Section 8
Geomorphic Evaluation

8.1 Fundamentals of Fluvial Geomorphology

Fluvial geomorphology is the science of how moving water shapes the land. It is the fundamental discipline of river science and allows the quantitative description of stream behavior now and reasonable predictions of future behavior under specified conditions. Fluvial geomorphology and the related disciplines of hydrology and hydraulic engineering, geology and soil science together provide the technical underpinnings for sound watershed management. The paragraphs that follow are a brief overview of geomorphic principles with emphasis on their application to stream and watershed management.

8.1.1 Major Models

Streams exist in a state of dynamic equilibrium in which the forces driving channel form are balanced by the resisting forces. The driving force is gravity and acts on the stream as the rate at which water and sediment move through a stream while the resisting forces are the strength of the channel boundary materials and friction expressed as the channel shape. When the driving forces exceed the resisting forces, the stress applied by water or sediment exceeds the channel strength. The stream channel responds by altering its shape in plan, profile and cross section to accommodate the change in flow volume and applied shear. Once disturbed, the processes by which streams respond are: 1) incision or degradation, 2) widening, 3) aggradation or deposition and 4) plan form adjustments. Through these processes, streams eventually re-establish equilibrium. Determining which process is dominant and the likely progression of stream processes is one of the principle challenges of stream management.

While gravity and friction are first principles and drivers of channel form at the most fundamental levels, stream managers grapple with their many manifestations including sediment source, sizes and abundance, varying hydrologic conditions, vegetative influences and a broad range of geological influences. Given the large number of independent variables and the complex relationships between the many dependent variables, it is reasonable to seek robust, relatively straightforward models that organize these variables. In disturbed systems such as Stevens Creek, the chosen approach evaluates each channel process separately then develops an integrated assessment using energy relationships.

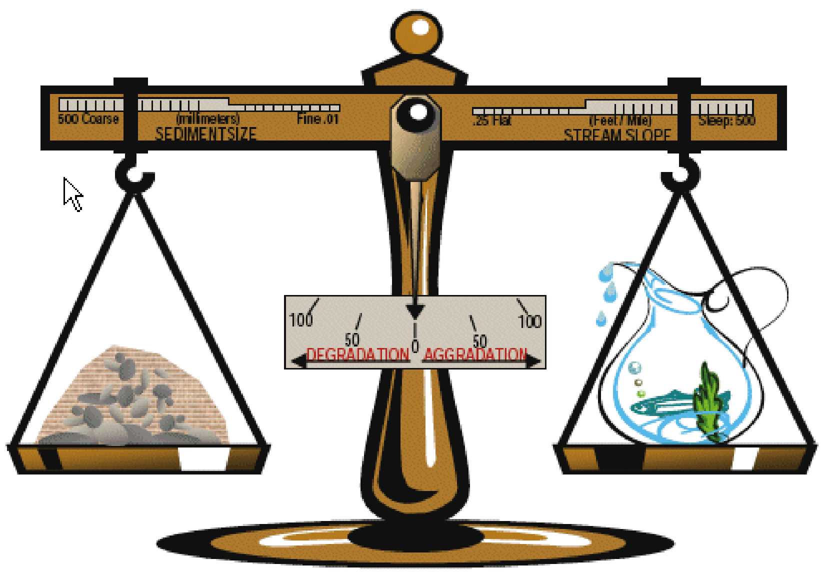
Although there are three commonly recognized approaches to stream design, each with advantages and limitations (Skidmore et al. 2001), the two simplest approaches, often called analog and empirical methods, explicitly assume equilibrium conditions regarding hydrology and sediment transport. Because Stevens Creek is not in equilibrium, the analytical approach is used.

Lane's Relationship

In 1955, E. W. Lane expressed the relationships between the driving and resisting forces for channel change in the following simple proportionality. The expression is also illustrated in Figure 8-1.

$$QS\ D50 \propto S\ QW$$

Where QS = Rate of sediment flow
D50 = Median size of mobile particles
S = Slope of the channel bed
QW = Rate of water flow



(Sediment LOAD) x (Sediment SIZE) ∝ (Stream SLOPE) x (Stream DISCHARGE)

(Adapted from Lane, E. W., *The Importance of Fluvial Geomorphology in Hydraulic Engineering*, 1955)

Figure 8-1
Lane's Stable Channel Balance

Here the D_{50} stands as proxy for boundary strength and S for channel shape. From this relationship, it is clear that a change in any of these parameters will, once a threshold is exceeded, induce a change in one or more of the others. The familiar increase in Q_w associated with urban development illustrates this point well. The response to this increase is some combination of the following: a decrease in channel bed slope (incision), an increase in sediment load (increased erosion) and an increase in the median size of mobile particles. When considering all four parameters, these responses often occur in sequence as described below:

- Initial change: Q_W↑; response: Q_S↑. Often the bed slope remains relatively unchanged at first, so to maintain the proportionality, Q_s increases. The increase in sediment load is generated by down cutting of the channel bed (incision), scour of the streambanks or both. The incision locally steepens the channel slope, compounding the driving force for more erosion. This local steepening of bed slope is called a knickpoint. Knickpoints migrate upstream liberating sediment as they progress. When the streambanks exceed their critical height, mass failure ensues. This reconfiguring of the channel geometry continues until the equilibrium described by Lane is reestablished.

- Initial change: Q_W ↑; response: D_{50} ↑. This condition occurs when there is little sediment initially available in the bed or banks. So, to maintain Lane's proportionality, the size of the median mobile particles increases. Under this condition, rock armor that previously protected a structure becomes mobile as the D_{50} increases. Subsequently, the service life of the infrastructure declines. Moreover, the natural bed armoring aggregate, previously mobile only during less frequent floods, becomes mobile during more frequent events and the underlying, more erosion-prone bed and bank materials are exposed to greater and more frequent erosive force.

- Initial change: Q_W ↑; response: S ↓. If the channel bed is relatively resistant to incision, the stream may respond to increased flows by decreasing its slope. The stream accomplishes this decrease in slope by meandering or increasing the channel length over the same change in elevation. The downstream progression of point bars (crescent-shaped sediment deposited on the inside bank of stream bends) opposite the downstream progression of eroding and failing cut banks (steeper outside banks of stream bends) are classic signs of meandering.

- Initial change: S ↑; response: Q_S ↑. Increasing channel slope is often accomplished through channel straightening to achieve greater flood conveyance or to optimize land development. This increase in slope causes an increase in sediment load, in mobile D_{50} size or both. Bed and banks erode to generate the sediment that deposits downstream where channel slopes are flatter. The effective change in water surface slope may extend upstream well beyond the actual channel straightening, extending the accelerated erosion. The sediment eroded from upstream of the channelization and deposited downstream counteracts the effect of the channelization and improvements in flood conveyance are often less than anticipated.

Lane's Relationship is useful for broad conceptual understanding of stream behavior. The following models more specifically address stream process.

Channel Evolution – Evaluating Channel Changes in Cross Section

When considering streams from a management perspective, it is especially helpful to note that streams trend toward the equilibrium condition. Schumm (1984) and most recently Simon (1989) have described a process by which streams reacquire equilibrium after a disturbance in the watershed. Simon separates changes in channel morphology into six stages: I) Pre-Disturbance, II) Disturbance, III) Incision, IV) Widening, V) Deposition, and VI) Recovery and Reconstruction. Determining the phase of channel evolution in the various project reaches was an important part of the analysis.

Widening followed by meander advance on the Lower Main Stem of Stevens Creek

At Stage I, the channel is stable and transports the water and sediment delivered to it without significant adjustment. Although not a universal feature, internal floodplains are common in stable streams including those in the Central Midwest. Bankfull floodplains occur at the elevation corresponding to the dominant discharge. The dominant discharge is the flow that, over time, accomplishes the most work on the stream channel. In undisturbed streams, the dominant discharge typically occurs every 1.5 to 2 years. The bankfull floodplain performs a valuable function by lowering the bank shear during higher flows and effectively managing the stream energy.

During Stage II, natural or manmade events disturb the channel. In disturbed systems, the dominant discharge often occurs far more frequently and may not support the development of internal floodplains. Common forms of manipulation include increases in the rate, volume or timing of flow, or direct alteration of channel dimensions or alignment.

Incision arrested by tree roots on Stevens Creek (Tributary 45)

In Stage III, the stream cuts downward, lowering its channel slope to redistribute energy. This incision process migrates upstream. The migrating face of an incision front is referred to as a knickpoint or knickzone. The typical shape of these channels is V- shaped or narrow U-shaped. In soils such as loess, incision may proceed rapidly; migration rates exceeding 1,000 feet/year occur in the Central Midwest. Incision proceeds until the channel has reached a stable slope, the incision reaches a more resistant layer or the streambanks begin failing because of mass wasting.

Channel widening through mass wasting of the streambanks, Stage IV, follows incision. There are two common mechanisms of bank failure. Fluvial action erodes soil away from the toe of the slope resulting in a cantilevered bank, which eventually fails through toppling. Alternatively, the incision cuts deeply enough into the bed that the streambanks exceed their critical height and fail. Both mechanisms may operate in a stream.

Deposition on Stevens Creek (Tributary 45)

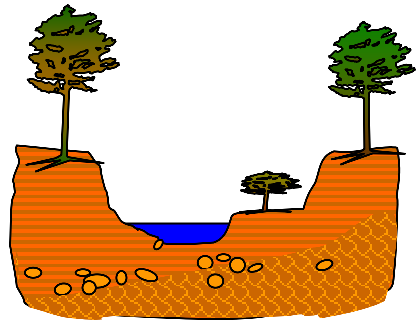
The next phase of channel evolution is Stage V, when the channel has sufficiently widened and begun depositing sediment eroded from upstream reaches in the bed. The deposits occur as channel bars and occasionally as internal floodplains.

In Stage VI, the channel regains the equilibrium condition and efficiently transports both water and sediment. If a substantial increase in Q_w precipitated the adjustment, final dimensions of the channel will probably be larger than the pre-disturbance condition.

Each of these phases is depicted on Figure 8-2.

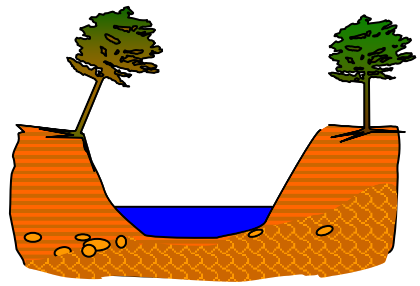
Stage I - Pre-Disturbance

- Bed and bank materials balanced with erosive forces
- Permanent woody vegetation near the water line
- Two-stage channel shape evident at about 1.8 year return interval



Stage II - Disturbance

- Channel altered, hydrology or sediment inputs modified
- Removal of permanent woody vegetation near the water line
- Two-stage channel shape eliminated or no longer supported by flow conditions



Stage III - Incision

- Downcutting liberates sediment
- Lost or perched bankfull floodplains
- "U" shaped channel
- Woody vegetation high on bank with many "surfer" trees

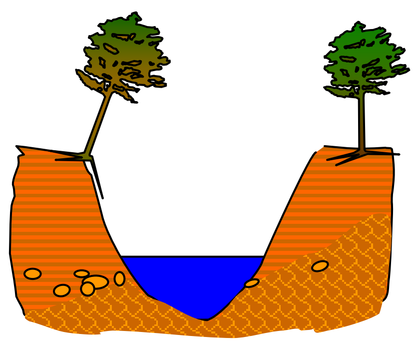
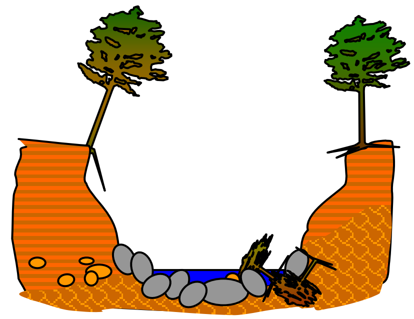


Figure 8-2
Channel Evolution Model (Simon 1989)

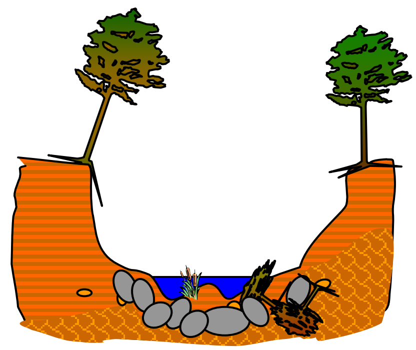
Stage IV - Channel Widening

- Widespread bank failures as banks exceed critical height or were undercut by toe scour
- Channel adjusts to new flow regime
- Significant sediment loads generated; most significant erosion hazard in this phase
- Bank armoring generally ineffective, rocks fall into channel



Stage V - Deposition

- Deposition begins from liberated sediment
- Vegetation establishes near water line



Stage VI - Recovery and Reconstruction

- Bankfull floodplains may be reconstructed from liberated sediment
- Woody vegetation establishes near water line
- Stability re-established

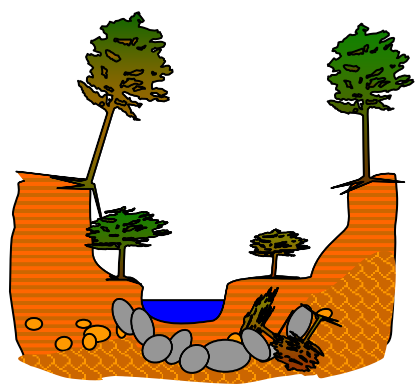


Figure 8-2
Channel Evolution Model (cont.)

Meander Formation and Migration – Evaluating Channel Change in Plan Form

Adjustments in plan form are common and have an important influence on the sustainability of a stormwater system as well as on the safety and service life of near-stream infrastructure. Some plan form adjustments can liberate significant sediment and present major erosion hazards. The management requirements of plan form adjustment differ from those of an incising or widening stream. Consequently, distinguishing between these processes was an important part of the investigation and analysis.

Meander advance on Stevens Creek (Tributary 96)

Straight stream channels are rare and require a narrow set of circumstances to maintain dynamic equilibrium in a natural setting. Like all other open systems, streams adjust their form to minimize the expenditure of energy. The formation of pool-riffle patterns and meanders are consistent with this trend towards maintaining an equilibrium condition. Meanders are complex in both formation and behavior. Meander formation graphically demonstrates the principle of cause and effect in stream mechanics. The cause is the force applied by moving water and sediment and the effect is the shape of stream channel.

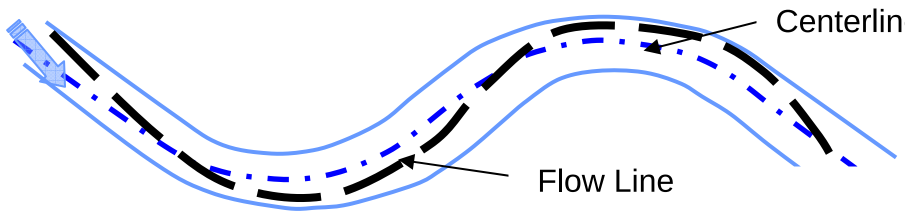
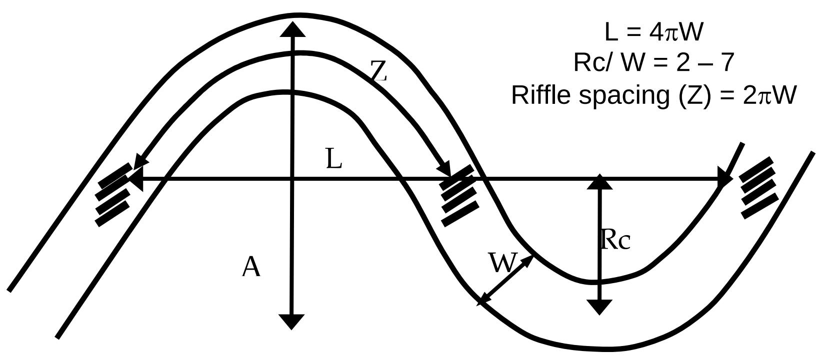


Figure 8-3
Meander Formation and Migration

To describe the basic process of meander formation, the distinction between the meander flow or discharge centerline and the channel centerline is important. As illustrated on Figure 8-3, the channel centerline (effect) lags the discharge flowline (cause). The flow in a stream does not progress in straight lines parallel to the stream channel. Rather the flow is comprised of a primary flow oriented downstream and transverse flows oriented perpendicular to the primary flow. Along the discharge flow path, these inward and outward transverse flows are balanced. However, along the channel flow path, there is considerable asymmetry. Because of the variable turbulence and secondary flow patterns, the flow velocity, sediment transport and boundary shear stress are non-uniform across the channel. These areas of turbulence produce alternating pulses of sediment, scour, and deposition.

Areas of scour and deposition alternate along the axis of discharge flow producing a pool along the outer bend and a corresponding point bar on the inner bend. As the pattern of scour and deposition alternates from one side of the channel to the other, the thalweg (deepest portion of the channel cross section) and maximum flow velocity cross over the center of the channel. These cross-over points become the riffles. The alternating pattern of bar building and bank scour causes straight streams to evolve into meandering ones with a sinuous pattern. Specifically, this is how channelized reaches eventually reacquire a sinuous shape.

Although the process of creating riffles and pools encompasses highly variable processes, the riffles and pools occur at generally predictable intervals. The spacing of these riffles or pools along the thalweg relates closely to the width of the stream at the elevation of dominant discharge. Figure 8-4 illustrates riffle geometry in plan form. Further, the spacing of the pools, which are near the outside bend and slightly downstream of the maximum curvature of the meander, have essentially the same relationship to channel width as the riffles.



L = wavelength   Rc = radius of curvature
A = amplitude   W = width at dominant discharge

Figure 8-4
Meander Geometry

In alluvial streams of homogeneous material, meanders take the form of sine-generated curves. Leopold and Langbein (1969) demonstrated that this shape is the most hydraulically efficient form for turning water. Further, Chang (1998) presents a more analytical assessment of this meander plan geometry. These relationships between stream width, riffle spacing, meander wavelength and radius of curvature are remarkably consistent for streams and rivers throughout the world.

Most stable relationships in channel geometry include the channel width at the elevation corresponding to the dominant discharge. Riffle spacing (Z) generally occurs every 6.3 bank widths (W) where W is the width at the dominant discharge, this spacing is essentially 2πW. Meander wavelength is approximately 12 bank widths, which approaches 4πW.

The radius of curvature is also related to the channel width at dominant discharge elevation. The ratio of meander radius of curvature (R_c) to channel width (W) generally ranges between 2 and 7. Bagnold's (from Thorne et al. 1997) investigation of energy losses at bends confirmed the empirical observations by determining that flow energy losses are minimized through this shape. A tighter radius causes a flow separation and severe energy losses, a hydraulic inefficiency that is not persistent. In natural rivers, channel bends erode to an R_c/W ratio from 2 to 5 and then maintain that form, which indicates that the hydraulic efficiency is optimized by this form.

In streams containing heterogeneous media and in confined channels, the meander pattern is interrupted by variations in bank structure, infrastructure, confluences, geologic features, and channel manipulation. Streams out of equilibrium also display distortions in meander pattern and growth. Nevertheless, the fundamental relationships describing these patterns remain broadly applicable.

Consistent with the location of peak stress downstream of each bend apex, meander waveforms migrate downstream. In stable streams, the meander migration generally occurs at a rate that does not affect infrastructure. However, accelerated migration may pose a substantial risk. A rapid increase in sediment load delivered from an incising or widening reach upstream is the most likely trigger for accelerated migration in Stevens Creek.

Profile Analysis

Stevens Creek flows through erodible soils and has a low threshold for incision. A profile analysis reveals reaches where, by virtue of bed slope and material strength, incision is likely. Abrupt changes in channel profile indicate areas where incision is occurring now or where the degradation is arrested by manmade or natural structures. In Stevens Creek debris jams are the most common natural structures restraining the advance of incision. The advancing front of incision is known as a knickpoint or where slope changes are slightly less abrupt, knickzone. It is especially important to identify and manage incision because it usually precedes processes that are more destructive.

Energy Relationships

Other fundamental relationships used to understand stream mechanics are energy, continuity, and loss relationships. Remembering that energy can neither be created nor destroyed, that mass is conserved, and that all dynamic systems have losses, we can calculate flood elevations and erosive stresses.

First, the total energy in a system can be expressed as:

$$E = w + v^2/(2g) + z - L$$

Where: E = energy (ft-lb/lb)
w = work per unit mass
$v^2/(2g)$ = kinetic energy
z = potential energy
L = losses

The total energy at any point is equal to the total energy at any other point and is expressed as:

$$w_1 + v_1^2/(2g) + z_1 = w_2 + v_2^2/(2g) + z_2 - L$$

Additional equations such as continuity[1] and Manning's loss equation[2] allow the designer to calculate the depth and velocity at any point in the system. Energy, continuity, and Manning's equations are the bases for programs such as HEC-RAS. Bringing these concepts together in the context of stream mechanics, work is the movement of sediment by water, kinetic energy is the movement of water, potential energy is the depth of the water, and losses are friction and sound. HEC-RAS does not include a separate calculation of work. The energy exchange of work moving sediment is included by default in losses and kinetic energy.

Some designers consider sediment transport competency for major projects by establishing a sediment budget to analyze sediment movement through the designed intervention. More sophisticated techniques include computer based analyses. For small projects, it is usually difficult to justify a sophisticated model. The designer, however, can achieve a basic understanding of sediment transport competency and erosion hazard from data and analyses used to determine water surface elevations. The designer estimates area of erosion and deposition from the continuity of the stream power or boundary shear stress. Routines in the HEC-RAS model calculate stream power and boundary shear stress. The values of either stream power or boundary shear stress are plotted against the longitudinal profile. The designer compares the zones of highest and lowest values to his field observations of size and distribution of bed material and the location of scour and erosion. The designer then establishes threshold values from these observations. Improved sediment transport competency results from using these threshold values in design. Boundary shear stress is the product of density, depth and slope. The designer predicts areas of scour and erosion by comparing the boundary shear stress to the shear resistance of the bed or bank toe materials. The shear resistance for granular materials is calculated using empirical relationships. The shear resistance for cohesive materials is usually compared to measured or tabulated values.

Lane's proportionality allows the designer to understand and predict the effect of forces on a stream. Energy and continuity equations allow the designer to predict the depth and average velocity at any point. The energy and continuity equations are the bases for understanding the exchange of energy modes. Perhaps the simplest useful way to apply these principles is to think of energy as either kinetic or potential. For the purposes of stormwater, flooding occurs when potential energy is higher than we can accept and accelerated erosion occurs when kinetic energy is higher than we accept.

8.1.2 Temporal and Spatial Implications

The dominant process in a stream reach is influenced by its location in the watershed as shown on Figure 8-5.

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[1] For modeling purposes, the continuity relationship expresses the concept that the quantity of water in any one point in a system is the same as the quantity of water at another point or changes only gradually. At each confluence, hydraulic models are partitioned into discrete reaches.

[2] Manning's loss equation is commonly expressed as $Q = 1.49(R^{2/3}S^{1/2})A/n$

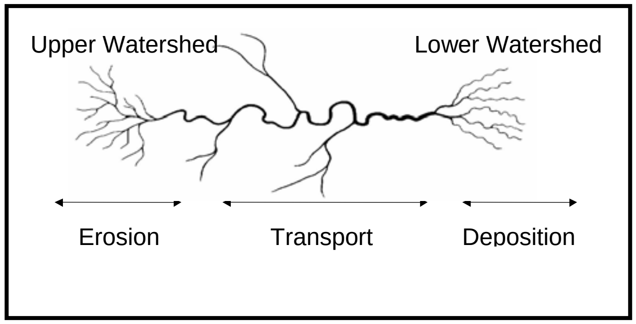

Figure 8-5
Stages of a river system (adapted from Rienick and Singh 1980)

As shown on Figure 8-6, the profile of the channel slope becomes flatter progressing downstream. In the most general sense, incision dominates the steep, upper watershed and plan form adjustments are most common in the relatively flat lower watershed.

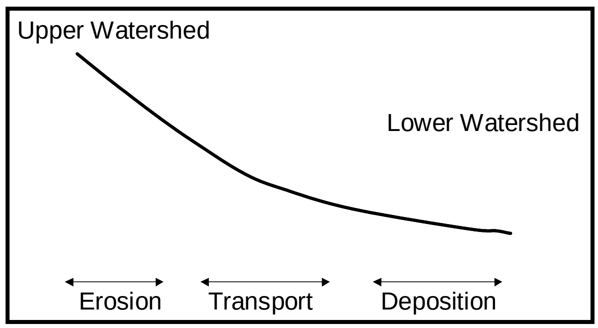

Figure 8-6
General channel profile of a watershed

In disturbed watersheds, this pattern may be reset by infrastructure. For example, a dammed stream can act as the end of a watershed, where sediment and water is deposited in the receiving lake (Figure 8-7). Here the outfall behaves like a spring beginning the next watershed.

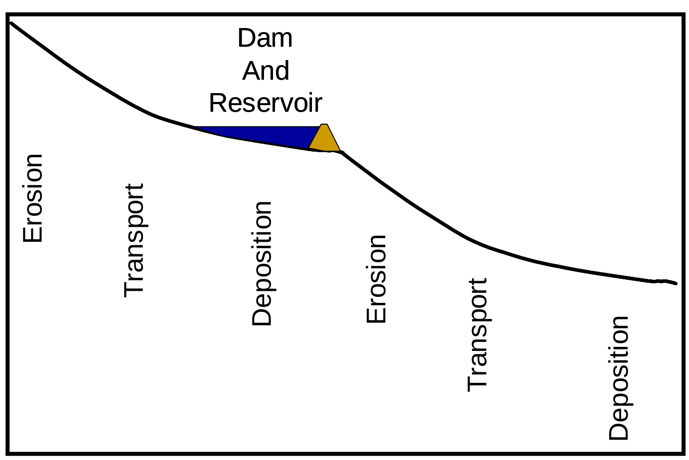

Figure 8-7
Effect of a dam resetting the stream formation sequence

Stream crossings such as bridges and culverts can also reset river formation, as shown on Figure 8-8. In developing areas, the characteristic profile shape of natural watersheds may be repeated after each hard crossing that materially effects transport of water and sediment. These obstructions may geomorphically isolate the reach.

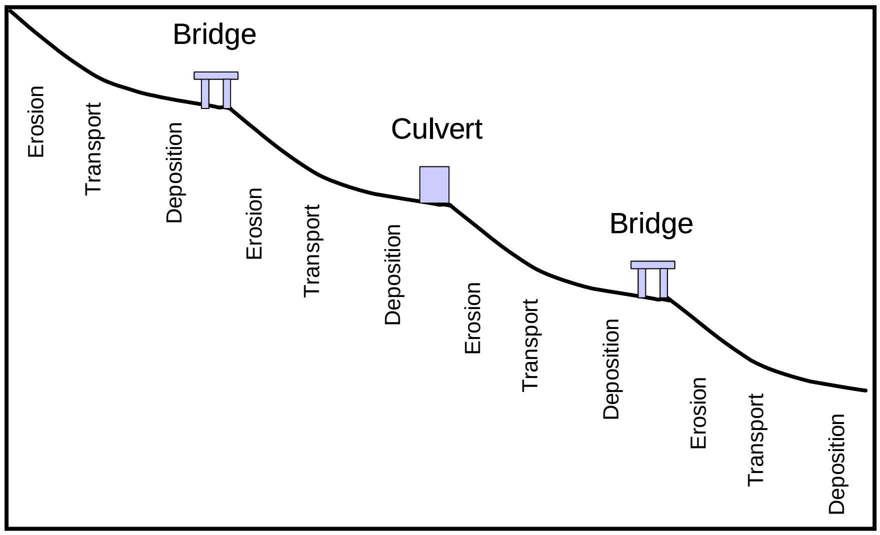

Figure 8-8
Effect of stream crossings resetting the stream formation sequences

8.1.3 Sediment Transport

Natural channels transport both water and sediment through the watershed. Sediment and water movement play parallel roles in flood and erosion control and in the performance of bridges and culverts. For this discussion, sediment includes large woody debris, man-introduced materials, and other debris that comes to rest on the streambed. A stream in dynamic equilibrium maintains the movement of water and sediment without sudden and wholesale areas of erosion and deposition. Flow rate governs both the initiation of sediment movement and its deposition, moving material when the system has sufficient kinetic energy and depositing it when the kinetic energy is depleted. As described earlier, gravity, expressed here as hydraulic slope, is the driving force acting on the system. The movement of water transfers that force to dislodge and keep particles moving. Figure 8-9 is a generic hydrograph and sedigraph relating the rate of flow to time. Note that there is a lag between the flow of water and the movement of sediment ($t_{s\ i}$). The lag represents the flow necessary to exceed the critical shear stress as described in Section 6.5. At the peak water flow there is often a decrease in the transport of sediment as the hydraulic slope decreases. The falling leg of the hygrograph may coincide with the peak of the sedigraph with the particles already mobile and an increase in hydraulic slope.

As the flow recedes and kinetic energy declines, the stream deposits particles of decreasing particle size. This process forms the riffles between pools. In Stevens Creek, this is most apparent where the woody debris jams morphologically behave as riffles.

Issues of sediment transport are particularly relevant to stream managers at infrastructure crossings. Bridge, culvert, and pipeline crossings may interrupt the hydraulic slope with predictable, adverse consequences. A crossing backwatered under high flow conditions decreases the hydraulic slope and may induce deposition that reduces flow capacity. Over-widened or excessively smooth crossings increase hydraulic slope and induce scour. The scour may occur immediately downstream and undermine the structure or may, as the result of an upstream drawdown curve, induce incision. This incision migrates upstream until the stream reaches a stable bed slope.

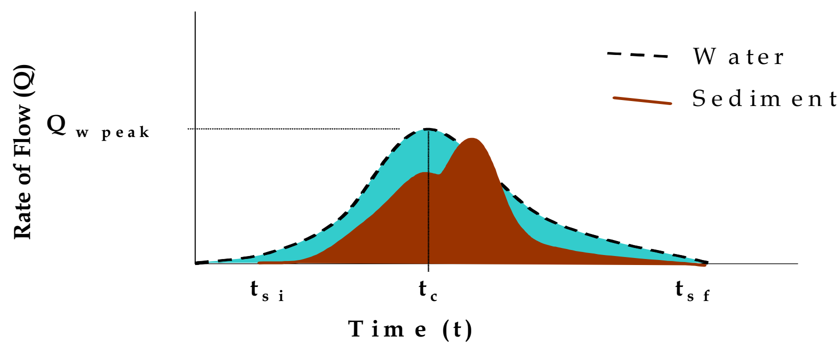

Figure 8-9
Hydrograph and Sedigraph

Management activities that remove or add material to the stream also interrupt equilibrium sediment transport and may have similarly adverse consequences. Snagging, straightening, and widening a channel all disrupt the sediment balance. These and similar activities induce upstream erosion and eventual deposition at the site of disturbance. Undesigned bank armor such as dumped riprap or waste concrete disrupts sediment transport when it migrates into the bed. These large, rough particles induce deposition where they enter the bed but induce scour downstream. Dumping materials on the bed can also reset the pool and riffle sequence if the dumped material becomes the hardest point in the reach.

8.2 Stevens Creek Evaluation

The stream stability analysis included an extensive background and field investigation to document the key geomorphic characteristics of the main channel and tributaries. This included walking 81 miles of stream to assess, record, and photograph the condition of the streambed, streambank, riparian vegetation and to assess the overall stability of the stream. Details of the geomorphic field investigation are presented in Section 2.5.2.

Generally, the field investigation revealed widespread instability. The instability most commonly occurs as incision, a downward cutting of the channel, migrating upstream from the lower main stem and extending through the tributaries. The bed and bank materials are relatively weak and are responsive to increased stress. Streambank failures are common in all parts of the watershed. The bank failures are usually a consequence of the incision. The absence of a vigorous woody corridor protecting the streambanks increases the frequency and severity of bank failures.

8.2.1 Channel Geometry

Stevens Creek was evaluated in plan, cross section, and profile. Detailed information regarding individual reaches is provided in Volume II, Appendix I, Stream Reach Descriptions.

Plan Form

Evaluating the shape of the watershed in plan form provides insight on whether and how parts of the basin differ from one another. For example, subbasins with a greater degree of geologic control, higher density of tributaries, or more severe degrees of channel manipulation may require different management approaches than the remaining subbasins. The drainage basin analysis was conducted in accordance with the method described by Lueder (1959). Consistent with the regional geology, the drainage network analysis indicates relatively high erodibility and low permeability. The angle at which the tributaries intersect each other and intersect the main stem suggests manipulation, most likely channel relocation along farm field lines.

Outside of the highly altered southern third, there are no major differences from one subbasin to the next. The minor differences include a slightly higher tributary density and higher tributary sinuosity east of the main stem relative to the west. The differences are within the range one might expect to be associated with the greater degree of urbanization on the west side and do not imply a need for different management methods based on subbasin location.

Meander geometry evaluation revealed that, at the broadest levels, the basic ratios of radius of curvature to width (Rc/w) and wavelength to width (λ/w) fall within the reported values as indicated on Figures 8-10 and 8-11. In analyzing the data, the ratio of radius of curvature to width is higher than the normal boundary for some of the eastern tributaries in the 5- to 10-foot width class. Similarly, the drainage network density is greater on the eastern tributaries indicating that these soils may be weaker and more erodible, therefore unable to hold a tighter radius as shown on Figure 8-12.

The wavelengths appear slightly longer relative to channel width than is typical, particularly on the lower main stem (Figure 8-13). This may accurately reflect the channel conditions or may be an artifact of using the aerial two-foot contour to determine width.

Eighty-one per cent of the radius of curvature to width ratios falls within published norms (Nanson and Hickin 1983). Areas that are substantially outside the norm were noted on the GIS layer and field evaluation focused on determining why the anomalous data occurs. No specific differences were observed during the field work. Geometry outside the norm does not necessarily imply instability either now or in the future. Especially tight or flat curves may simply indicate a vegetative or geologic control or the presence of a stabilized manmade structure.

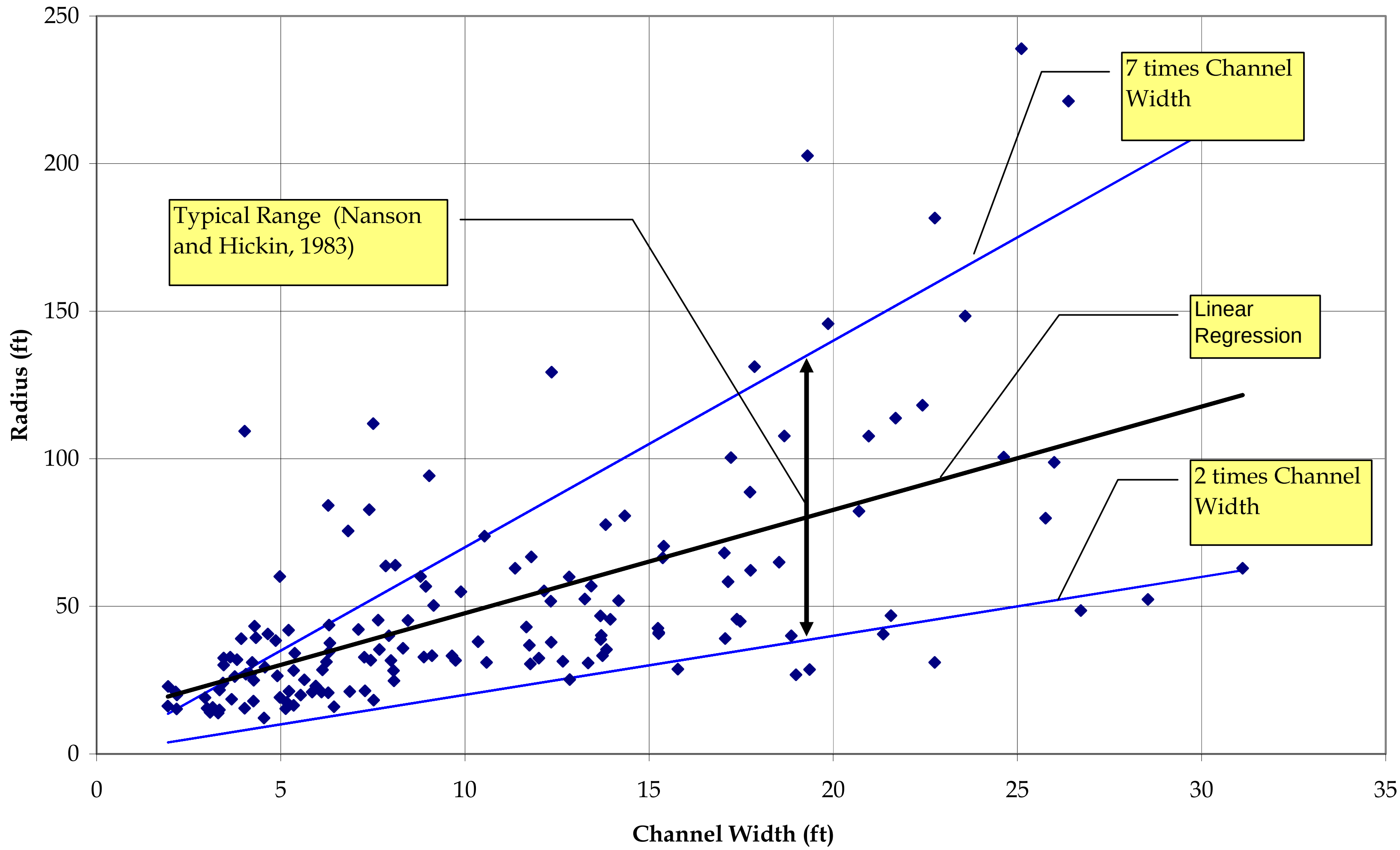

Figure 8-10
Width versus Radius

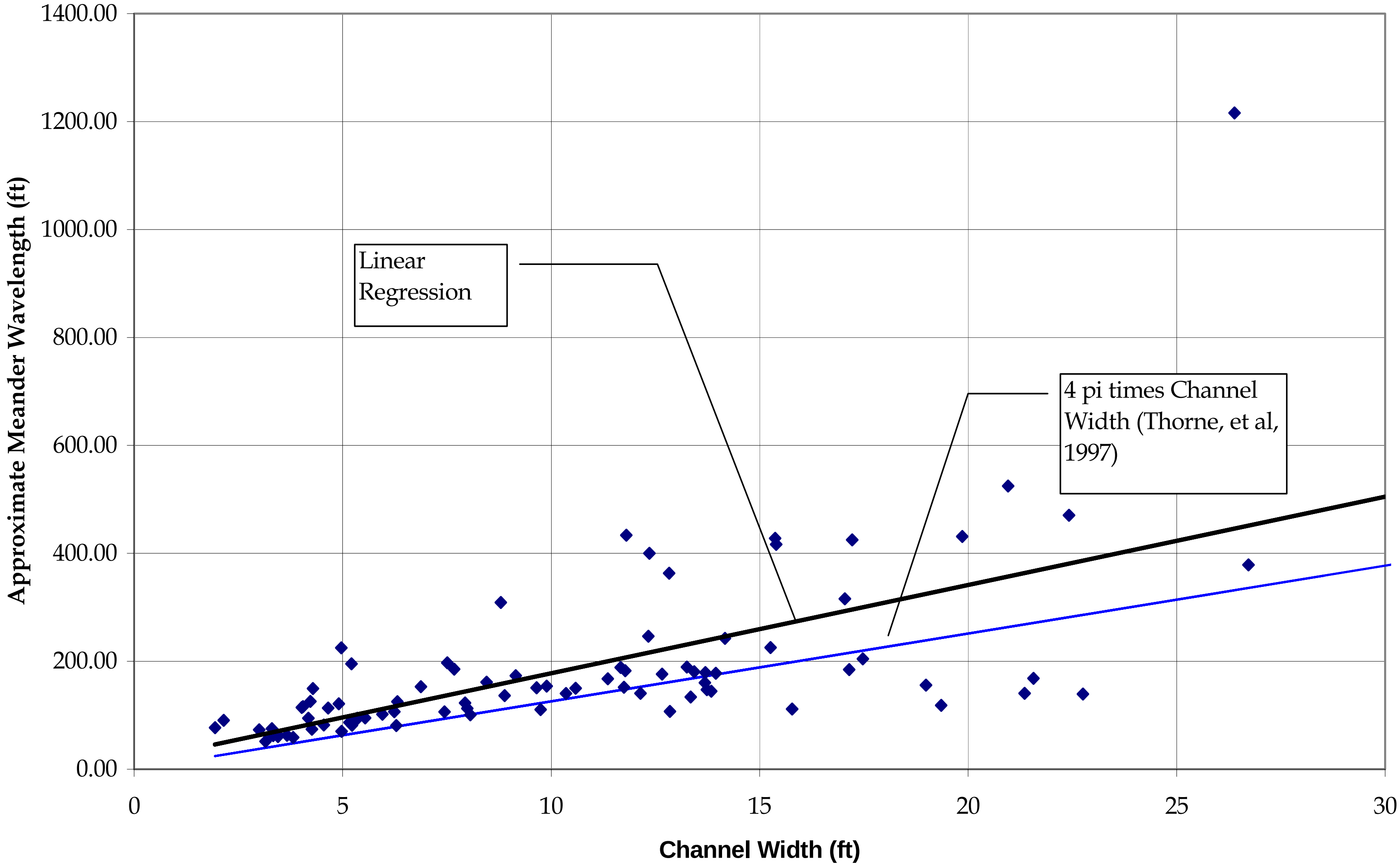

Figure 8-11
Width versus Meander Wavelength

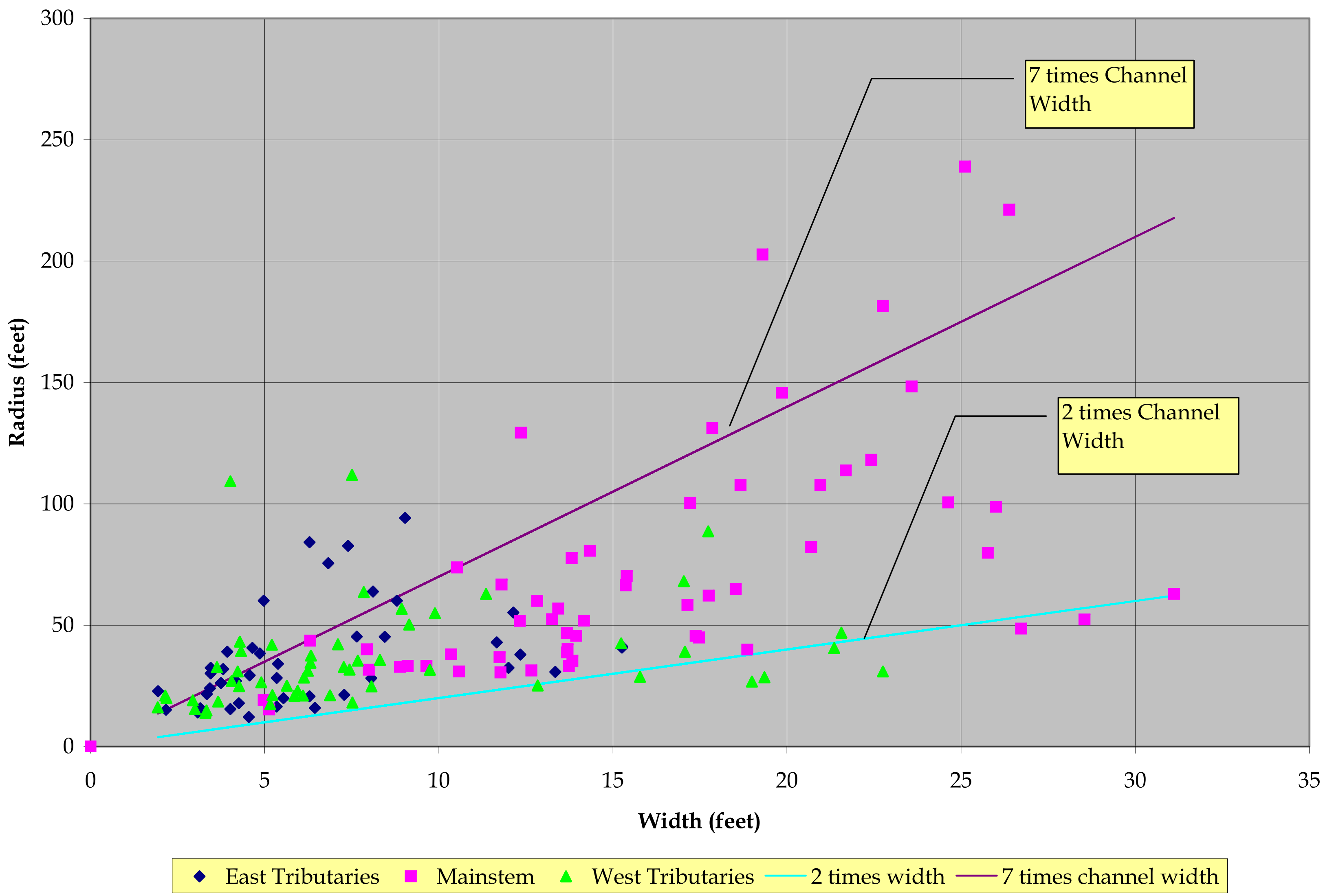

Figure 8-12
Radius versus Width by Location

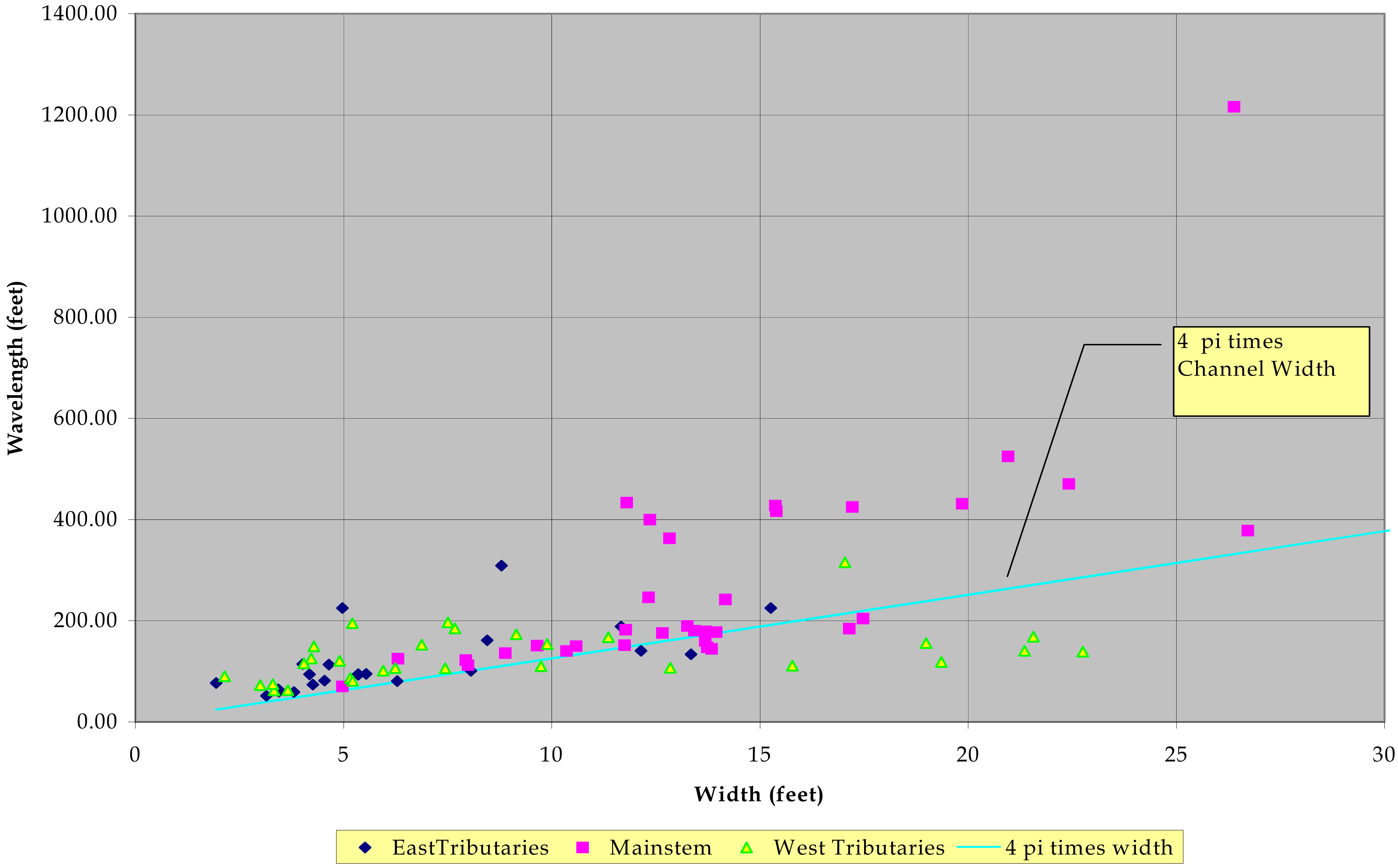

Figure 8-13
Wavelength versus Width by Location

Cross Section

The cross sectional shape of a stream channel indicates the stage of channel evolution. When integrated with plan and profile indicators such as bar building or knickpoints, cross section data are used to determine the dominant channel process. No one data set is adequate to diagnose channel process, the foundation of stream management, but analyzed in the aggregate, it is possible to build a defensible case. Figure 8-14 illustrates the point. Here channel bed profile, the 2-year water surface elevation, and breaks in bank slope are plotted together. The breaks in bank slope used in this analysis are generally at the lowest elevation of an abrupt flattening of the slope. In many stable streams, the lowest break in bank slope occurs at a consistent elevation corresponding to the dominant discharge, roughly the 1.8-year return interval. The field investigation revealed very few bankfull features at any elevation. Those few features identified as potential bankfull floodplains occurred at elevations between 1.5 and 5 feet above channel bed, well below the major breaks in slope now dominating the channel cross section. In Figure 8-14 it is clear that the lowest consistent breaks in bank slope are substantially lower than the 2-year elevation. This finding is consistent with Section 6.5, which demonstrated the increased frequency of dominant discharge.

Figure 8-14 also includes two lines representing the average bed elevation and the average elevation of breaks in bank slope. There are four reaches where the section break occurs below the average for the main stem. The lower three of these are areas of channel widening as determined from analysis of the hydraulic and field data. This follows since for lower flows the water surface level will drop in wider reaches as compared to narrower reaches.

The cross-sectional data is useful in developing Bank Stability Charts for the watershed. The plot of bank angle versus bank height is a Bank Stability Chart. Bank stability is the relationship between bank height, angle, material, and saturation level. A Bank Stability Chart can be a powerful planning tool. Just because a bank is steep and bare of vegetation does not necessarily mean that it is unstable and that a landslide might occur after the next major flow event. Simple measurements of height and angle and observation of groundwater and other conditions can be checked against the chart to assist in determining the probability of a bank failing as a result of a landslide.

The method for creating bank stability charts and their application is explained in Chapters 7 and 8 of *Stream Corridor Restoration, 1998* [3]. The method entails recording the heights, angles, and groundwater conditions of both failed and intact slopes throughout the watershed. A parametric analysis is performed using slope stability software such as ARS Bank Stability Model, Static Version 2.1. (USDA 2002). In the analysis, the limits between stable, meta-stable, and unstable are confirmed by calculation. Meta-stable is the condition of eminent failure where changing any one of the conditions could result in a landslide. For the Stevens Creek analysis, the default values for silt and a simple model of one layer of silt and a planar slope were used. In the parametric analysis the water table was varied to match conditions observed in the field.

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[3] Stream Corridor Restoration, Principles, Processes, and Practices, The Federal Interagency Stream Restoration Working Group, National Technical Information Services (NTIS), November 1998, PB 98-502487, ISBN-0-934213-60-7

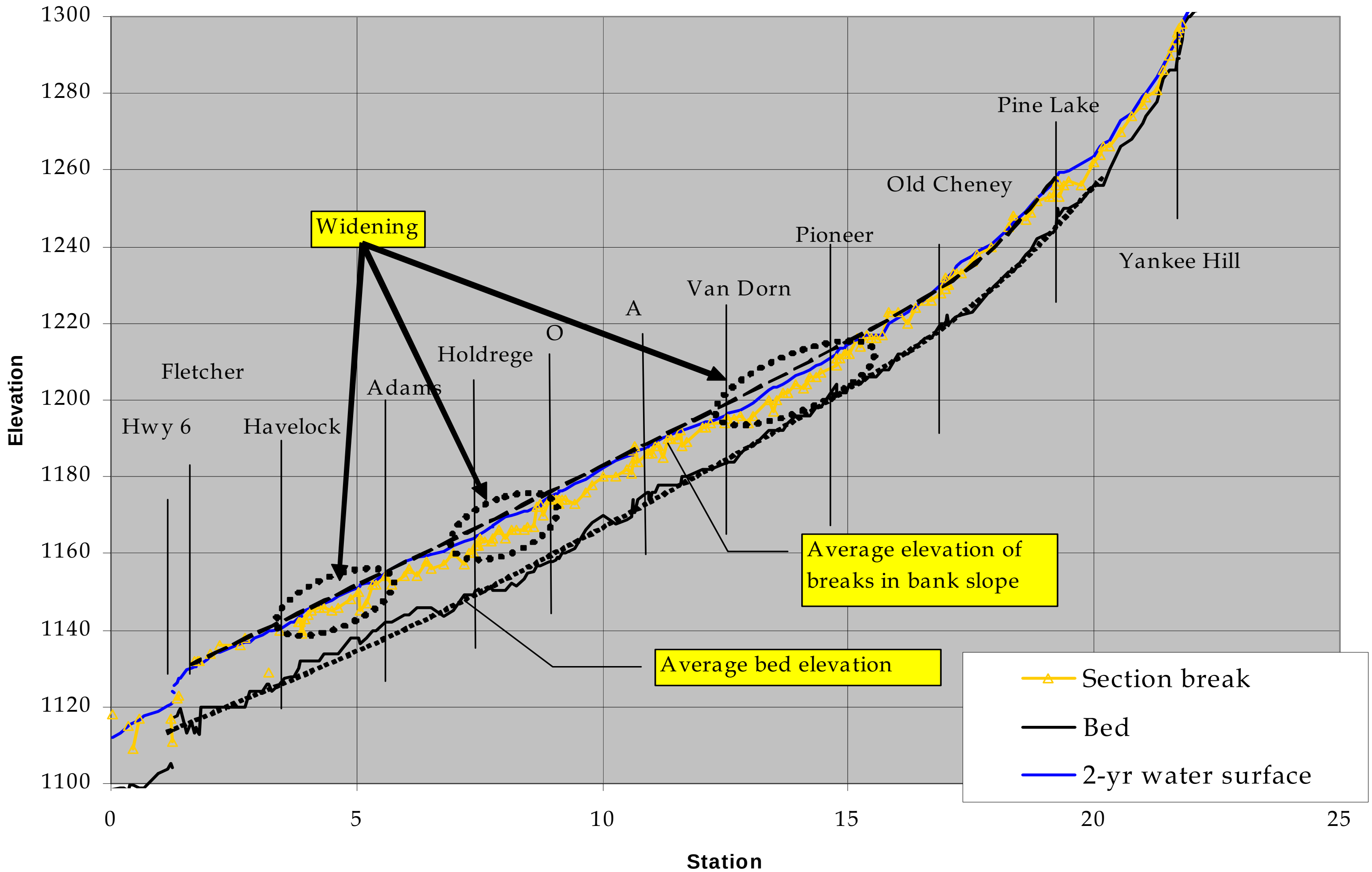

Figure 8-14
Channel Bed Profile

Two separate conditions were modeled, a saturated low steep slope and a partially saturated, high steep slope. The saturated low steep slope is typical of the conditions in the tributaries and upper watershed that has not incised beyond 5 feet. The Bank Stability Chart for the low saturated bank is presented on Figure 8-15. The partially saturated high steep slope is typical of the rapidly incising channel greater than 5 feet high. The relationship between gravity and capillary tension prevents saturation of steep slopes greater than about 5 feet. The Bank Stability Chart for the partially saturated high bank is presented on Figure 8-16.

The reader will note that there are many points above the unstable limit for the partially saturated condition. These include complex cross-sectional geometry, vegetated reinforced slopes, unsaturated conditions, possibly stronger soils, and other conditions beyond the scope of this analysis. It is likely that many of the slopes are meta stable and will fail, particularly under saturated conditions.

Longitudinal Profile

The longitudinal profile of a stream is one of the most useful diagnostic tools for determining the fluvial processes active in a stream system. Figure 8-17 is the longitudinal profile of the main stem from the HEC-RAS analysis. The channel bed is from the 2-foot interval contour and is shown as a black line with black rectangles at data points. The dashed (red) line represents the typical longitudinal profile of a stream, steeper at the headwaters and flattening downstream. Notice that the channel bed measured from the 2-foot contour is below the typical longitudinal profile downstream of Holdrege. This indicates a knickzone between Adams and Holdrege; the channel has incised to Adams and is currently incising towards Holdrege. Collected field data confirms this diagnosis.

The longitudinal profiles of Stevens Creek and its tributaries are typical of a stream that has undergone several waves of manipulation. The combination of road and railway crossing, channelization, and land disturbance has interrupted the fluvial process. Using Figure 8-17 as an example, the channel is interrupted near the crossings as explained in Section 8.1.2 and is shown by the solid (blue) line. Between each interruption, the profile is the shape of a watershed. Interruptions are at Highway 6, MoPac Trail, Holdrege, A, Pioneer, Pine Lake, and the NRD dam. These interruptions can affect sediment transport continuity and therefore fluvial process and will be discussed in Section 8.2.4.

Although there are differences in bed composition, in general, meta-stable reaches have a bed slope of 0.03 per cent. The bed slope for widening reaches varies from 0.03 to 0.13 percent. Incising reaches have higher slopes.

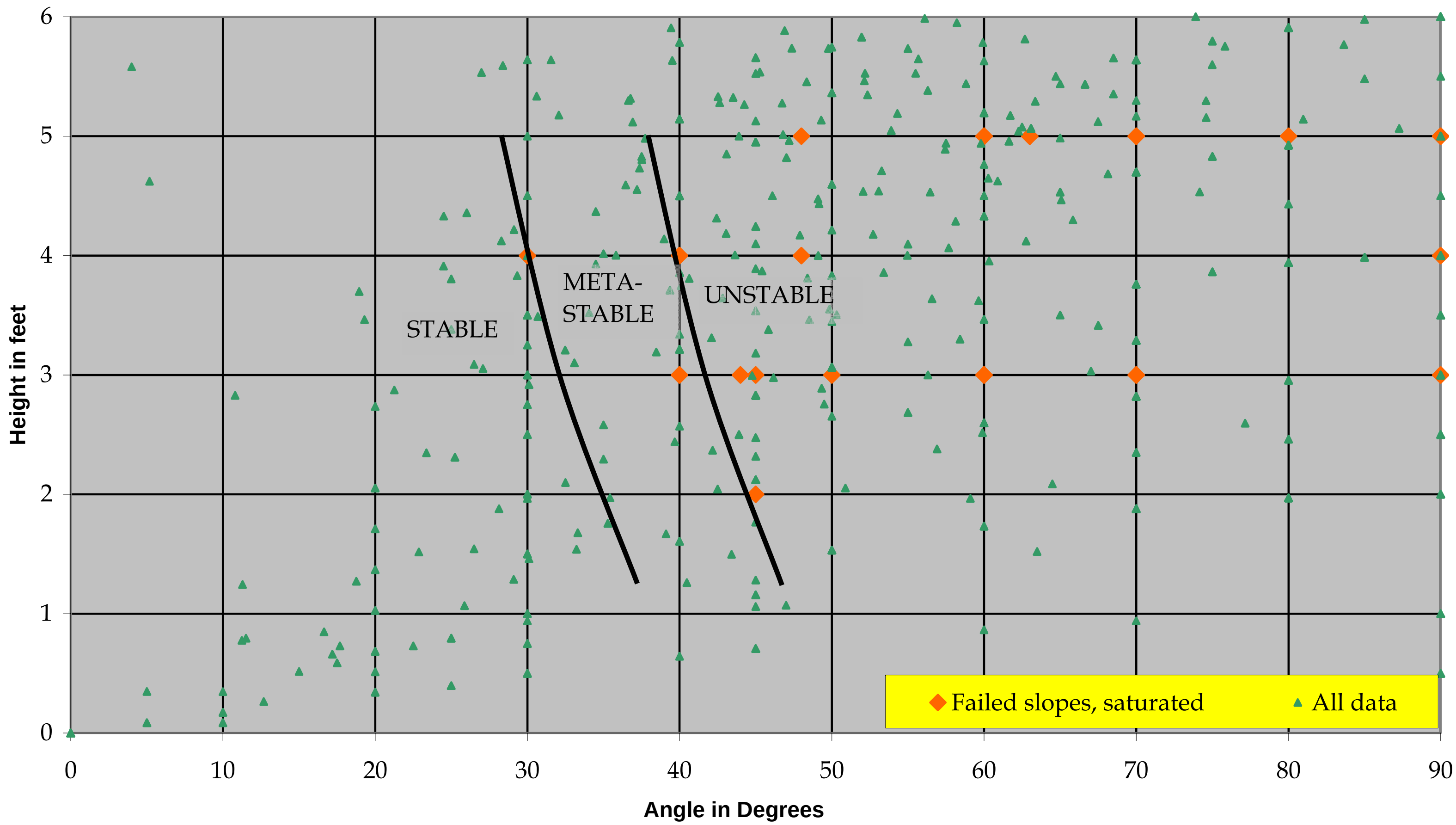

Figure 8-15
Critical Bank Height and Angle for Saturated Condition, Slopes <5 Feet for Tributaries and Upper Watershed

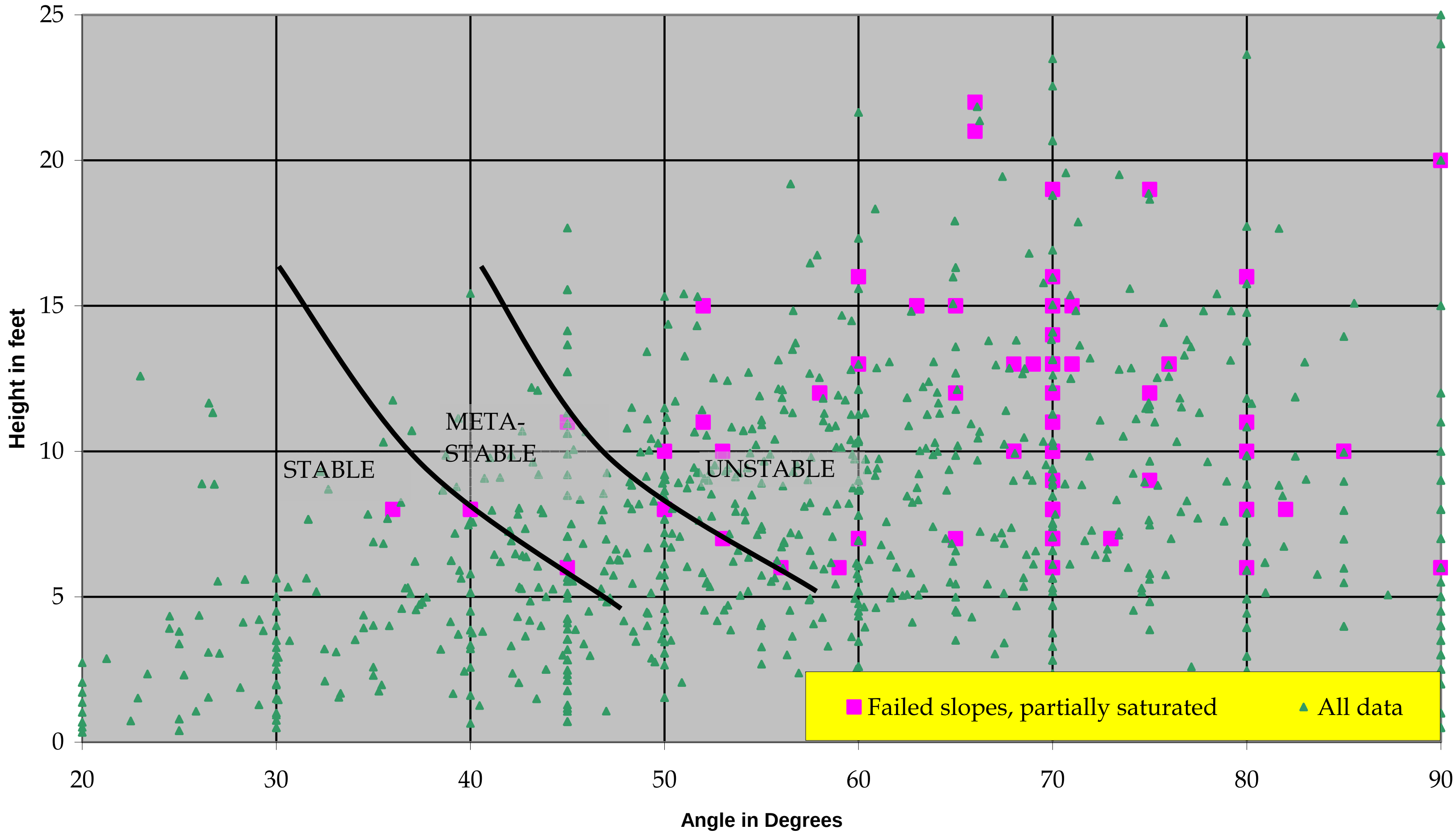

Figure 8-16
Critical Bank Height and Angle for Slopes > 5 Feet High, Partially Saturated Condition for Rapidly Incised Channel

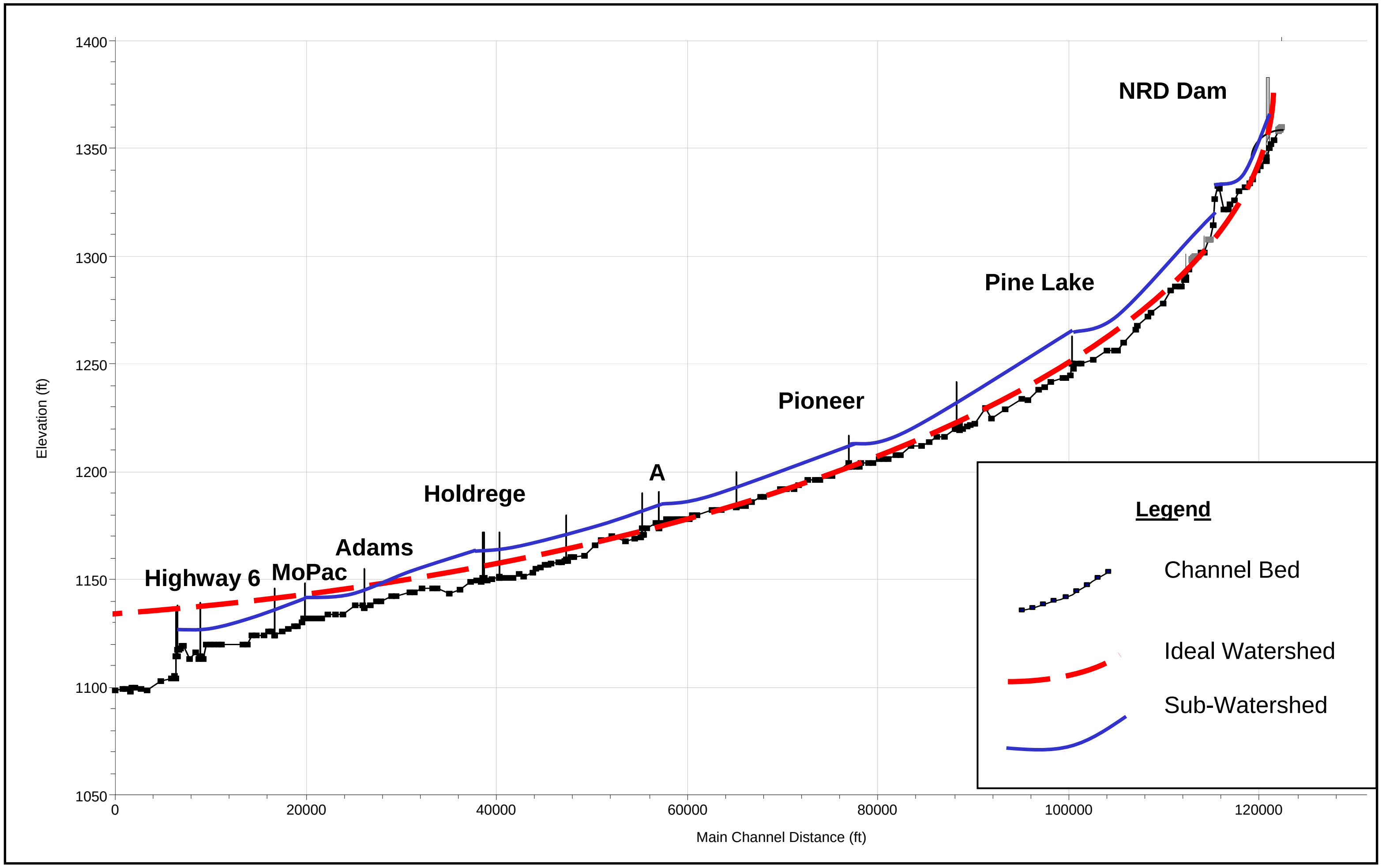

Figure 8-17
Main Stem Longitudinal Profile

The reach average slopes used in the geomorphic analyses were calculated from longitudinal profiles generated from 2-foot contours. The longitudinal profile was also surveyed for specific reaches of Stevens Creek as illustrated on Figure 2-2. Comparison of the two profiles (contour-generated vs. surveyed) validated the accuracy of the reach average slope calculated from contour-generated profiles. The reach average slopes are nearly identical with that of the surveyed profile. Localized changes in slope between contours were recorded during field observations. Rather than survey a longitudinal profile of the entire watershed, the profile information gathered as a GIS layer during the field investigation was used for this analysis. The strong correlation between surveyed profiles, contour data and field data provides confidence in the validity of the findings.

8.2.2 Boundary Material

The bed and bank materials are composed of the native soil, large woody debris, introduce debris and rock, vegetation, and groundwater.

Soil

Soils throughout the basin are clayey silts, silty clays, and clay. In general, the soils are weak and erodible. They become less plastic with depth until the clayey till contact. The banks are moderately well drained; however, saturation increases the mass and weakens the soil. The most common failure modes are circular, wedge, and toppling. If the silt-till interface is exposed, the banks usually fail on this surface. Reaches that have incised deeper than 10 feet with bank angles around 60 degrees are meta-stable. The incision has lowered the groundwater table and drained the near-bank soils. This increase in capillary tension increases the apparent strength of the soils. These banks however, are susceptible to raveling by drying and freeze-thaw cycles and to undercutting by toe erosion. These higher banks are also susceptible to failure as saturation increases. Critical bank height and angle are discussed in Section 8.2.1.2.

As the clay content increases, the fluvial process shifts from incision to widening. This is demonstrated on the main stem between Fletcher and Adams. The main stem has incised down to the till, which is more resistant to incision. That reach of channel is now responding by widening.

Critical shear resistance for the silt is estimated as 0.15 psf. Critical shear strength for the silty clay and clay is estimated as 0.26 psf.

Debris

This discussion of debris includes large woody debris, dumped concrete, rock, and other waste. Other waste includes discarded appliances, hay bales, fence, and similar materials. Dumped debris falls into several categories; waste, bank armoring, or bed armoring. With the exception of infrastructure protection, there is little systematic armoring in this stream. Whether intended to stabilize a failing bank, arrest incision or dispose of waste, the dumped material in the stream is not effective in improving stream stability and in some cases aggravates the instability.

The natural response to incision in this region is the development of woody debris jams. As trees and shrubs fall into the creek, the woody debris is distributed throughout the system forming a pool and riffle system. The debris jams generate the profile form that manages energy. The jams reinforce the bed and increase the hydraulic roughness dissipating erosive energy. The backwater effect of the jams lowers the hydraulic gradient for low flows. The critical shear resistance for woody debris is estimated at 3 psf.

While debris jams may contribute to local flooding, they also reinforce local stability. Removal of debris jams without reinforcing the bed usually leads to incision, widening, or meandering. The location of debris jams is presented as a GIS layer.

Vegetation

The vigor and integrity of riparian vegetation plays an important role in the physical, chemical and biological health of stream systems. In their landmark report, Riparian Areas: Functions and Strategies for Management (National Research Council 1999), the authors define riparian areas as "transitional between terrestrial and aquatic ecosystems and are distinguished by gradients between biophysical conditions, ecological processes, and biota. They are areas through which surface and subsurface hydrology connect water bodies with their adjacent uplands." Diverse stands of healthy native vegetation process and sequester pollutants, temper the volume and timing of surface runoff, moderate soil moisture, and increase the shear strength of streambanks. By adjusting the rate of evapotranspiration as plant-available moisture varies, trees and shrubs moderate the extremes of soil moisture and help maintain optimum moisture for soil strength.

The riparian corridor of Stevens Creek is in poor condition. While there are some stands of trees remaining, most of the watershed is denuded. When not farmed to the edge, the banks are often lined with a thin band of cottonwood, mulberry, or locust. The sparse trees and shrubs do not provide the benefits expected of a vigorous woody corridor. Both the water quality and physical stability of the system suffer as a result. The absence of an intact corridor increases the sensitivity of the banks to groundwater related failures. In the absence of extensive root reinforcement to mechanically strengthen the soil and evapotranspiration to reduce the saturation near the surface, the banks are excessively vulnerable to failure under mild stresses.

Groundwater

The depth to groundwater is seasonal. The water table varies from 1 to 6 feet below the surface. The water table for the Crete loam along Tributary 5 in the northwest may be 12 feet below the surface. The channeled Nodaway silt loam that comprises much of the channels has a high water table, typically 6 feet below the surface. The effect of groundwater on soil behavior is discussed in Section 8.2.2.1. The near-stream groundwater table appears to be directly related to the depth of incision. As the streams incise, the groundwater table lowers. A binary system has developed with high groundwater in shallow streams and suppressed groundwater levels in steep, deep stream reaches.

8.2.3 Hydraulics

The HEC-RAS analysis provided the shear stresses applied to the bed and channel. This in turn allowed assessment of which reaches of the stream are likely to erode under a specified condition. The results of this analysis were compared with the field assessment of geomorphic stability with generally good agreement. The HEC-RAS was developed using the 2-foot contour data. The applied shear stresses for the 2-year flows are used in analysis. This is the lower limit that is reasonable to use based on the topographic data and the arrangement of the model. Shear values are calculated at discrete cross sections in the model. Reach-average shears compare well with reach-average fluvial process.

Applied shear strongly influences channel process. Reaches with high shear are generally incising. Reaches with low applied shear are most often in deposition or are meta-stable. For incising reaches total shear and bed shear are the same when the flows are contained in the channel. For other processes the comparison will vary.

Figure 8-18 presents a portion of the watershed near Van Dorn and 134th. The figure identifies knickpoints and the total shear values where the circle size is proportional to the magnitude of the shear stress. Knickpoints provide an indication of ongoing or recent incision. For these tributaries the total shear is high in areas with knickpoints. This indicates ongoing incision. There are also relatively fewer knickpoints along the main stem where the shear values are lower. This portion of the channel has incised but is currently widening. The strong correlation between applied shear and fluvial process is consistent throughout the watershed.

8.2.4 Sediment Transport Competency

Stevens Creek is exporting sediment to Salt Creek. Stevens Creek is competent to transport sediment throughout the watershed. Once dislodged, the soil particles are easily transported only depositing in reaches with low bed slope or debris jams. As demonstrated in Section 6, the frequency of flows capable of transporting fine sediment has increased. This decreases the time for the soil to consolidate and for vegetation to become established. Although a lot of sediment is being delivered to the system, little is stored in bars.

Three reaches along the main stem appear to be in dynamic equilibrium. These reaches are above Highway 6, O Street, and Pioneer. These bridges hold grade and meter the movement of sediment.

The main channel below Highway 6 meanders in response to the changes in proportions of the rate of water and sediment. Insufficient time has elapsed to determine if bed slope is increasing or decreasing.

Headwater tributaries 5, 105, 40, 460, and 396 are in dynamic equilibrium.

8.3 Physical Stability of the Watershed

8.3.1 Existing Channel Process

The dominant fluvial process in Stevens Creek Watershed is incision. Areas of channel widening interrupt areas of incision. Widening occurs when the bed is more resistant, either from an increase in clay content or the formation of debris jams. Meta-stable zones exist on the main stem upstream of three bridges as explained in Section 8.1.3, Sediment Transport Competency. Two areas of meandering are active, below Highway 6 and below the confluence of Tributary 96 and 196. Current fluvial process for reaches in the

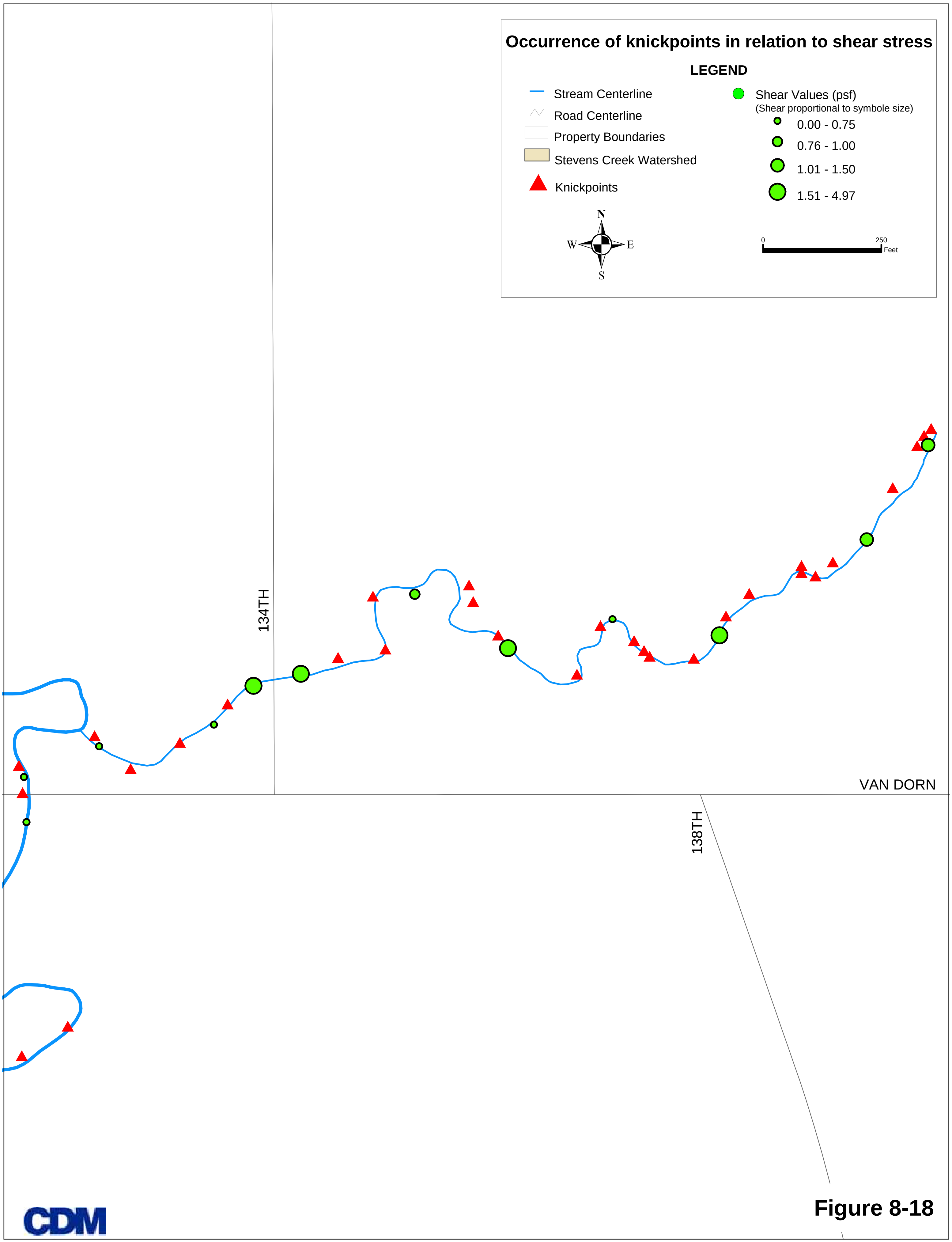
Occurrence of knickpoints in relation to shear stress
LEGEND
Stream Centerline
Road Centerline
Property Boundaries
Stevens Creek Watershed
Knickpoints
Shear Values (psf)
(Shear proportional to symbole size)
0.00 - 0.75
0.76 - 1.00
1.01 - 1.50
1.51 - 4.97
N
W
E
S
0
250
Feet
134TH
VAN DORN
138TH
CDM

Figure 8-18

watershed is determined from the geomorphic observations and analysis and from the hydraulic analysis.

Figure 8-19 is a screen capture of some geomorphic data developed in a GIS format and demonstrates how the data is used in analysis. Figure 8-19 is of the confluence of the main stem, Tributary 60 and Tributary 65. These reaches have similar bed and bank material and scour patterns. However, there is an obvious increase in the number and frequency of knickpoints for the incising reach.

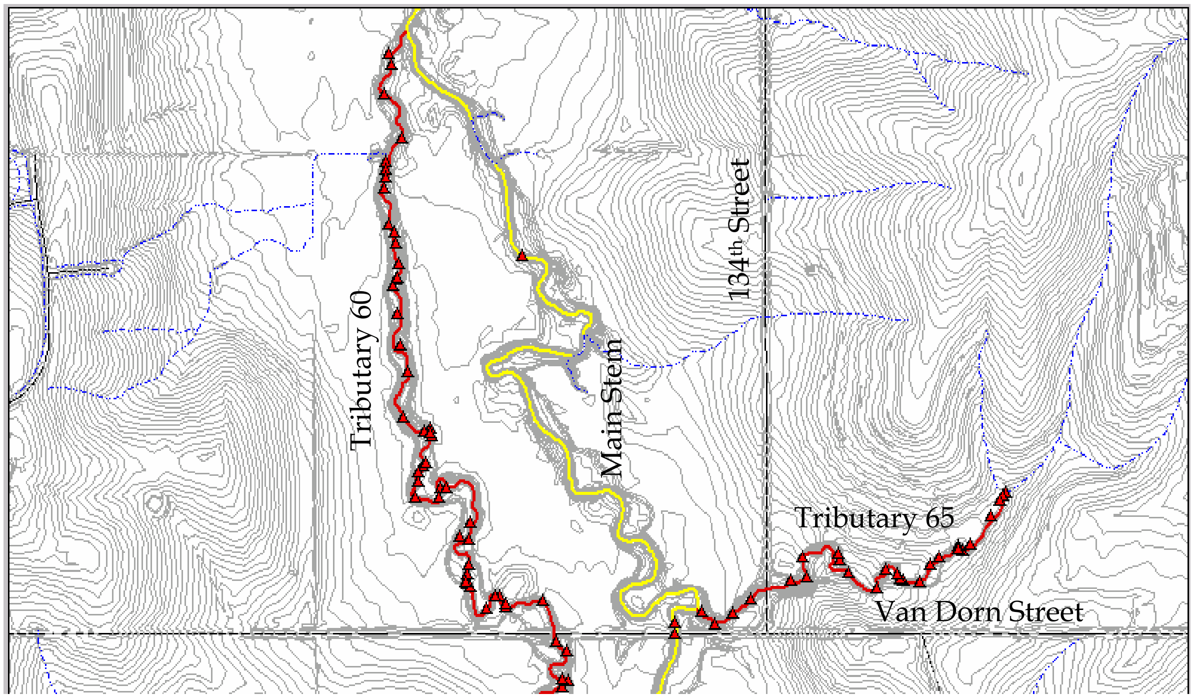

Figure 8-19
Difference in the number and frequency of knickpoints along an incising reach (red) versus a widening reach (yellow)

The results of the process analyses are presented on Figure 8-20. Green reaches are stable, yellow are widening, red are incising, and orange are meandering.

8.3.2 Erosion Hazard

Stevens Creek will continue to degrade until the driving forces are limited and channel interventions are installed. Generally, until then the current fluvial processes will continue. Incision and widening will continue. If streams incise below the critical bank height and angle for soil saturation conditions (see Section 8.2.1.2 for a discussion of critical bank height) mass wasting will occur. The channel will either widen or begin meandering. The fluvial processes are presented on Figure 8-20. Stable reaches in headwaters of western tributaries (Tributaries 5, 105, 10, 30, 25, 460, and 396) are threatened by possible incision moving upstream.

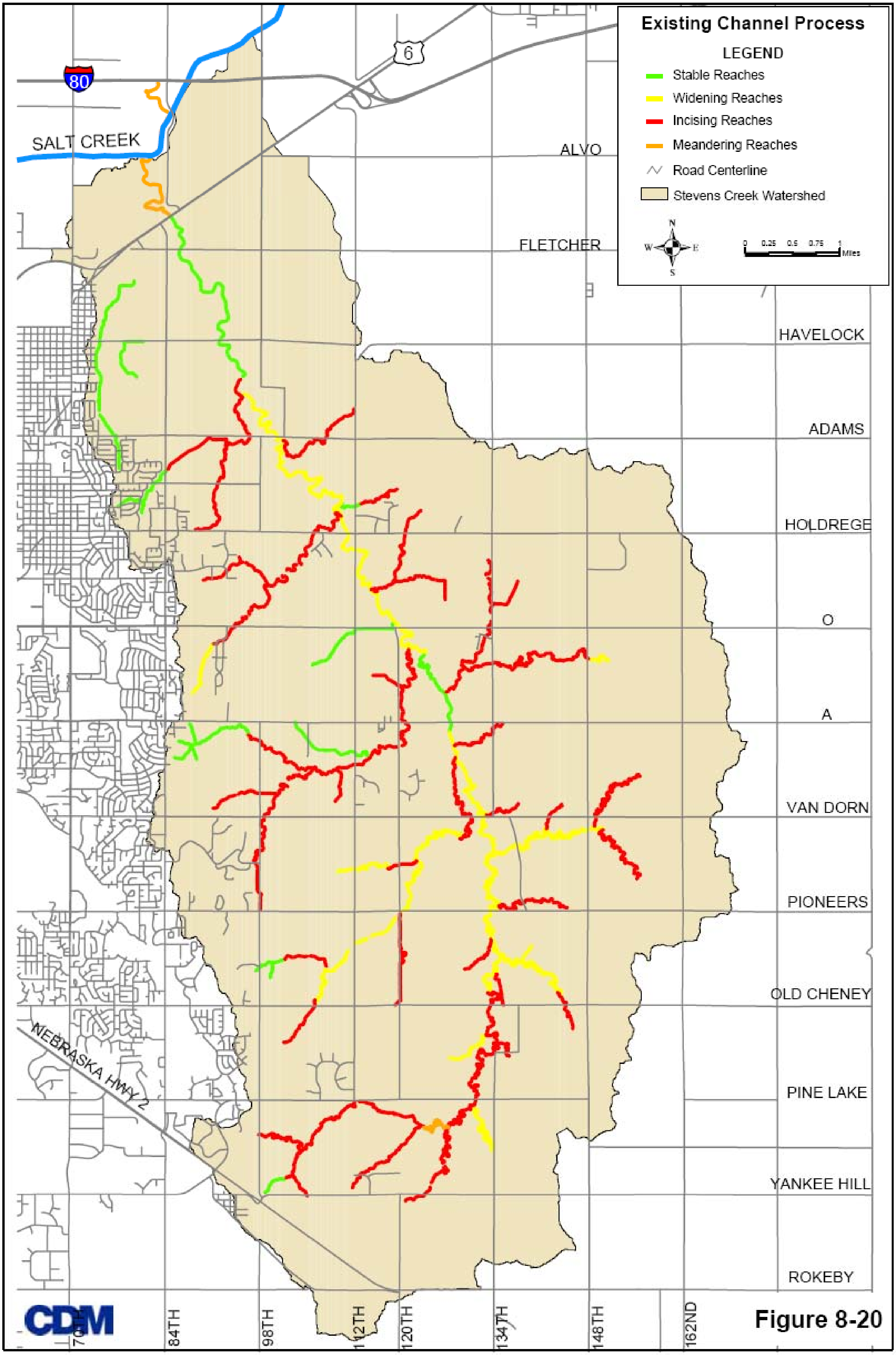
Existing Channel Process
LEGEND
Stable Reaches
Widening Reaches
Incising Reaches
Meandering Reaches
Road Centerline
Stevens Creek Watershed
N
S
W
E
Miles
80
6
SALT CREEK
ALVO
FLETCHER
HAVELOCK
ADAMS
HOLDREGE
O
A
VAN DORN
PIONEERS
OLD CHENEY
PINE LAKE
YANKEE HILL
ROKEBY
NEBRASKA HWY 2
70TH
84TH
98TH
112TH
120TH
134TH
148TH
162ND
CDM

Figure 8-20

8.4 Methods of Management

8.4.1 Watershed-Scale Stability

Arrest Channel Incision

Arresting channel incision is the single most beneficial action available to stabilize the Stevens Creek Watershed. Incision causes most of the problems throughout the basin including mass wasting, scoured or sedimented crossings, and plan form adjustment. Fortunately, incision responds well to treatment. Stopping the incision "short circuits" the cycle of channel evolution and improves the likelihood that the channel will self-heal. The knickpoints and knickzones are sites where the hydraulic slope is locally high enough to induce upstream-migrating erosion. Grade control structures will lower the slope below the threshold for bed erosion in this stream. Because of the high erodibility of the streambed, it is necessary to dissipate energy gradually over the length of the structure. For this application, Newbury-style grade control structures offer compelling advantages over concrete or sheet pile drop structures. These rock structures, illustrated on Figure 8-21, provide artificial riffles along the streambed. In addition to distributing energy, these rock structures improve water quality by increasing dissolved oxygen and providing refuge for benthic organisms.

Restore Riparian Buffers Throughout the Watershed

The second major issue influencing systemic stability is the poor condition of the riparian corridor. Without the root reinforcement and hydraulic roughness afforded by streamside vegetation, the banks are vulnerable to even minor insult. The few trees that are left become vulnerable to toppling and eventually become debris jams. A wide band of native trees and shrubs supports stream stability by increasing bank strength and reducing the influence of surface runoff. Streambank vegetation influences sediment dynamics by trapping and storing suspended sediment. Good canopy cover also improves water quality and habitat by shading the stream and providing leaf litter important for benthic species. When coupled with comprehensive grade stabilization and controlled post-development hydrology, a re-established woody corridor is a major step towards improving the condition of the stream now and preventing serious problems in the future.

The corridor should be wide, dense, and extend the entire length of the stream. Headwater reaches are particularly vulnerable to erosion and benefit from a protective corridor as much as lower reaches. Species represented should include canopy and understory trees, shrubs, and where appropriate, native grasses and forbs. Turf grasses have little value and should not be included in riparian buffer areas. Detailed, thoroughly researched guidance on the design and benefits of riparian buffers is available in the recent text released by the National Academy of Science (National Research Council 2002).

The actions described above will make progress towards improving the stream's current condition. Protection against future degradation requires watershed management outside the stream channel. The management guidelines recommended in Section 6.7.4 maintain the hydrologic equilibrium critical to preventing future problems.

8.4.2 Local Stability

Stevens Creek has an abundance of failed streambanks, undermined or filled in culverts and a few areas of meander adjustment. Most of these problems are a consequence of

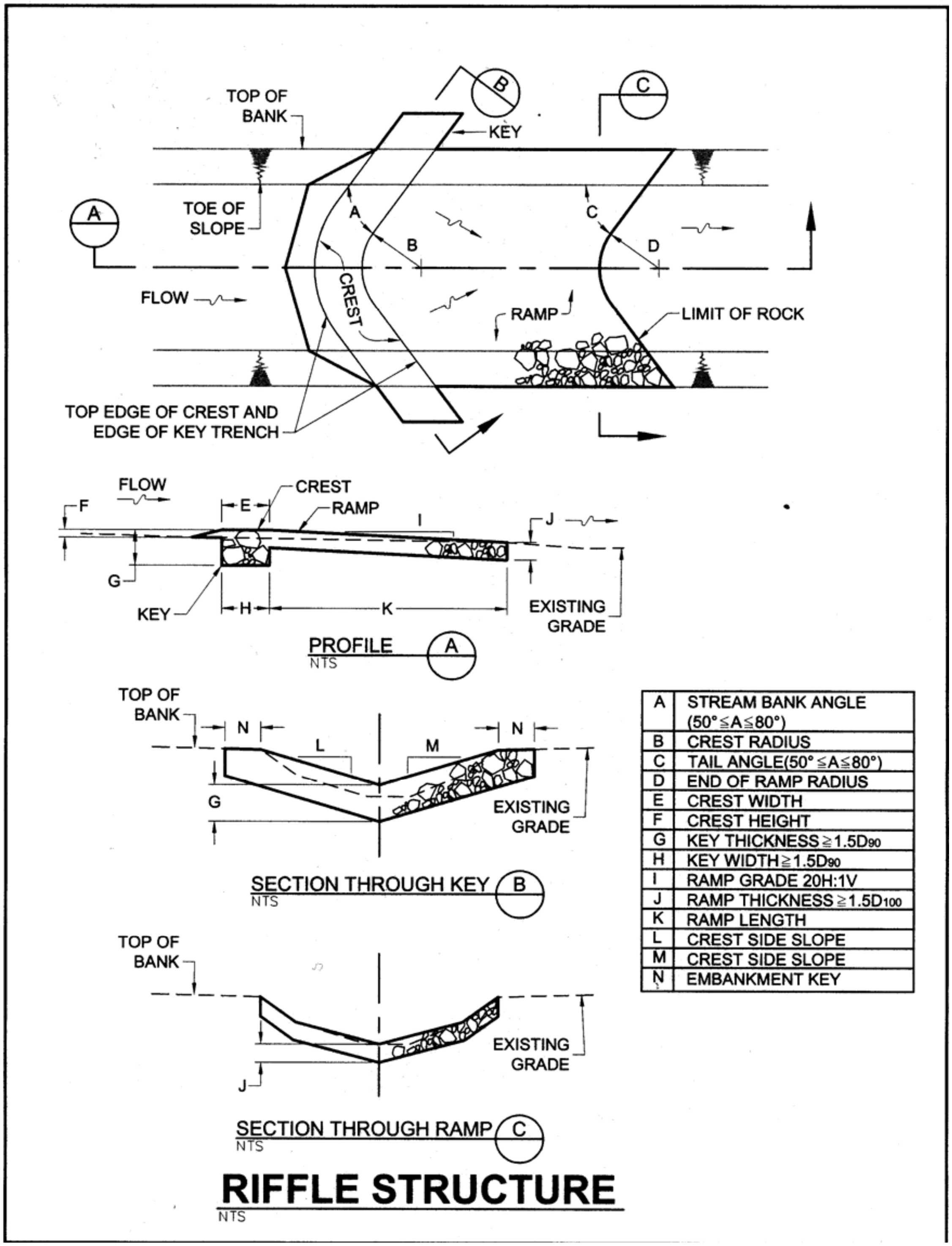

Figure 8-21
Newbury-Style Grade Control Structures

incision and are best addressed in a context of systemic grade control. Once systemic incision is controlled, the driving force for bank failure will have been removed. However, streambanks with substantial toe scour or those standing near or above critical bank height will continue to fail until a stable cross section is achieved. Attempting to prevent all of these failures and repair all streambanks that are failing now is prohibitively expensive. It is appropriate to treat areas of threatened infrastructure using methods consistent with systemic stabilization.

The organizing principle for local stability is, like systemic stability, energy management. The goal is to manage energy throughout the intervention so that neither scour nor deposition is induced in the adjoining reaches. This implies managing hydraulic roughness, focusing flows and achieving an equilibrium channel shape. Where streambank repair is necessary, it is preferable to reduce the stress acting on the bank while strengthening, rather than hardening, the bank. Lowering the slope of the bank above the effective discharge elevation and increasing the near-bank hydraulic roughness will lower the applied shear stress. Vegetative reinforcement and selective use of armor will provide the necessary strength.

Excessive erosion and the development of scour pools occur at every pond outfall with the exception of the newest pond, which had not yet been stressed. Scour immediately downstream of a pond is exacerbated by the lack of sediment in the discharge water. Similar to streambank repair, it is preferable to reduce the stress acting on the stream. Lowering the slope of the bed with grade controls or a designed stilling basin and increasing the near-bank hydraulic roughness will lower the applied shear stress. Vegetative reinforcement and selective use of armor will provide the necessary strength. The armor should fully encompass the zone of the influence of the structure including the potential hydraulic jump downstream.

8.4.3 Conclusions

The soils in this basin are highly erodible, creating a low threshold for stream disturbance, and even relatively minor physical and hydrologic changes may induce undesired changes in the stream that threaten people or property. The channelization of Salt Creek, historic farming practices, and early suburban developments have induced extensive channel downcutting and widening. There are some stream reaches that are stable and have fairly good habitat. However, this stability is threatened by the advancing knickpoints and bank failures progressing through the system. There is scant evidence that the stream is close to regaining its equilibrium, and the condition is likely to worsen.

The current Stevens Creek Watershed farming techniques such as no-till and contour plowing are major improvements from past practices, and their widespread use improves the sustainability of the watershed. Most of the improvement projects recommended in Section 9 are designed to correct past practices. Comprehensive grade stabilization will remove the driving force for continued bed degradation. Concurrent with this action, the site-specific structural BMPs described in Section 6 are recommended to offset the effects of urbanization on hydrology and stream stability. The third major recommendation is the restoration of the woody riparian buffer along Stevens Creek and its tributaries. Together, these management measures contribute to a more robust, self-managing stream system.