	80	CO/BO	GRS	15	GABION RSP TOE
	41L	50	11	65	BO	GRS/BB	75	RSP
	44L	38	15	45	BO/CC	SH	5	GROUTED RSP
	44R	38	15	45	BO/CC	SH	5	GROUTED RSP

Table 6 (continued): Erosion Sites with Stabilization Efforts

	Site #	Length (ft)	Height (ft)	Angle (^{o})	Material Type	Veg Type	% Veg Coverage	Treatment Type
Failing Sites (6% of Total Bank Distance)	04L	57	8	80	CO		0	GABION
	09L	57	15	90	CC	GRS	10	CC WALL CC TOE
	10R-A	350	16	70	RIP RAP	SH	80	RIP RAP
	16R	234	30	90	CO/CC		0	GABION TOE, CC WALL
	30L	150	12	50	CC	AN/GRS	40	RSP
	33R	49	12	90	GR/CO	BB	60	GABION
	39L	28	7	70	CO/BO	W/BB	30	RSP/GABION
	41R	140	20	70	CC/ASP	GR/TR	40	ASPHALT & SACKCRETE
	42R	50	8	50	CC	TR/AN	40	CC SLABS

CC = Concrete	RSP = Rock Slope Protection
CO = Cobble	ASPH = Asphalt
BO = Boulders	TR=Trees
SA = Sand	GRS=Grass
SI = Silt	AN=Annuals
GR = Gravel	SH=Shrubs
BB = Black Berry Bush	WD=Wood

See Appendix B for a complete description of all sites.

nearly 20,000 years ago. The hydraulic mining debris is a thick unconsolidated well-sorted sand layer, with a small clay component and relatively low cohesion. The organic topsoil present along Dry Creek has both a large fraction of clay and vegetation roots, which increase stability. Based on the characteristics of each of these soil types, the slope of the stream bank at which failure will occur is very different for these three distinct units. Locations where bank material actually overhangs are characteristic and can be observed in either the channel deposits or the organic topsoil layer. Many bank failures will occur during the wet winter months due, in general, to either the increase in the slope mass during saturation, and/or the increase in pore pressure and the ability of water to separate the interconnectedness of individual soil grains, allowing a failure plane to form. Below we discuss four common types of bank failure, though the primary type observed along the banks of Dry Creek is composite failure. **Figure 9** provides a schematic of each of the failure types discussed below.

Shallow failure

Shallow failure occurs when loose bank material at the surface of the stream bank slides and rolls down the bank face (**Figure 9A**). This is the most easily identifiable failure on Dry Creek. Banks can be observed with unconsolidated sand maintaining a slope angle of approximately 35°, the angle of internal friction (Φ) for sand. The sandy hydraulic mining debris chronically fails by the gradual loosening of individual grains that slide parallel to the slope. The erosion of material by water flow at the toe of the stream bank increases the slope angle of the sandy deposit and perpetuates chronic erosion. During large rainstorms or after high creek levels, unvegetated sandy banks may fail at angles as low as 20°, well below the angle of internal friction. This is because the weight of the material on the bank has significantly increased and seepage pressure of the water counteracts the normal stress maintaining stability. Shallow failures can be observed at erosion sites E25 as shown in **Figure 10A**.

Planar failure

Planar failure occurs when a block or wedge of compacted sandy soil slides downwards along a planar failure surface (**Figure 9B**). Due to the consistently coarse nature of riverbank material and the predictable undercutting that occurs at riverbanks, planar failure is the most common failure mechanism for eroding riverbanks (Thorne, 2000). Planar failure occurs in Dry Creek during wet conditions when the sandy hydraulic mining deposit becomes slightly cohesive and slips as a unit of material rather than grain by grain, as it does during dry conditions (i.e. shallow failure).

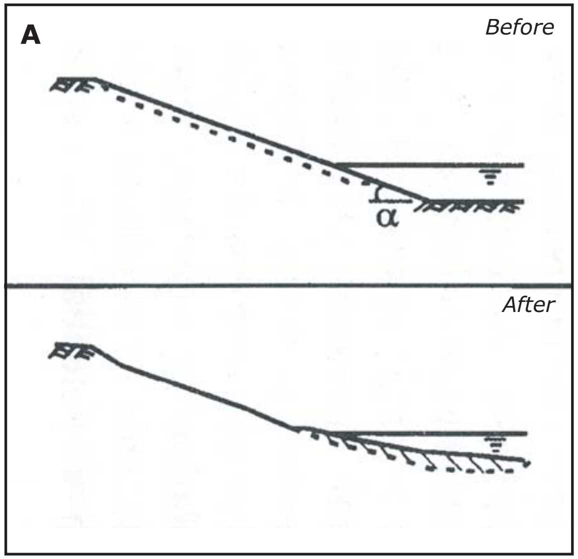
Slab failure

Slab failure is prevalent on steep or near vertical banks when cohesive, clay rich material is present. Large portions of bank material dislodge intact and fall to the base of the stream bank. The erosion of the organic soil layer in Dry Creek fails by slab failure, and blocks of this material can be seen at the toe of the bank with bank top vegetation still intact. **Figure 10B** illustrates the overhang of the organic soil layer due to undercutting at a meander bend. When the shear strength is exceeded by the shear stress, the material will fail via slab failure.

Composite failure

Composite bank failure occurs when independent failure mechanisms influence the different soil layers composing the bank. The presence of three distinct geologic deposits in the Dry Creek stream banks makes composite failure quite common. Composite failure is common where cohesive topsoil overlays a non-cohesive gravel and sand layer. The sand layer erodes at a much higher rate (by shallow and planar failure) than the organic rich units above. Eventually the surface layer is undercut at such an extreme angle that an overhanging bank remains suspended at the top of the bank (**Figure 9C**). Eventually the blocks of soil topple into the channel and can remain intact at the foot of the bank with vegetation still present. The erosion present at both 29R (**Figure 6**) and 38L (**Figure 10B**) are classic examples of composite failure observed within the subject reach.

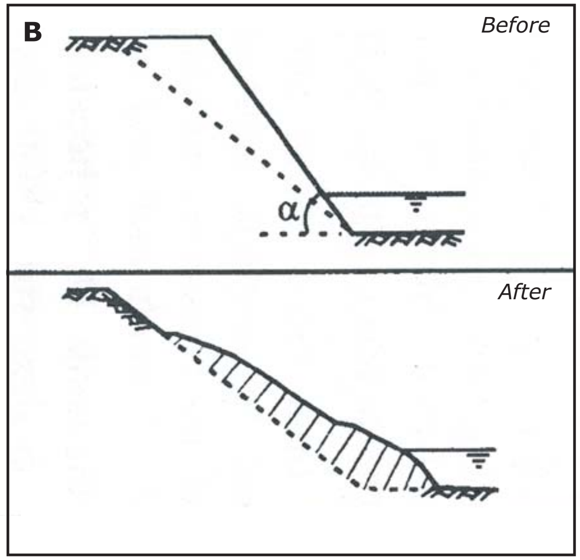
SHALLOW FAILURE



Shallow Failure Characteristics include:

- Shallow bank angle, α.
- Usually in non-cohesive banks.
- Failure nearly parallel to slope at $\alpha = \phi'$ (angle of internal friction).
- Water seepage from bank can substantially reduce stable α.
- Vegetation will normally help stabilize against failure.

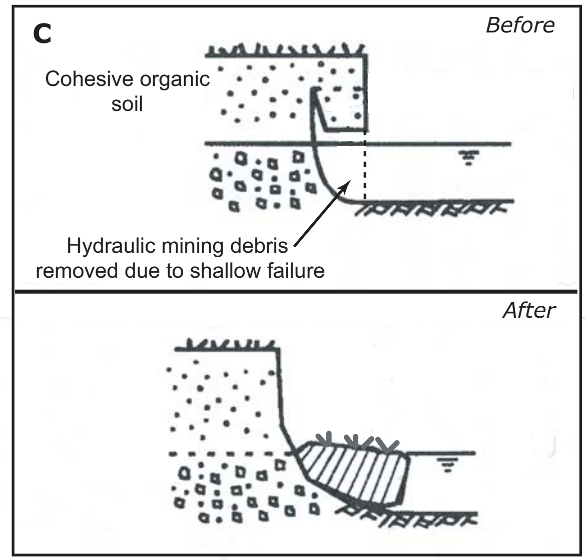
PLANAR FAILURE



Planar Failure Characteristics include:

- Steep or vertical bank angle, α.
- Frequently (but not always) in non-cohesive banks.
- Water table/channel water level usually low relative to bank height.

COMPOSITE BANK FAILURE



Composite Bank Failure Characteristics include:

- Occurs where upper cohesive layer overlies erodable sand/gravel.
- Bottom layer erodes and fails due to shallow failure mechanism.
- Top layer fails by sliding and/or toppling, known slab failure.
- After failure, slab usually remains intact at base of bank with vegetation.

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Figure 9: Mechanisms and characteristics of common bank failure. The primary mechanism observed in the Dry Creek project reach is composite bank failure. Adapted from Hey et al, 1991.

Photo of Site 25L (See Figure 8-E)

Figure 10a - Shallow Failure
Channel incision and floodplain encroachment have resulted in an over steepened bank at Site 25L. The unconsolidated sandy hydraulic mining debris on this steep slope continues to erode by slow particle loss i.e. shallow failure

Photo of Site 38L (See Figure 8-D)

Figure 10b - Slab Failure
Site 38L is a classic example of toe undercutting of the outer bank at a meander bend in Dry Creek. Undercutting over steepens the unconsolidated bank material and exacerbates both slab and planar failure.

7. Bank Stability Survey

The bank stability survey was conducted for the entire subject reach and both the right and left banks were assigned an erosion potential rating, which ranged from very low to extreme based on the analysis described in Section 2. The results are spatially presented on an aerial photograph in **Figures 8A-8G**. **Table 7** provides a statistical analysis and summary of the bank stability results, illustrating that none of the subject reach was characterized with low or very low erosion potential. Approximately 34% of the entire subject stream reach (for both the right and left banks independently) was identified to have either very high or extreme erosion potential.

Table 7: Bank Stability Survey Results Summary

Stream Bank	Bank Erosion Potential	Linear Feet	% of Subject Reach	Stream Bank	Bank Erosion Potential	Linear Feet	% of Subject Reach
Right	Very Low	0	0%	***Left***	Very Low	0	0%
	Low	0	0%		Low	0	0%
	Moderate	996	11%		Moderate	1242	14%
	High	4940	55%		High	4611	52%
	Very High	1789	20%		Very High	1891	21%
	Extreme	1209	14%		Extreme	1190	13%
	Total	**8934**	**100%**		**Total**	**8934**	**100%**

8. Erosion Site and Existing Bank Protection Survey

The inventory of all of the identified erosion sites within the Dry Creek reach is provided as **Appendix B**. **Appendix B** provides photograph(s) of each site and a brief summary of existing conditions and potential feasible repairs or corrective measures. Sites are separated into those that have and those that have not received stabilization efforts. All site-specific data and recommendations provided in **Appendix B** are based on limited observations and qualitative analysis performed in the field. The recommendations provided are very general, due to the limited scope of this study and the vast number of sites investigated. The project development procedures outlined in Section 10 should be consulted before an actual project is considered for implementation.

Table 5 lists all of the existing erosion sites that currently have not received any bank protection treatment and summarizes existing physical conditions. **Table 6** lists all of the sites with existing bank protection structures and provides detailed information concerning their geometry, materials, and current conditions. Sites within **Table 6** are divided according to the success or failure of past efforts at stabilization. A successful site was considered to be one that provided long-term slope stability and included a reasonable amount of habitat enhancing elements such as shade, channel complexity, and vegetation, without creating adverse destabilizing effects on adjacent banks.

Table 8 provides a selection of areas exhibiting the potential for flood plain enhancement opportunities. These areas were chosen based primarily upon our knowledge of existing land use constraints and site conditions. For each of the sites chosen, the potential area of enhancement and potential increase in flood plain storage volume are calculated. Flood plain storage volumes are calculated assuming the creation of a flood plain bench at an elevation associated with the bankfull flow depth.

Existing Failed Bank Protection Structures

A number of erosion sites observed within the project reach are the direct result of the failure of previous bank protection projects. **Table 6** summarizes the specifics of each existing bank protection structure. Many bank restoration efforts previously conducted within the project reach of Dry Creek have been conducted with a very narrow objective in mind: to stabilize bank erosion at a particular location. As the field of stream restoration continues to improve, much can be learned from historic 'narrow' approaches to bank stabilization. For instance, the placement of poorly designed rip-rap to armor an eroding bank has the potential to disperse or transfer the energy of the steam to a different location. In addition, concrete riprap does not satisfy the goal of habitat enhancement and actually minimizes the establishment of riparian habitat and natural aesthetic values (**Figure 11A**).

Table 8: Floodplain Enhancement Opportunities

Floodplain ID (see Figure 8)	**Area (sq.ft)**	**Potential additional floodplain storage provided (acre-ft.)**	**Description**
FP1	75,399	6.9	Site is located along right bank adjacent to Adelante High School, at location selected for Adelante Restoration Project
FP2	9,786	0.9	Publicly owned parcel located on right bank along access road to Adelante Restoration Site. Site is partially constrained by existing dirt road.
FP3	56,655	5.2	Strip of left bank along Northern Saugstad Park. Area contains exiting utilities and may be site of old landfill.
FP4	51,891	4.8	Strip of left bank along Southern Saugstad Park. Area contains exiting utilities and may be site of old landfill.
FP5	28,918	2.7	Vacant parcel located on right bank, just north of Darling Way. Site is partially constrained by bridge and may have existing utilities present.
FP6	29,380	2.7	Narrow strip of right bank just South of Darling Way bridge. Location of proposed Darling Way Restoration Site.
FP7	51,620	4.7	Flat vacant parcel located on right bank at confluence with Cirby Creek., just upstream of Riverside Ave. bridge.

Typically, a failed bank protection structure exhibits one or more of the following characteristics:

- Erosion of material from behind the structure by seepage piping.
- Corrosion or fatigue of structural materials.
- Structural failure of bank protection materials or foundation soils.
- Flanking caused by eddy formation and turbulence at end points.
- Undercutting at toe, due to localized scour or channel incision.
- Transfer of erosive forces to adjacent bed and banks.

Photo of Site 23L (See Figure 8-E)

Figure 11a - Bank Protection Failing
While rip-rap may provide relatively long-term stability for the subject bank failure, the energy focused at amored sites can be dispersed and influence adjacent sites if not carefully designed. In addition, cemented rip-rap does not fulfill the habitat enhancement objectives for overall reach enhancement.

Photo of Site 4L (See Figure 8-G)

Figure 11b - Bank Protection Failure
This failed gabion at site 4L illustrates a local 'band aid' solution that is likely to perform poorly in the context of local geomorphology. This structure was most likely placed to protect against toe erosion occurring on the outside of the left bank bend. However, it addressed only one spot instead of the entire outside maeander bend and appears to not smoothly transition into the upstream or downstream banks.

An example of a failed retaining structure can be observed at the Adelante High School Site (**Figure 11B**). This gabion basket retaining wall was constructed to protect and support the steep bank behind it, now observed to be well vegetated. It appears the wall was placed along the stream bank with square ends protruding into the direction of flow. The large scour hole and eroded bank at the upstream end of the gabions suggests eddy formation and deflection of flows beneath and around the structure and into the unprotected bank. The toppled appearance of the gabion wall suggests that scour at the toe caused the slumping of the upstream portion of the structure. It appears that future similar design efforts could benefit from consideration of the following principles:

- The footing of new structures must be set below the maximum scour depth of the creek so that even during and after high flows, the foundation remains intact.
- Walls and hard structures should be smoothly transitioned into the upstream and downstream banks, to minimize eddy formation and reduce the risk of flanking.
- Rock structures should use angular quarry rocks that absorb energy and resist sliding and rolling, as compared to rounded cobble.
- Flexible vegetated rock slope protection is superior to a semi-rigid wall design, as it can absorb minor failures by deformation.

Figure 12 is an example of a successful combination of a hardscape retaining structure that has been modified to include the ecological benefit of the riparian alders. Future strategies in bank protection should consider the benefit of bioengineered alternatives to cement retaining walls, riprap and other purely structural solutions.

9. ENGINEERING CRITERIA FOR BANK PROTECTION DESIGN

Prioritization of bank protection projects should be conducted to focus efforts on providing the greatest benefit to both the site-specific failure and the overall recovery of the Dry Creek system, while working in the collective set of limitations inherent in an urbanized watershed. The tendency to provide a short-term “band-aid” solution to dissipate bank erosion fails to consider the potential impact of the alteration on adjacent stream reaches and, typically, does not provide a long-term solution to improve the function and/or habitat of the system. Successful restoration designs must consider both the historic function of the channel in question, as well as the current morphology of the overall stream reach. Projects should be selected and designed in order to maximize improvements to the riparian and aquatic habitat while developing long-term bank stability and providing reasonable flood control for the local area.

9.1 Key Strategies in Design

Future bank stabilization strategies within Dry Creek should initially consider two main approaches. The preferred method to improve morphological and habitat complexity of the channel, stabilize the stream banks and maintain reasonable flood control is to create or maintain channel geometry which is physically and geomorphically appropriate for the reach in question, and which incorporates naturalistic materials and native revegetation. We will refer to this approach as a *Level 1* restoration. However, in many locations within the subject reach, existing land uses may preclude the establishment of ideal conditions on one or both of the banks. Where channel realignment, widening, or other manipulations are not feasible, bank stabilization techniques that eliminate bank erosion while providing some ecological function are preferred. Depending upon the extent of the constraints, these sites will be classified into *Level 2* or *Level 3* restoration sites. **Appendix B** lists the classification of all erosion and bank stabilization sites recorded in the field.

Figure 12 - Alders Supporting Gabions
The above photos clearly show the ability of roots to secure soil against scour, stabilizing the toe of the bank.

9.2 Level 1 Restoration

Restoration of the channel could take many forms, but the ideal treatment must be selected based on the specific opportunities and constraints of an existing erosion site or potential project. The goal should always be to enhance or create geometry with characteristics appropriate to the reach. When properly implemented, these applications will significantly reduce the occurrence of bank failures by the direct elimination of conditions that lead to failure. These are not 'band-aid' solutions and will typically have a life expectancy far greater than other forms of bank protection, while providing benefits to adjacent stream reaches. For treatment of isolated bank failure sites, typical strategies for the establishment of appropriate conditions might include:

- Decreasing bank slopes to angles that will allow for the establishment and success of protective native vegetation.
- Improving flood plain connectivity, by creating a low flow channel with a bankfull flow bench to allow natural morphological processes to influence sediment sorting and transport continuity, while maintaining reasonable flood capacity.
- Reducing shear forces through widening of the channel at incised locations.
- Reducing erosive forces on banks through roughening of the channel section using groins, woody debris, or native plantings to create channel complexity.

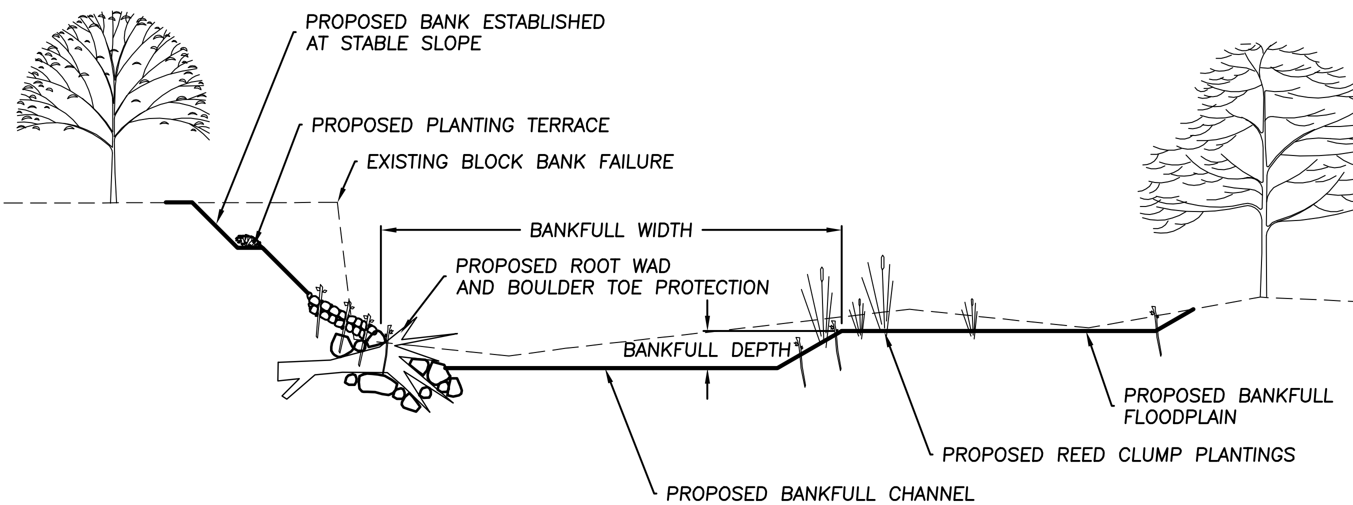
Figure 13 displays some of the above concepts being put to use in a conceptual cross section with characteristics typical of the project reach.

When *Level 1* restoration is considered feasible for an entire reach of channel (rather than a small section), more alternatives become available for consideration. These might include alterations to the channel's profile grade or horizontal alignment. In locations where channel straightening has resulted in an increased profile grade (common within the subject reach) the optimal solution might be to reestablish the natural meander pattern, thus increasing channel length and reducing the profile grade. This approach will simultaneously reduce hydraulic forces and set the stage for increased channel diversity and habitat complexity. However, the application of this reach-wide approach is often in conflict with existing land uses, which preclude the possibility of widening and reconfiguring large sections of the channel. An alternative method for altering local profile grade would be through the placement of weirs or other grade control structures. Properly designed and constructed, weirs can be very effective at reducing profile grade over short reaches. The subject reach shows numerous examples of improved habitat conditions and low flow meander development at locations immediately upstream of man-made grade control structures such as sewer crossings and bridge abutments. Clear drawbacks to the use of weirs are their potential adverse impacts on fish passage, their limited life expectancy, and their inability to adjust to long-term profile adjustments. **Figure 14** depicts an example of some of the concepts that might be incorporated into a geomorphic reconfiguration of a typical section of the project reach.

9.1.1 Level 2 and 3 Restoration

Where *Level 1* restoration is found to be infeasible due to existing constraints, the proposed alternatives for bank protection would consist of methods aimed to eliminate bank erosion while providing benefits to the aquatic and riparian habitat. Depending on whether one or both banks are constrained, these sites have been categorized as *Level 2* or *Level 3* restoration sites, respectively. Protection could consist of any of the recommended upper bank and toe protection applications provided in **Tables 9 and 10**. Examples of the application of some bank protection measures are provided in **Figures 15 and 16**.

LEVEL II RESTORATION



CONCEPTUAL EXISTING CONDITIONS

1. SEDIMENT TRANSPORT DISCONTINUITY HAS RESULTED IN EXCESSIVE DEPOSITION AT THIS SECTION.
2. CHANNEL HAS DIVERTED AROUND DEPOSITED BAR AND HAS UNDERCUT THE LEFT BANK.
3. UNDEVELOPED SPACE IS AVAILABLE AT THE TOP OF EACH BANK, ALLOWING FOR GEOMORPHIC RECONFIGURATION (REFER TO FIG. 15 FOR CONCEPTUAL PLAN AND PROFILE).

CONCEPTUAL PROPOSED CONDITIONS

1. RECONTOUR THE STEEP SLOPE TO A MORE STABLE ANGLE.
2. INSTALL ROOT WADS AT TOE TO PROTECT AGAINST UNDERCUTTING OF BANK, PROVIDE SHADING, AND IMPROVE AQUATIC HABITAT.
3. REVEGETATE BANKS WITH NATIVE RIPARIAN SPECIES.
4. PROVIDE DESIGN BANKFULL SECTION TO INCREASE SEDIMENT CONTINUITY.

FIG 13: CONCEPTUAL DESIGN EXAMPLE WHERE EXISTING CONDITIONS ALLOW FOR DEVELOPMENT OF GEOMORPHICALLY APPROPRIATE CHANNEL DIMENSIONS

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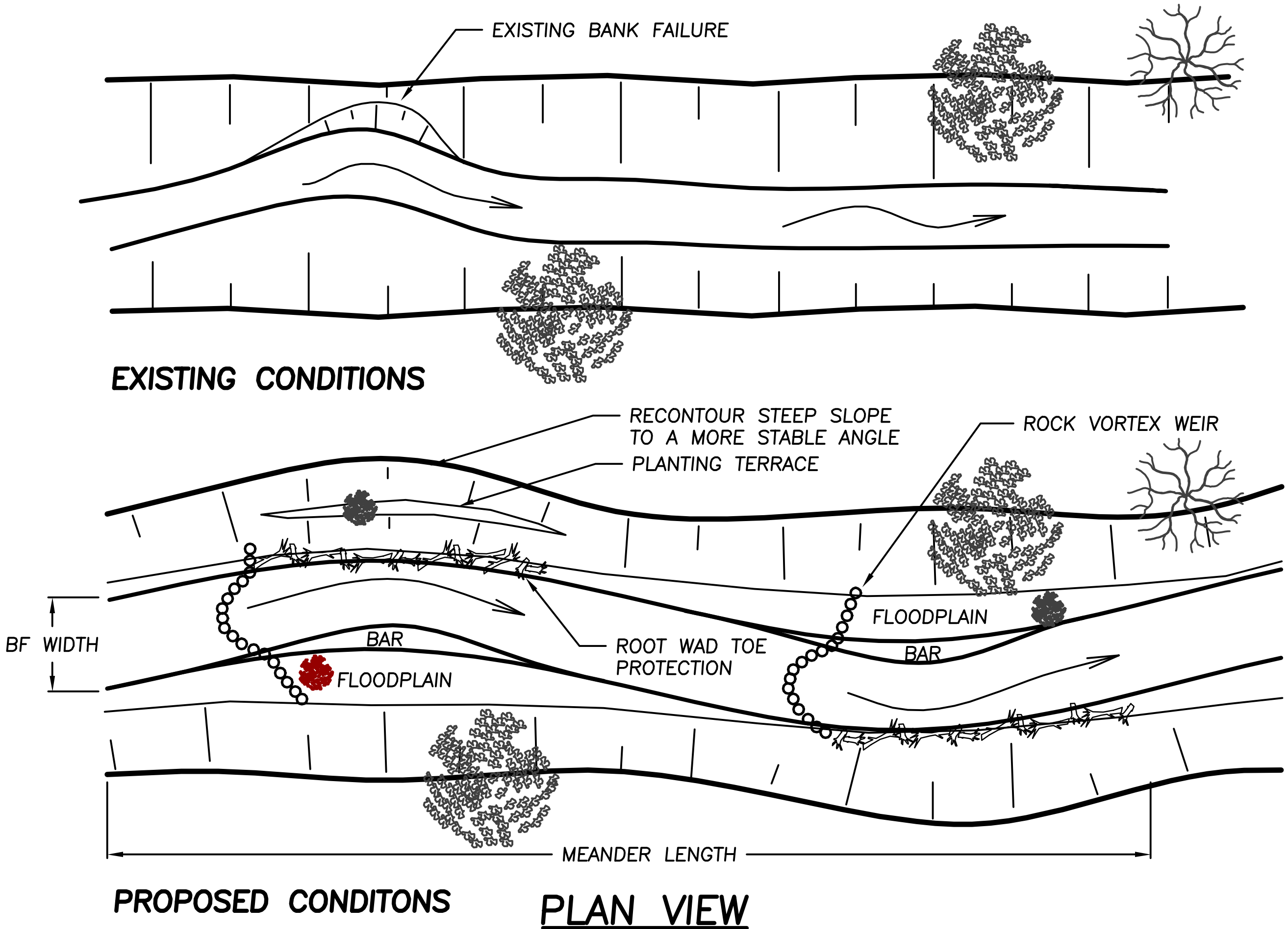
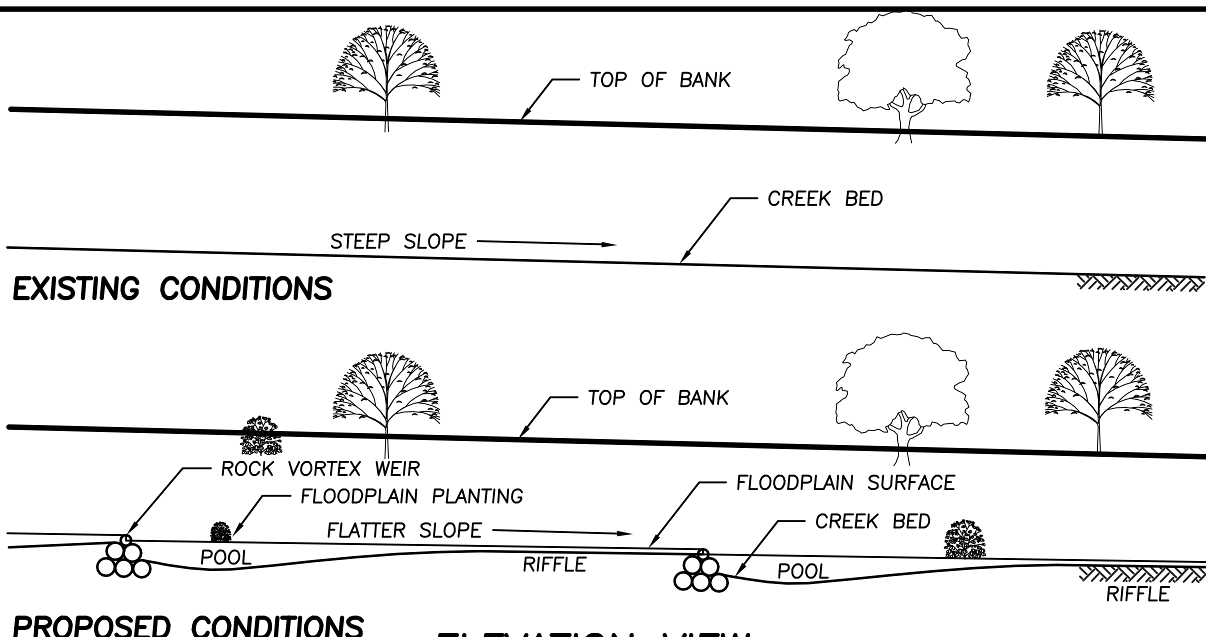


PLAN VIEW
NOT TO SCALE



ELEVATION VIEW
NOT TO SCALE

FIG 14: CONCEPTUAL EXAMPLE OF LEVEL 1 RESTORATION

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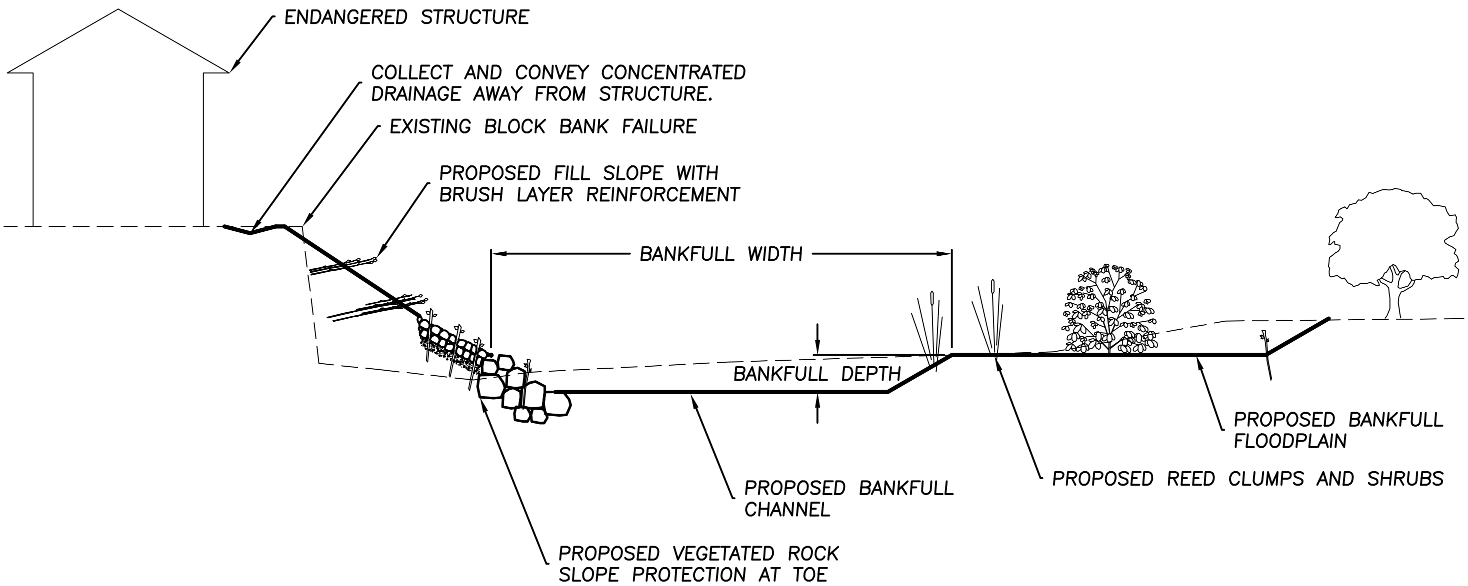
LEVEL II RESTORATION



CONCEPTUAL EXISTING CONDITIONS

1. UPSTREAM BANK HARDENING HAS DEFLECTED FLOW INTO THE LEFT BANK.
2. EXISTING DEVELOPMENT CREATES CONDITIONS WHERE SPACE IS NOT AVAILABLE AT THE TOP OF THE LEFT BANK.

CONCEPTUAL PROPOSED CONDITIONS

1. RECONTOUR ERODED LEFT BANK TO A STABLE ANGLE. USE BRUSH LAYERING TO REINFORCE THE FILL.
2. INSTALL ROCK SLOPE PROTECTION AT TOE TO PROTECT AGAINST UNDERCUTTING OF FILL.
3. CREATE BANKFULL FLOODPLAIN ON RIGHT BANK TO REDUCE STRESS ON LEFT BANK DURING FLOOD EVENTS.
4. PLANT FLOODPLAIN WITH RIPARIAN VEGETATION THAT WILL PROVIDE SHADE AND HABITAT OPPORTUNITIES.

FIG 15: CONCEPTUAL BANK STABILIZATION DESIGN EXAMPLE

FOR USE UNDER PARTIALY CONSTRAINED CONDITIONS

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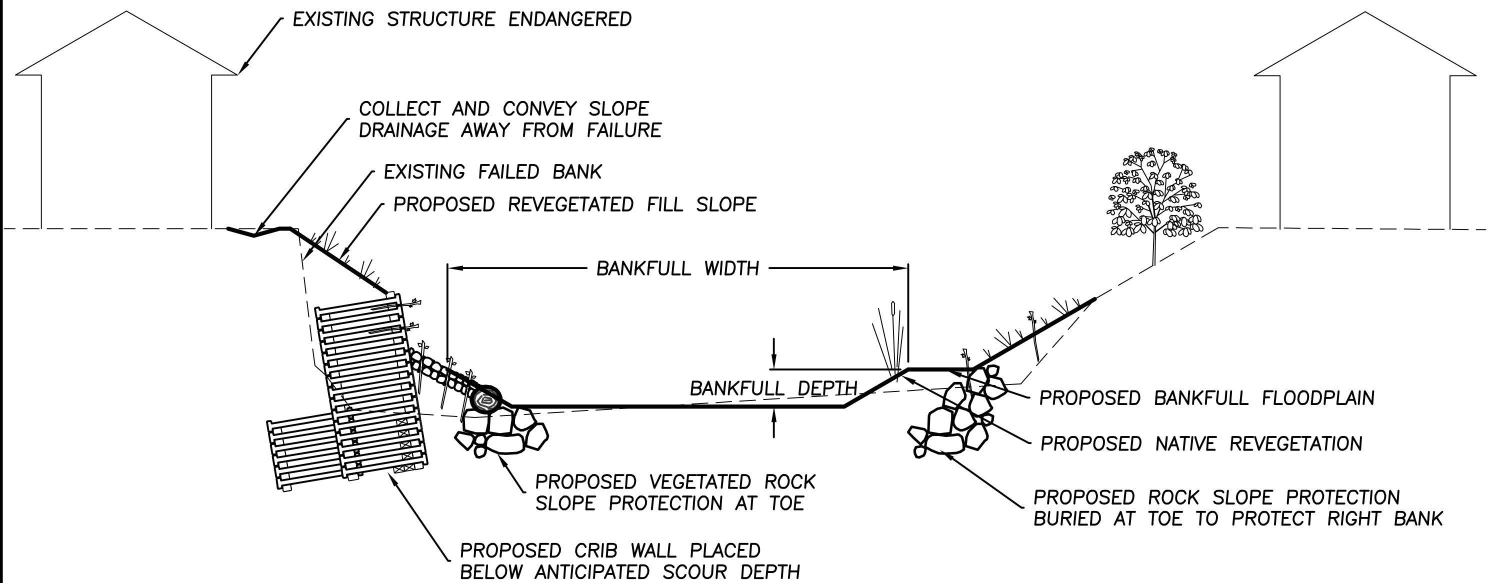
LEVEL III RESTORATION



CONCEPTUAL EXISTING CONDITIONS

1. CHANNEL IS CONFINED AND INCISED.
2. UNDERCUTTING OF BANK DUE TO CHANNEL INCISION HAS CAUSED SLOPE FAILURE.
3. FUTURE SLOPE FAILURE WILL THREATEN STRUCTURES.

CONCEPTUAL PROPOSED CONDITIONS

1. BANK STABILIZATION SOLUTION IS REQUIRED TO PROTECT EXISTING STRUCTURE.
2. CRIB WALL OR OTHER STRUCTURAL SOLUTION IS REQUIRED TO SUPPORT STEEP SLOPES, WITHOUT FURTHER ENCROACHING UPON CHANNEL.
3. ROCK SLOPE PROTECTION AT TOE WILL PROTECT AGAINST UNDERCUTTING OF BANK AND ALLOW FOR SUCCESS OF PLANTINGS.
4. PROVISION OF SLIGHTLY WIDER BANKFULL SECTION WILL REDUCE FLOW DEPTH, SHEAR AND VELOCITY. THIS WILL REDUCE LOCAL SCOUR AND BANK EROSION.
5. CREATION OF A BANKFULL FLOODPLAIN WILL PRODUCE VARIABILITY IN THE RIPARIAN ZONE.

FIG 16: CONCEPTUAL BANK STABILIZATION DESIGN EXAMPLE

FOR USE UNDER EXTREMELY CONSTRAINED CONDITIONS

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Table 9: Recommended Upper Bank Protection Alternatives

TYPE	DESCRIPTION	APPLICATIONS	ADVANTAGES	DISADVANTAGES	LIFESPAN	HABITAT VALUE	APPEARANCE	COST
Broadcast Seeding	Riparian species seed mix, often with mulch and tacking agent	Flatter slopes with shallow flows or used in conjunction with other measures	Hydro-seeding/mulching technologies enable affordable application over large areas.	Installation is seasonally dictated, unless irrigation is provided. Mulch is often required.	Long-term, assuming proper match of seed to sight conditions	High	Natural	$
Sod Placement	Sod slabs or turf squares salvaged from nearby areas and placed on slopes	Mild slopes with low to moderate velocities. Stacked application on bends or steeper banks	Vegetation can be established very quickly. Appearance is great. Can be low materials cost, if readily available.	Poor material availability or location may lead to high construction cost. Installation is seasonally dictated, unless irrigation is provided.	Long-term, pending proper site conditions conducive to sustained growth	High	Natural	$$-$$$
Contour fascines	Branches are tied into bundles (fascines) and staked in ditches dug along the slope's contours.	Cut or fill slopes, subject to low to moderate velocities, often in conjunction with live staking	Can place horizontally or at an angle for drainage control. Material is often readily available at no cost. Unskilled or volunteer labor is and option.	Large quantities of plant material required. Must construct during dormant season. Method is labor intensive.	Long-term, pending proper site conditions conducive to sustained growth	High	Natural	$$
Brush layering	Live branches are placed in terraces, as fill proceeds up slope.	To be used to reinforce and revegetate fill slopes, where soil moisture will support growth	On mild slopes, machines can be used. Material is often readily available at no cost. Method takes immediate advantage of structural benefit of vegetation.	Method is labor-intensive and requires large amounts of material. Installation is seasonally dictated, unless irrigation is provided.	Long-term, pending proper site conditions conducive to sustained growth	High	Natural	$$-$$$
Erosion control mat	Combinations of natural and synthetic fibers formed into mats	For use on the surface of a slope, in a wide variety of applications	Different mats can be chosen for various applications	High materials cost. Only works in conjunction with other measures	Short term (prior to vegetation establishment)	Low	Artificial	$$
Cellular web	Polyethylene honeycomb mat	For use on the surface of a slope, where steepness or erosion potential too great for mats	Contains soil in structural matrix, allowing for establishment of vegetation under extreme conditions.	High initial cost and poor aesthetics. Do not degrade naturally, as vegetation takes over. Can snag debris, leading to failure	Long-term	Low	Artificial	$$-$$$

Table 10: Recommended Toe Protection Alternatives

TYPE	DESCRIPTION	APPLICATIONS	ADVANTAGES	DISADVANTAGES	LIFE SPAN	HABITAT VALUE	APPEARANCE	COST
Reed Clump Planting	Reeds are planted in clumps or "plugs"	Low velocity terraces and floodplains	Plants can improve water quality through uptake of nutrients and by inducing sediment deposition.	Need moist, fertile soil and sunlight. Short construction period, in early spring. 3 years to reach full growth.	Long-term	Very high	Natural	$
Live wood Stakes	30"-80" long branches (often Willow), of ½" to 3" diameter stripped of most leaves and staked into soil.	Used in all velocity conditions where soil, sunlight, and water are available in sufficient quantity.	Simple to plant, with high success rate. Root strength provides excellent enhancement bank strength. Low design cost.	Installation is seasonally dictated, unless irrigation is provided. May require long-term maintenance where conveyance is limited.	Long-term	Very high	Natural	$
Root-Wad Revetment	Large root crowns are secured at the toe, often with trunk buried in bank, or cabled in place.	Used in medium to high velocity zones, where reduced conveyance due to increased roughness is acceptable	Provide excellent habitat and scour resistance, through use of what is often an affordable and readily available resource.	Material availability or transport may be a challenge. Added roughness may cause unwanted sediment deposition or snag debris.	Medium-term	Very high	Natural	$
Deflector Groins	Rock or log groin that extends into channel to deflect flows away from banks	Used on outside bank of bends and at points of flow incidence, where increased sediment deposition is desirable	May reduce material and placement costs by avoiding protection of entire bank. Can trap large amounts of sediment to rebuild floodplain.	High design cost. May induce scour elsewhere. May trap excessive sediment, leading to reduced conveyance. Placement causes high impact to stream.	Long-term	High-Very high	Constructed	$$
Vegetated Rock Slope Protection (RSP)	Rock is placed on angle of slope, with tubes and/or soil backfill for planting. Often filter fabric is used at rock/soil interface.	High velocity toes and banks, where geometric constraints require "hard" treatment.	Vegetation can obscure rock, once grown. Rock is flexible and adjusts to minor changes in subgrade conditions. Design costs are relatively low. Very reliable and versatile.	Purchase and transport costs of rock may be high. Uniform and sterile appearance of rock can be poor, if vegetation component is not properly planned and implemented.	Long-term	Medium	Color, size and placement dependent.	$$$
Rock Breast Wall	Stone wall with or without mortar	Used in high velocity locations, where steep bank angle is required	Can achieve steep slopes, allowing for use in highly constrained conditions. May retain weak slopes.	Rock source and transport are required. Skilled labor is required. Design costs are relatively high. Appearance is often poor.	Medium-term	Very Low	Constructed	$$$$
Gabion Wall	Rectangular wire basket with rock infill	High velocity or shear locations where near-vertical bank angle is required	Can achieve steep slopes, while still allowing for some settlement. Revegetation is possible.	Wire corrodes and may snag debris. Requires stable foundation, keyed below scour. High cost. Poor aesthetics	Medium-term	Low, unless backfilled with soil to allow planting.	Constructed	$$$$

Unlike *Level 1* restoration, which evenly distributes the erosive forces at work on the stream banks, *Level 2 & 3* applications typically improve a bank's strength or resistance to the acting hydraulic and physical forces. Accordingly, these applications will eventually fail, if not designed and constructed with vegetation as a key long-term structural component. Often, short-term strength will be dependent on rocks, fabric or other structural elements, but the strength and roughness provided by vegetation will be relied upon long after these other materials have ceased to be effective. Unlike concrete or other traditional bank stabilization materials, vegetation has the ability to provide protection that improves with time, in addition to satisfying the overall goal of habitat improvement. A prime example of this trait is shown in **Figure 12**. Here, the alder trees exhibit a property termed "edaphoecotropism" (Gray & Sotir, 1996), or stress avoidance. This property allows vegetation to grow around and within a structure without causing damage to the structure itself. The obvious strength of the well-developed root mass has stabilized the toe below the gabion structure, protecting it from scour. Without the strength of the alders, this wall would clearly have been undercut through channel incision. In addition to stability, these trees provide habitat and improved aesthetic value.

10. PROJECT DEVELOPMENT PROCEDURES

Below is the recommended process that landowners and/or agencies interested in conducting a bank restoration project within Dry Creek should follow. **Figure 17** is an easy to follow summary of the sequence of actions that should be conducted to ensure a successful project. The obvious first step is the selection of a specific location where the need for restoration has been identified. Local watershed, resource or city agencies should select a project location based on a prioritization of the existing bank erosion sites. Landowners must decide whether an organized effort to reduce erosion and improve their property is necessary. Regardless of the process, once a site location is selected, it is recommended that the project manager follow the project development procedures described below.

1. Evaluate existing site-specific and reach specific parameters

Following the selection of a site for a restoration project, the project coordinators must collect both site-specific and stream reach data that will help identify the physical characteristics, such as cause of failure, the mechanisms of failure, and the existing geometric, geotechnical and hydraulic conditions acting at the site.

- *Hydrology*: The hydrologic characteristics of the subject reach have been determined and are provided within.
- *Longitudinal profile trends*: Based on **Figure 3A**, is the site located in a pool, or riffle? A detailed profile should be conducted extending 500 ft upstream and downstream of the site. Determination should be made as to whether the site is currently aggrading, downcutting, or stable.
- *Hydraulics*: The site-specific hydraulics must be determined. The 2002 HEC-RAS modeling is based on over 40 updated cross-sections and flow data for the 2, 5, 10, 50, and 100-yr flow events. Site-specific hydraulic data will include: velocity distributions at the site during Q_{bkfl} and various flood stages, shear forces associated with design flows, maximum estimated scour depth, eddies, hydraulic jumps, and others.
- *Detailed Site Map*: A survey and site map should be conducted of the subject site showing existing vegetation, topography, property ownership lines, utility locations, etc.
- *Channel Geometry*: Detailed cross sections should be conducted at the site to determine channel depth, width, capacity, bankfull area, bench heights, bank slopes, bend curvature, etc.

Figure 17: Project Development Procedures for Future Enhancement Efforts

INITIAL STEP - Select Project Location (based on prioritization of existing bank erosion sites or landowner selection)

STEP 1

Evaluate Existing Site & Reach Specific Parameters

Investigate hydrology, longitudinal profile trends, hydraulics, channel geometry, geotechnical properties, surface and bank drainage, and riparian vegetation.

STEP 2

Confirm Goals and Objectives of Project

Potential goals/objectives include:

- maintain flood protection,
- improve and promote ecological habitat,
- enhance morphological complexity (pools & riffles),
- create long-term solutions,
- minimize impact to adjacent properties.

STEP 3

Identify Opportunities and Constraints

Determine funding availability, land availability, land access, and permitting requirements.

STEP 4

Develop Two or More Conceptual Design Alternatives

Include estimated costs, project duration, and ability of potential design to satisfy stated goals and objectives.

STEP 5

Contact Local Resource Agencies and Entities for Review

Agree upon feasible, practical solution. Discuss permitting and construction details.

STEP 6

Select Preferred Alternative and Develop Final Plans

STEP 7

Implement Project

STEP 8

Post Project Monitoring

Annual monitoring to evaluate both site and reach specific success.

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- *Geotechnical properties*: The final set of design parameters describes the bank composition and properties at the site. Geotechnical engineers will sample and test the soil for particle size distribution, maximum density and cohesion. The geotechnical engineer will provide the design engineers with a soil classification, allowable toe pressure, angle of internal friction, allowable slope angle and a slope stability analysis.
- *Surface and bank drainage*: Investigations should include a complete understanding of off site drainage. The bank failure may be the result of chronic local drainage to the top of the bank, inducing bank saturation and failure. The drainage properties and mechanisms of the slopes once saturated, must also be understood.
- *Riparian Vegetation*: A qualitative assessment should be conducted of the species types, health and density of existing riparian vegetation.

2. Confirm goals and objectives of project

Future restoration and bank stabilization projects should incorporate as many of the following goals and objectives as possible. Site-specific needs may allow the project coordinators to expand this list.

- Accelerate the natural recovery of the Dry Creek reach toward a stable geometry and plan form.
- No net increase in existing water surface elevations during storm flows.
- Educate private and public landowners to assist with coordination of efforts to improve channel stability while enhancing stream ecosystem function.
- Improve aquatic and riparian habitat and function with an emphasis on fish passage and habitat.
- Where possible, establish morphological channel complexity including low flow meanders, alternating pool and riffle sequences, and gravel substrates.
- Increase local bank stability with long-term solutions.
- Minimize negative impact of proposed channel alterations on adjacent properties.

3. Determine ideal conditions for site

Based on reach and site-specific conditions of the project, project coordinators and design consultants can determine the ideal physical conditions for the site. The ideal conditions should aim to satisfy as many of the above goals and objectives as possible. While the ideal conditions for maximum restoration may not be feasible given various constraints, the best project approach may be to develop and present the ideal future conditions and downscale the scope of the project following the determination of specific constraints. Aim big and settle for smaller. The ideal physical conditions should include:

- *Channel geometry*: Is geometric reconfiguration possible given obvious adjacent land uses? If a possibility does exist, what is ideal geometry for the channel to meet the goals and objectives of the project? How does the ideal geometry at the site conform to upstream and downstream conditions?
- *Bank stability needs*: If geometric reconfiguration is not possible, is upper bank or toe bank protection or both feasible and necessary. Identify the stabilization techniques that are feasible and possess the most benefit for the natural system.
- *Vegetation opportunities*: Identify all potential opportunities for use of revegetation strategies to stabilize banks with native vegetation and eliminate exotic invasive species. Identify locations to increase riparian vegetation and provide shade for stream waters.
- *Substrate complexity*: Identify techniques to improve low flow channel complexity, allow bar development and grain sorting to provide physical variations in the stream channel.

- *Habitat complexity*: Improving riparian vegetative cover and substrate complexity will directly improve habitat complexity for the all trophic levels inhabiting stream environments.

4. *Determine project opportunities and constraints*

The details of the potential project designs, such as area of project, complexity of project, and potential techniques are highly dependant upon the opportunities and constraints. Identification of the opportunities and constraints of a potential project will assist with project alternative feasibility and greatly improve the focus of the conceptual design stages. Factors that will dictate the project characteristics will include:

- *Funding availability*: The amount of money available to conduct the project will limit the scale and scope of the potential alternatives. Funding opportunities are available from numerous resource agencies and local grants to improve the ecological function of urban streams. Invaluable resources for funding alternatives include the Dry Creek CRMP and the City of Roseville.
- *Land availability and access*: Many locations within the subject reach are limited by adjacent land uses. The project coordinators must identify the potential area of the project and determine the existing easements and access limitations. Community involvement and acceptance of the project may create opportunities to include adjacent properties in the design alternatives. The location of public utilities should also be identified.
- *Permitting requirements*: The permitting requirements and associated costs for the potential project should be investigated with the City of Roseville, Placer County, and local resource agencies.

5. *Develop two or more conceptual design alternatives*

Based on the ideal conditions and the reality of the opportunities and constraints, develop two or more conceptual design alternatives for the project. Many design options applicable to Dry Creek bank stabilization projects are provided in Section 7 of this report. The ability of each alternative to satisfy the goals and objectives of the project should be identified. The advantages and disadvantages to each design should explore the potential impact to the overall reach and adjacent properties, estimated cost and duration of project.

6. *Contact local resource agencies and entities to review alternatives*

The project coordinators and consultants should review the potential project alternatives with the local agencies for agreement upon a feasible, practical and suitable solution prior to permit applications. Involve agency personnel in the decision making process as soon as possible. Details of permitting and construction details should be coordinated.

7. *Select preferred alternative and develop final plans.*

Cooperative selection of the preferred alternative should be followed by the 100% completion of the construction designs and details.

8. *Implement project*

Approval of the final plan, schedule and cost should be made. Project should be constructed.

9. *Monitor site and adjacent reach.*

Annual monitoring of the site and adjacent reach should be conducted for at least 5 years to determine project success and identify any small adjustments that could periodically improve the longevity of the project. Monitoring variables should include, but are not limited to:

- Annual cross-section monitoring of site and 500 ft upstream and downstream.
- Cross-sectional monitoring of subject reach every three years or following a flow exceeding 10 year RI.
- Monitoring of vegetation plantings periodically for first three years to ensure success. Replace any failed plants or trees.
- Slope stability and function of installed structures should be monitored every spring following winter rains to ensure success. Modifications should be explored if necessary, to ensure long-term stability.

11. RECOMMENDATIONS

Results of the bank stability, erosion site and existing bank protection site surveys were analyzed to develop a list of the top priority sites for implementation of immediate corrective measures. Criteria considered in this determination consisted primarily of the sites' sediment contribution, habitat condition and potential for damage to existing structures. **Table 11** provides a summary of the sites selected.

Table 11: Recommended Priority Bank Stabilization Sites

SITE ID	Length (ft)	Height (ft)	Angle (degrees)	Material Type	Veg. Coverage (%)	Notes
1R	72	8	70	SA/GR	0	Bank is steep, composed primarily of sandy material and is eroding at toe. Channel section appears to have sufficient width, with point bar formation on opposite bank.
3L/4L	32	20	90	SA	5	Located on outside of right-hand turn. Bank is steep, composed primarily of sandy material. Channel section appears to have sufficient width, with good bar formation on opposite bank. Existing gabion wall has failed from flanking and subsequent eddy formation. Wall was constructed from rounded river-run cobble, a poor choice for gabion fill
	57	8	80	CO	NONE	
29R	223	15	70	SA	10	Wide cross section, located on outside of left-hand bend. Steep composite bank failure is advancing. Profile grade break and channel width expansion have resulted in a large sediment transport discontinuity (bar formation on opposite bank). Toe protection is in place on opposite bank.
32R	100	10	60	SA	GRS	Existing bank is eroding immediately downstream of existing grade control at the intersection of Cherry and Willow Streets. Street intersection above bank failure is threatened by advancing erosion.
38L/39L	77	15	80	SA/GR	10	Existing gabion structure has become flanked at upstream end, causing severe erosion of bank below existing residence.
	28	7	70	CO/BO	W/BB	
45L	47	20	80	SA	60	High and steep bank failure located on outside of right-hand bend. Existing parking lot at top of slope is threatened. Banks are sandy and poorly vegetated, contributing excessive amounts of sediment.

* Refer to Appendix B for additional details and photos of each site

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APPENDIX A:

HEC-RAS Results – Velocity and shear stress at bankfull, 10-year, and 100-year recurrence intervals.

Appendix A: HEC RAS results for channel velocity and shear stress at bankfull, 10 year, and 100 year occurrences.

River Station (See Figure 8A-G)	**Total Flow (cfs)**	**Channel Velocity (ft/s)**	**Channel Shear Stress (lb/sq ft)**
84214.4	1570	3.5	0.9
84214.4	5403	4.7	1.3
84214.4	9726	5.3	1.4
84011.8	1570	2.7	0.6
84011.8	5403	3.8	0.9
84011.8	9726	4.5	1.0
83548.9	1570	2.7	0.6
83548.9	5403	3.2	0.6
83548.9	9726	3.8	0.8
83181.9	1570	2.6	0.4
83181.9	5403	3.6	0.7
83181.9	9726	4.5	1.0
82911.9	1570	2.3	0.3
82911.9	5403	3.7	0.8
82911.9	9726	4.8	1.1
82629.7	1570	4.1	0.7
82629.7	5403	5.1	0.9
82629.7	9726	6.1	1.2
82269.7	1570	4.7	0.9
82269.7	5403	4.6	0.7
82269.7	9726	4.1	0.6
81989.7	1570	5.9	1.5
81989.7	5403	5.7	1.2
81989.7	9726	3.6	0.4
81669.7	1570	4.9	1.0
81669.7	5403	4.5	0.7
81669.7	9726	4.3	0.6
81379.7	1570	4.6	0.9
81379.7	5403	5.6	1.0
81379.7	9726	6.9	1.4
81041.2	1570	4.8	0.9
81041.2	5403	6.8	1.6
81041.2	9726	6.4	1.3
80726.2	1570	4.2	0.8

80726.2	5403	5.4	1.0
80726.2	9726	5.2	0.8
80677.5*	1570	3.9	0.6
80677.5*	5403	5.4	1.0
80677.5*	9726	5.6	0.9
80628.8*	1570	2.6	0.3
80628.8*	5403	3.4	0.4
80628.8*	9726	4.0	0.5
80580.1*	1570	2.2	0.2
80580.1*	5403	3.4	0.4
80580.1*	9726	4.1	0.5
80531.4*	1570	2.5	0.2
80531.4*	5403	3.7	0.4
80531.4*	9726	4.3	0.5
80482.7*	1570	2.7	0.3
80482.7*	5403	3.9	0.5
80482.7*	9726	4.5	0.6
80434.1	1570	3.7	0.6
80434.1	5403	4.6	0.7
80434.1	9726	5.0	0.7
80225.1	1570	4.5	0.7
80225.1	5403	6.4	1.2
80225.1	9726	8.2	1.8
79852.1	1570	2.4	0.2
79852.1	5403	3.8	0.4
79852.1	9726	4.7	0.5
79816.7	1570	2.5	0.3
79816.7	5403	4.2	0.7
79816.7	9726	5.3	1.0
79791.7	Bridge		
79766.7	1570	4.1	0.8
79766.7	5403	4.8	0.9
79766.7	9726	5.6	1.2
79715.1	1570	3.7	0.7
79715.1	5403	4.8	0.9
79715.1	9726	5.5	1.1
79468.8	1570	3.7	0.6
79468.8	5403	4.9	0.9

79468.8	9726	5.3	1.0
79243.6	1570	7.1	2.8
79243.6	5403	7.6	2.6
79243.6	9726	9.9	4.2
79194.4	1570	4.5	0.5
79194.4	5403	6.0	0.8
79194.4	9726	8.3	1.4
79191.4	1570	3.3	0.3
79191.4	5403	4.0	0.4
79191.4	9726	5.6	0.7
79166.05	Bridge		
79140.7	1570	3.3	0.3
79140.7	5403	4.6	0.5
79140.7	9726	6.6	1.0
79128.7	1570	4.4	0.5
79128.7	5403	6.4	0.8
79128.7	9726	9.2	1.6
79077.4	1570	3.9	0.4
79077.4	5403	4.9	0.5
79077.4	9726	6.8	1.0
78804.69	1570	3.9	0.4
78804.69	5403	5.8	0.7
78804.69	9726	8.1	1.3
78736.69	1570	4.9	0.6
78736.69	5403	7.5	1.3
78736.69	9726	11.2	2.7
78341.69	1570	4.6	0.9
78341.69	5403	5.6	1.1
78341.69	9726	6.0	1.2
78014.99	1570	5.3	1.1
78014.99	5403	7.9	2.2
78014.99	9726	7.5	1.8
77679.49	1570	6.1	1.6
77679.49	5403	8.8	2.7
77679.49	9726	7.5	1.8
77631.49	1570	5.9	1.5
77631.49	5403	9.4	3.1
77631.49	9726	6.9	1.5

77606.49	1570	6.1	1.6
77606.49	5403	9.6	3.3
77606.49	9726	8.6	2.5
77603.74	Bridge		
77600.99	1570	6.2	1.6
77600.99	5403	9.7	3.3
77600.99	9726	8.9	2.7
77571.99	1570	5.5	1.3
77571.99	5403	8.8	2.7
77571.99	9726	7.5	1.8
77511.69	1570	4.2	0.7
77511.69	5403	7.3	1.8
77511.69	9726	7.0	1.6
77251.49	1570	5.1	1.1
77251.49	5403	6.9	1.6
77251.49	9726	6.0	1.1
77218.89	1570	5.2	1.2
77218.89	5403	6.7	1.5
77218.89	9726	7.2	1.6
77175.89	Bridge		
77132.89	1570	5.7	0.9
77132.89	5403	7.1	1.1
77132.89	9726	8.8	1.6
77078.29	1570	5.0	0.7
77078.29	5403	6.6	1.0
77078.29	9726	8.4	1.4
76871.09	1570	3.8	0.4
76871.09	5403	4.6	0.5
76871.09	9726	5.7	0.6
76536.69	1570	3.4	0.3
76536.69	5403	4.6	0.5
76536.69	9726	5.7	0.7
76150.19	1570	4.2	0.4
76150.19	5403	7.1	1.1
76150.19	9726	9.1	1.7
75808.6*	1570	3.7	0.7
75808.6*	5403	4.8	1.1

75808.6*	9726	4.3	0.8
75780.19	1570	3.9	0.9
75780.19	5403	4.8	1.1
75780.19	9726	4.2	0.8
75752.3*	1570	4.9	1.4
75752.3*	5403	5.7	1.6
75752.3*	9726	4.5	0.9
75724.4*	1570	5.2	1.6
75724.4*	5403	5.7	1.6
75724.4*	9726	4.5	0.9
75696.5*	1570	4.2	1.0
75696.5*	5403	4.9	1.1
75696.5*	9726	4.3	0.8
75668.6*	1570	3.7	0.8
75668.6*	5403	4.5	0.9
75668.6*	9726	4.1	0.7
75557.19	1570	3.4	0.6
75557.19	5403	3.5	0.5
75557.19	9726	3.6	0.6
75233.4	1570	3.3	0.6
75233.4	5403	3.9	0.7
75233.4	9726	4.1	0.7
74898.1	1570	3.2	0.6
74898.1	5403	3.7	0.6
74898.1	9726	4.0	0.7
74518.1	1570	4.4	1.0
74518.1	5403	7.0	2.3
74518.1	9726	7.1	2.2
74008.1	1570	4.2	0.9
74008.1	5403	5.6	1.2
74008.1	9726	7.1	1.8
73943.3	1570	1.7	0.1
73943.3	5403	3.1	0.4
73943.3	9726	4.3	0.6
73919.3	Bridge		
73895.3	1570	2.4	0.3
73895.3	5403	3.9	0.6
73895.3	9726	5.5	1.1

73820.4	1570	3.9	0.7
73820.4	5403	5.7	1.2
73820.4	9726	7.7	2.1
73692.8*	1570	3.4	0.5
73692.8*	5403	4.7	0.9
73692.8*	9726	6.3	1.5
73565.3	1570	4.1	0.8
73565.3	5403	5.0	1.1
73565.3	9726	6.4	1.6
73523.3*	1570	4.3	0.9
73523.3*	5403	5.3	1.2
73523.3*	9726	7.0	1.9
73481.3	1570	4.4	0.9
73481.3	5403	6.3	1.7
73481.3	9726	8.8	3.0
73345.3	1570	4.8	1.1
73345.3	5403	7.5	2.3
73345.3	9726	7.6	2.2
73277.2	1570	5.3	1.4
73277.2	5403	6.9	1.9
73277.2	9726	6.4	1.5
73222.4*	1570	5.1	1.0
73222.4*	5403	6.5	1.4
73222.4*	9726	6.3	1.2
73140.2*	1570	5.5	1.0
73140.2*	5403	5.4	0.8
73140.2*	9726	5.3	0.7
73112.9	1570	4.3	0.5
73112.9	5403	3.8	0.3
73112.9	9726	3.9	0.3
72982.9	1570	4.1	0.4
72982.9	5403	6.0	0.8
72982.9	9726	7.1	1.0

APPENDIX B (presented in digital format):
Inventory of erosion sites and existing bank stabilization efforts

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Appendix B: Erosion Sites with Stabilization Efforts

Site 2L

Existing Conditions

- Located on inside of gradual left-hand turn
- Large concrete rubble at toe with rsp placed above
- Appears stable, but lacks mature vegetation or adequate habitat value
- Majority of the voids of concrete at toe contain no fines, and will not support revegetation

Possible Corrective Measure(s)

- Improve canopy through planting of riparian trees
- Create planting-pockets within voids of concrete and revegetate with natives

Priority: Low
Restoration Level Opportunity*: 2

*For description of Restoration Levels see section 9.1 of report.

Site 4L

Existing Conditions

- Located on outside of right-hand turn
- Bank is steep, composed primarily of sandy material
- Channel section appears to have sufficient width, with good bar formation on opposite bank
- Existing gabion wall appears to have failed from flanking and subsequent eddy formation
- Wall was constructed from rounded river-run cobble. Angular infill material would have provided greater stability

Possible Corrective Measure(s)

- Rebuild slope protection with use of rsp, extending toe outward from current location and encroaching into existing bar formation
- Regrade bar to form more stable bankfull channel geometry and to provide some additional floodplain relief
- Ensure replacement structure has appropriate conforms to avoid repeat failure
- Due to availability of space, this could be a prime location for woody-debris placement

Priority: High
Restoration Level Opportunity: 2

Site 6R

Existing Conditions

- Located on outside of left-hand turn
- Metal crib wall is protecting road alignment at top of slope
- Some signs of stress in wall, where headers have deformed under load
- Rsp at toe of crib wall appears relatively stable and to be providing some opportunity for revegetation
- Lacks mature riparian tree cover for shade

Possible Corrective Measure(s)

- Improve canopy through planting of riparian trees
- Create planting-pockets within voids of concrete and revegetate with natives

Priority: Low
Restoration Level Opportunity: 2-3

Site 7R

Existing Conditions

- Located on outside of left-hand turn
- Gabions form downstream transition from metal crib wall (site 6R)
- Appears to be stable and revegetating
- Lacks mature riparian tree cover for shade

Possible Corrective Measure(s)

- Improve canopy through planting of riparian trees
- Remove exotic vegetation

Priority: Low
Restoration Level Opportunity: 2-3

Site 8L-A

Existing Conditions

- Rsp placed at toe, with downstream end-section formed from rock-filled steel barrels stacked into slope
- Appears well stabilized
- 100% vegetation coverage has almost hidden the structure
- Lacks mature riparian tree cover

Possible Corrective Measure(s)

- Improve canopy through planting of riparian trees

Priority: Low
Restoration Level Opportunity: 2

Site 9L

Existing Conditions

- Located on straight reach just downstream of Folsom bridge
- Numerous concrete structures located within bank
- Erosion present at upper slope
- Exotic invasive species present
- Toe appears to be stable and revegetating, but lacks mature riparian tree cover for shade

Possible Corrective Measure(s)

- Improve canopy through planting of riparian trees
- Remove exotics and revegetate

Priority: Low
Restoration Level Opportunity: 2

Site 10R

Existing Conditions

- Located on straight section within confined channel reach
- Toe is stable and well vegetated
- Existing road at top of bank limits planting area
- Lacks mature riparian tree cover

Possible Corrective Measure(s)

- Improve canopy through planting of riparian trees within rsp

Priority: Low
Restoration Level Opportunity: 2

Site 10R-A

Existing Conditions

- Located on straight reach just downstream of Folsom bridge
- Toe appears stable, but bank is steep and failing in some locations
- Lack of mature riparian trees
-

Possible Corrective Measure(s)

- Improve canopy through planting of riparian trees
- Lay back the slope to stable angle where space permits, allowing for improved revegetation opportunities
- Add woody debris to the toe

Priority: Moderate
Restoration Level Opportunity: 2

Site 12L

Existing Conditions

- Located on straight reach
- Gabions appear stable, with vegetation at toe
- Lack of mature riparian trees or channel complexity

Possible Corrective Measure(s)

- Improve canopy through planting of riparian trees at top of slope
- Add woody debris and/or large rocks to the toe to add complexity and cover for fish

Priority: Low
Restoration Level Opportunity: 2

Site 13L

Existing Conditions

- Located on straight reach
- Large concrete rip rap has stabilized slope
- Some trees have been successfully established
- Voids in rip rap contain sufficient fines for vegetation recruitment

Possible Corrective Measure(s)

- Do nothing

Priority: None
Restoration Level Opportunity: 2

Site 14R

Existing Conditions
- Located on outside of gentle left-hand turn
- Rsp has stabilized the slope
- No vegetation has been established
- Lack of mature riparian trees or channel complexity

Possible Corrective Measure(s)
- Revegetate

Priority: Low
Restoration Level Opportunity: 3

Site 14R-A

Existing Conditions

- Small rsp at toe of well-revegetated slope
- Appears stable

Possible Corrective Measure(s)

- Do nothing

Priority: None
Type: 3

15L

Existing Conditions

- Rsp at toe of gabion wall
- Vegetation is well-established
- Wall and toe appear stable

Possible Corrective Measure(s)

- Do nothing

Priority: None
Restoration Level Opportunity: 3

Site 16R

Existing Conditions

- Gabion wall at toe of slope with concrete wall located above
- Concrete wall appears to be failing and may require eventual replacement
- Gabion wall appears stable, with some vegetation established at toe
- Lack of mature riparian trees or channel complexity
- Channel section appears to have sufficient width

Possible Corrective Measure(s)

- Add channel complexity and habitat at toe through use of groins or root-wads

Priority: Low
Restoration Level Opportunity: 3

Sites 17R & 18R

Existing Conditions

- Large concrete rip rap (18R) at toe of slope with soldier-pile wood wall (17R) at top
- Located at pool below steep riffle section
- Mature tree at toe provides shade for pool
- Rip rap provides cover and stability at outer edge of pool

Possible Corrective Measure(s)

- Do nothing

Priority: None
Restoration Level Opportunity: 3

Site 19R

Existing Conditions

- Multi-level gabion wall with mature alders lining the toe
- Alders appear to be stabilizing the toe against further scour
- Gabions appear stable
- Shade and cover under trees

Possible Corrective Measure(s)

- Do nothing

Priority: None
Restoration Level Opportunity: 3

Site 20L

Existing Conditions

- Small pieces of rsp and rip rap line toe
- Upper bank is eroded, with asphalt undermined
- Vegetation established near toe, where bank appears stable

Possible Corrective Measure(s)

- Recontour upper bank to stable slope
- Remove existing asphalt and revegetate a strip at top of slope
- Avoid damage to existing vegetation at toe and mid-bank

Priority: Low-Moderate
Restoration Level Opportunity: 3

Site 21R

Existing Conditions

- Small pieces of rip rap line toe
- Appears stable, though section is narrow
- Good vegetation established

Possible Corrective Measure(s)

- Do nothing

Priority: None
Restoration Level Opportunity: 3

Site 22L

Existing Conditions

- Located within straight, narrow, and steep reach
- Mid-sized rsp with successful revegetation
- Steep slope, but appears stable
- Great example of potential for revegetation of rsp

Possible Corrective Measure(s)

- Do nothing

Priority: None
Restoration Level Opportunity: 3

Site 23L

Existing Conditions

- Located within straight, narrow, and steep reach
- Large-sized concrete rip rap with soil backfill in voids
- Rsp appears stable, but needs additional revegetation
- Sheet erosion at top of bank
- High pedestrian traffic

Possible Corrective Measure(s)

- Establish additional vegetation at toe and within voids of rsp
- Develop access points for pedestrians to minimize total disturbance

Priority: Low
Restoration Level Opportunity: 3

Site 24R

Existing Conditions

- Located within straight, narrow, and steep reach
- Spotty placement of rip rap and rsp at toe and on banks is providing minimal protection
- Adjacent bridge location precludes widening
- Some well-established vegetation on upper banks

Possible Corrective Measure(s)

- Provide toe protection with vegetated rsp/rootwads or other method, matching existing grade at mid-slope and protecting existing mature vegetation at top of slope

Priority: Moderate
Restoration Level Opportunity: 3

Site 25L

Existing Conditions

- Rsp appears stable with newly established vegetation
- Some revegetation efforts appear unsuccessful

Possible Corrective Measure(s)

- Monitor existing vegetation for continued success
- Replace dead and dying vegetation plantings

Priority: Low
Restoration Level Opportunity: 2

Site 28L

Existing Conditions

- Located within wide aggradational section
- Rsp appears stable
- Vegetation is established and appears to be doing well in containers

Possible Corrective Measure(s)

- Monitor existing vegetation for continued success

Priority: Low
Restoration Level Opportunity: 1

Site 30L

Existing Conditions

- Large chunks of rip rap used to armor the toe and mid-bank
- Rip rap appears to be failing, slumping in many locations
- Bank lacks mature riparian trees and has poor habitat complexity

Possible Corrective Measure(s)

- Create bankfull floodplain bench to relieve stress on toe and mid-bank, pending location of existing utilities
- Remove large, ineffective concrete and replace with rock groins or woody-debris
- Integrate into larger Saugstad Park floodplain restoration effort

Priority: Moderate
Restoration Level Opportunity: 1

Site 32L

Existing Conditions

- Large-sized rsp used to armor failing slope at location of old landfill
- Slope appears to be well-stabilized, with some vegetation recruited at toe
- Rsp voids contain no fines and have little chance of recruiting vegetation, as is
- Upper bank has not mature riparian trees

Possible Corrective Measure(s)

- Backfill voids within rsp with finer material (gravels and sands) to create planting pockets
- Establish and maintain riparian trees at top of slope to develop shade
- Potential to integrate into larger Saugstad Park floodplain restoration project

Priority: Moderate
Restoration Level Opportunity: 1

Site 33R

Existing Conditions

- Gabion wall primarily vegetated with exotic blackberries
- Wall is bulging at toe
- Appears to have a poor footing and was constructed with rounded cobbles

Possible Corrective Measure(s)

- Monitor performance

Priority: Low
Restoration Level Opportunity: 1

Site 39L

Existing Conditions

- Existing gabion structure flanked at upstream end (gabion wall at right edge of top photo, not visible.)
- Appears to have been constructed with inadequate transition at upper end, and located within a non-cohesive cobble layer

Possible Corrective Measure(s)

- Provide toe protection and reconstructed slope at upper end, with native revegetation
- Or, lay back the slope to a stable angle and transition gradually to match wall geometry

Priority: High
Restoration Level Opportunity: 2

Site 40L

Existing Conditions

- Gabion wall located at upstream side of old concrete abutments
- Gabions look stable with excellent transition into native bank
- Abutments have constricted channel, resulting in upstream meander pattern and sediment deposition
- Site has numerous large trees shading channel

Possible Corrective Measure(s)

- Do nothing

Priority: None
Restoration Level Opportunity: 3

Site 41R

Existing Conditions

- Failing sackrete and small rsp located on mid-slope and toe
- Mature vegetation appears to be serving to stabilize slope
- Structure located at top of slope precludes expansion of section
- Opposite bank is lower, providing some floodplain relief
- Large cottonwoods being removed from opposite bank at time of survey
- There appears to be room to create additional channel capacity and to reduce erosive forces through excavation of bankfull floodplain on opposite bank

Possible Corrective Measure(s)

- Create bankfull floodplain on opposite bank and replace riparian canopy

Priority: Low
Restoration Level Opportunity: 2

Site 41L

Existing Conditions

- Stable rip rap of 2-5 ft. diameter placed at toe of slope, below roadway
- Good groundcover established, but poor canopy
- Slope appears stable, but steep and constrained tightly by presence of roadway

Possible Corrective Measure(s)

- Plant trees at top of slope

Priority: Low
Restoration Level Opportunity: 2

Existing Conditions

- Stable rip rap placed at toe in some locations
- Good canopy is established
- Opposite bank is developed with homes and fences at top of steep high slope
- Reach shows many signs of toe scour, where rip rap not present

Possible Corrective Measure(s)

- There appears to be sufficient space available to regrade the upper slope to create bankfull floodplain, relieving stresses and providing increased habitat benefits, per Darling Way Restoration Plan.

Priority: High
Restoration Level Opportunity: 2

Site 42R

Sites 44L/R

Existing Conditions
- Grouted rsp placed to protect sewer crossing
- Primarily stable, but undercut at ends with soil loss due to piping
- Zero revegetation opportunity

Possible Corrective Measure(s)
- Ends could be protected by backfilling lost soil, placing geotextile fabric, and constructing transitions from rsp
- Revegetate rsp

Priority: Moderate
Restoration Level Opportunity: 2