Summary Memorandum of Sediment Transport and Geomorphic Issues On Cherry Creek between Arapahoe Road and Piney Creek

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Simons & Associates

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Introduction

Cherry Creek flows in a generally northward direction from its rural watershed and through an area that is becoming increasingly urbanized as it approaches and flows through Cherry Creek Reservoir as shown below in the map and aerial photo of approximately the same area.

Figure 1. Topographic Map and Aerial Photograph of Cherry Creek

A number of studies have been conducted in an attempt to understand the hydrology, hydraulics, sediment transport, and geomorphology of Cherry Creek upstream of the reservoir. Cherry Creek has been experiencing significant changes in hydrology and channel and floodplain riparian vegetation dynamics which affect hydraulics and sediment transport, flood conveyance capacity and geomorphic response. These dynamic interactions affect property owners and development, as well as planning and infrastructure design along the corridor.

A site-visit to Cherry Creek was conducted on June 7, 2011 with Glenn Hamilton and Jim Wulliman (Muller Engineering) to observe current conditions of the creek along the reach of interest (from Piney Creek to Arapahoe Road) and to begin to understand the issues related to potential channel improvements. Other materials for review were provided by Muller Engineering, including a number of reports and aerial and ground photographs.

Figure 2. Riparian Vegetation along Cherry Creek (Muller)

Of particular interest were the recent reports prepared by George Cotton. Cotton, through four reports on Cherry Creek, provides information on available hydrologic and sediment data, sediment transport equations, sediment budget, and an evaluation of the effect of channel geometry scenarios on sediment transport and aggradation/degradation potential. A summary of key aspects of these reports that summarize his work are provided in the appendices (A-D) to this memorandum. A conference call was convened on July 21, 2011 between George Cotton, Muller, Simons, the

Southeast Metro Stormwater Authority (SEMSWA), and other interested parties to discuss these reports in an effort to better understand the work that had been completed, and Cherry Creek in general.

Before discussing what we can learn from this body of work as it relates to potential channel improvements, it is important to understand trends that are affecting Cherry Creek.

Hydrology

Cherry Creek has been experiencing urbanization which has affected the hydrology of the watershed. Urbanization increases the percentage of the watershed that is impervious, thereby increasing runoff. Similarly, increased lawn irrigation has further elevated the runoff potential within the watershed. Increased development and population has also resulted in the importation of water into the watershed, which is ultimately discharged (e.g. sewage treatment) into the system. Extraction of water from the system has also occurred over the years in the form of alluvial pumping. However, starting in the 1990s, this pumping has come under the State's administration of water rights. Most likely, this has reduced the quantities and rates of alluvial pumping compared to the period prior to water rights administration and may be contributing to a higher groundwater table and more prevelant surface flows in Cherry Creek. In addition, "live stream" requirements instituted in the 1990s for water rights exchanges may be a significant factor in maintaining more consistent surface flows in Cherry Creek in recent years. Investigations of subsurface water levels by Lytle Water Engineers show that there has been a significant rise in the ground water table in the vicinity of the Valley Country Club since the 1950s and that current ground water levels underlying the 10th fairway are above the Cherry Creek channel bottom.

These trends seem to match observations made by Valley Country Club staff that Cherry Creek in the project area has changed from a dry, sandy, wide streambed to a narrower channel with more continuous baseflows and well-vegetated overbanks. It is reported that this change has largely taken place since the 1990s, which is corroborated by an examination of historic aerial photography as discussed in the next section.

The surface flow hydrology of Cherry Creek can be quantified for evaluation by examining the daily flow data from the USGS. While more flow data are available, for the purposes of this analysis, focus is placed on more recent decades since the flow regime has changed as indicated above. To begin to understand the hydrology, Figure 3 presents the most recent 60 years of daily flow data at the Franktown gage.

These data show that the flow is predominantly less than 100 cfs with all except a relatively small number of days within the 60-year period over 100 cfs. Very rarely, the mean daily flow just exceeded 1000 cfs. Although the actual peak flow can be significantly greater than the mean daily flow during a flow event, the mean daily flows are quite low.

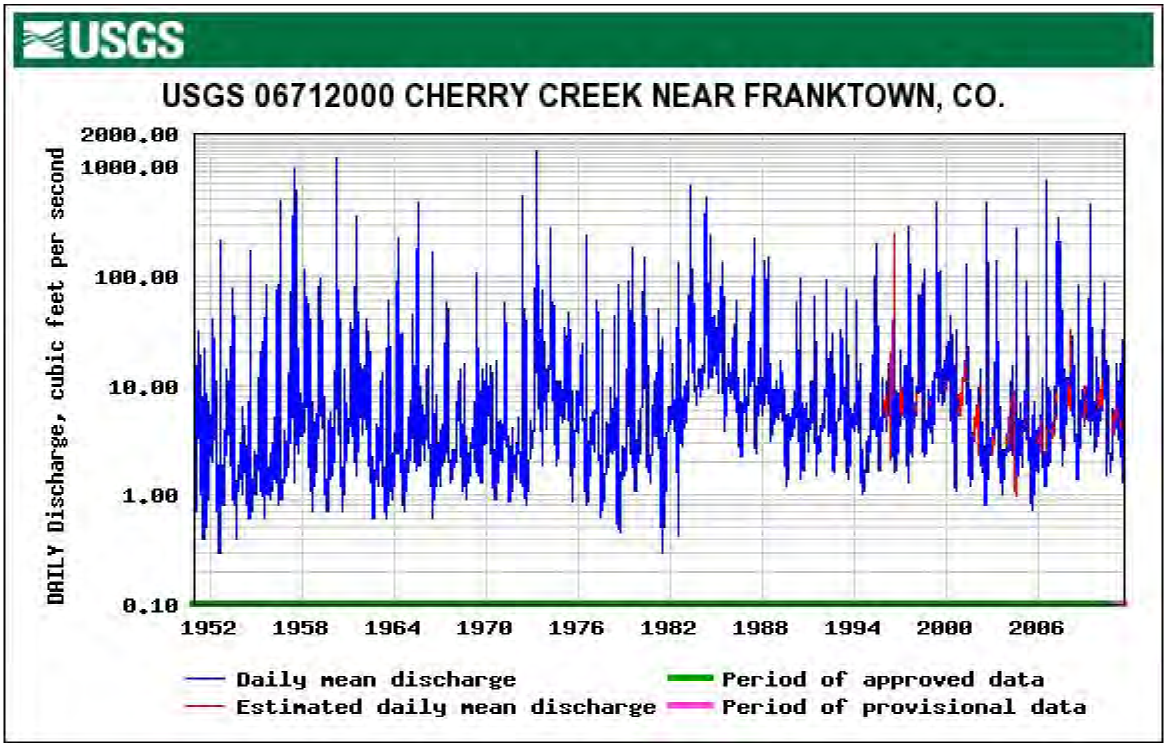


Figure 3. Cherry Creek near Franktown (1951-2011)

Figures 4 and 5 present the mean daily flow data for Cherry Creek near Franktown and Parker for the recent years from 2000 through part of August 2011. These recent data again show the dominance of low flows and the infrequence of high flows along Cherry Creek.

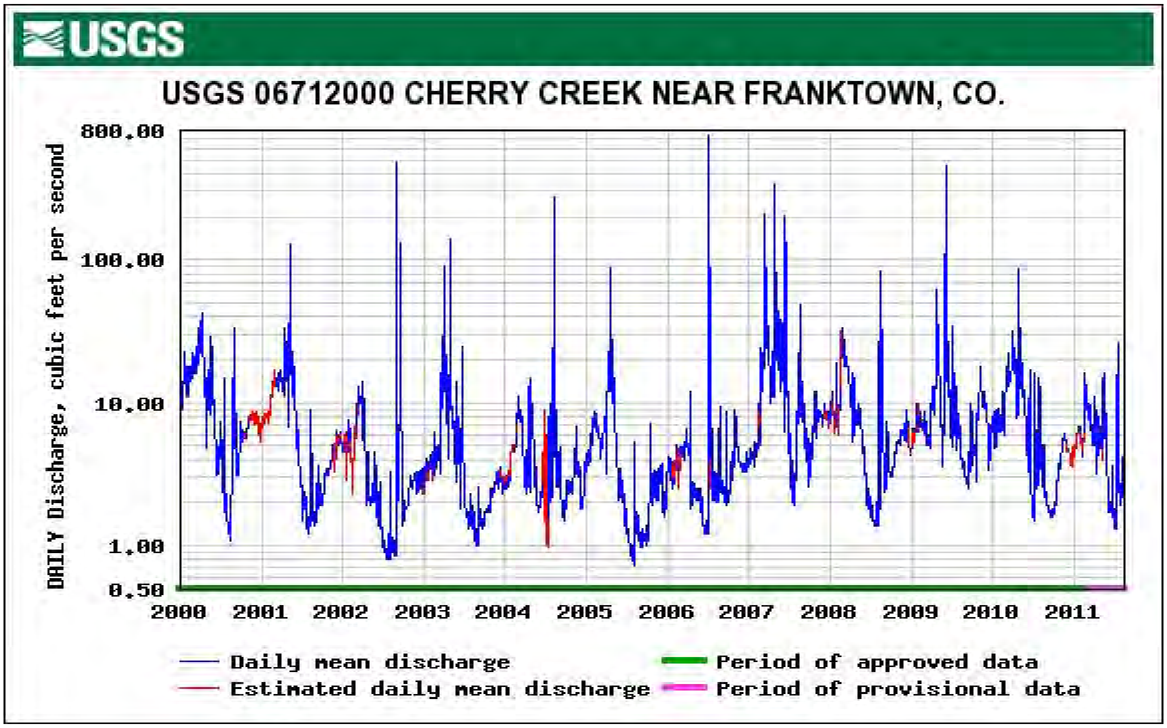


Figure 4. Cherry Creek near Franktown (2000-2011)

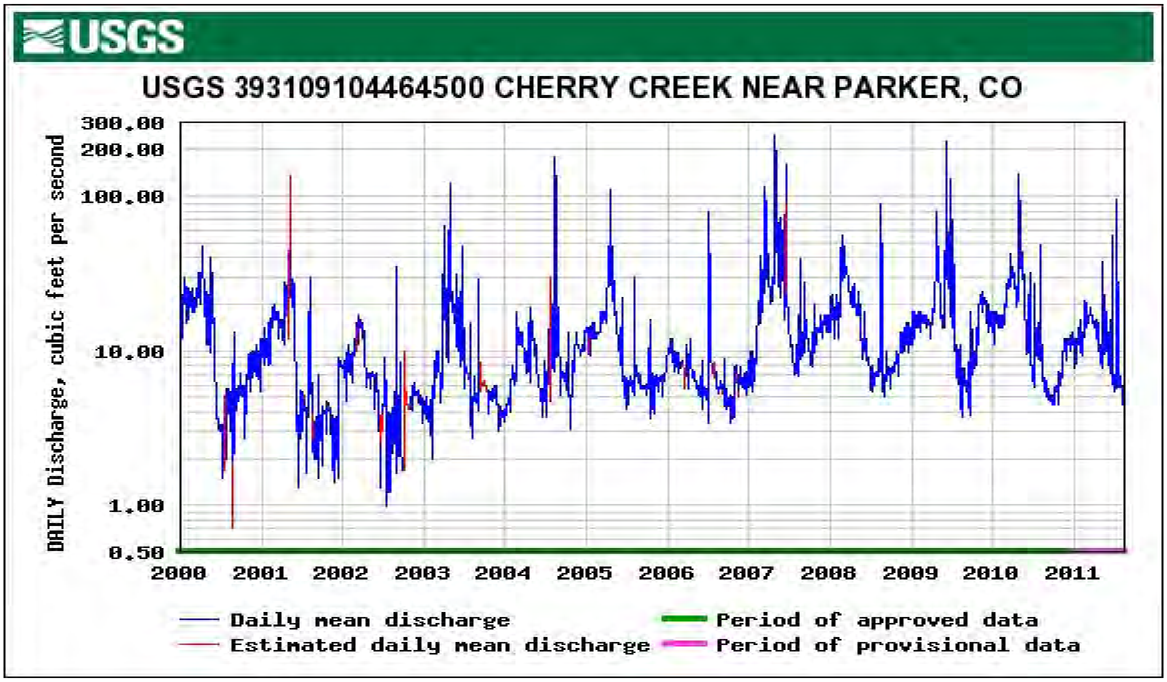


Figure 5. Cherry Creek near Parker (2000-2011)

Cotton has presented flow data from Cherry Creek in the form of flow-frequency and flow duration curves as shown below (Cherry Creek Sedimentation Study, Reservoir to Pine Lane, Project Data and Evaluation; November 2010).

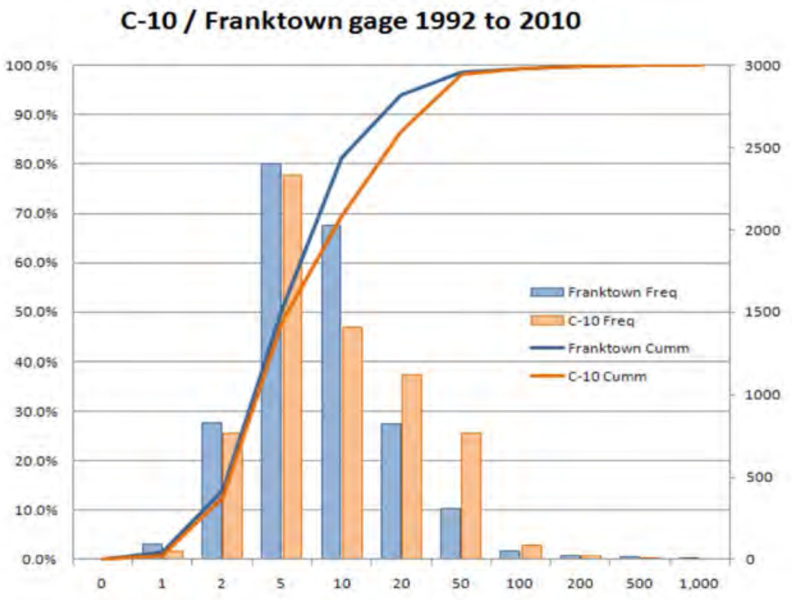


Figure 6. Comparison of mean daily flow (cfs-day) frequency between Franktown and C-10 gages (right axis shows the count within each bin and left axis shows the cumulative frequency)

Figure 6. Graphic Comparing Mean Daily Flow at Franktown and Cherry Creek Reservoir (Cotton)

Note: The C-10 gage is located at the crossing of the State Park perimeter road, near the location of the previous Melvin gage.

Based on these data in Figure 6, 90% of the time the flow is less than about 20 cfs. Mean daily flows are less than 100 cfs approximately 98% of the time. According to these data, Cherry Creek has been dominated by relatively low flows with a few scattered higher flow events of very short duration.

As described by Cotton, it should be noted that the mean daily flow record does not capture the flashy nature of Cherry Creek, where peak flows can be significantly greater than the mean daily flow (November, 2010). According to Cotton's analysis, the peak flow typically ranges from 7 to 10 times the magnitude of the mean daily flow. It is possible, however, that with the existing floodplain riparian vegetation processes and the associated increased resistance to flow, which can create dampening and attenuation tendencies within the system, the flashy nature of the system may now be somewhat less dramatic.

Another factor that affects sediment transport along Cherry Creek is the tendency for the stream to lose water in the downstream direction ("Water supply development in the Cherry Creek basin results in the reach between Parker and Cherry Creek reservoir being a losing reach. It is expected that on average there will be about 32% less stream flow at the lower end of the study reach compared to inflow at the upper end." Cotton, May 2011). In general, the loss of water decreases sediment transport capacity and promotes aggradation. While this tendency may exist, and may contribute to aggradation on the floodplain, it may not override other factors that can cause degradation in the active channel, as will be discussed later.

Expansion of Riparian Vegetation

The earliest aerial photograph of Cherry Creek included in the Cotton work (1937) shows that the channel was relatively wide, and the floodplain sparsely vegetated (Figure 7). The channel did not show significant changes in the 1955 photograph (Figure 8). In contrast, the Figure 9 photo, taken in 2007, shows the significant increase in riparian vegetation that has taken place in recent decades.

Figure 7. 1937 Aerial photograph (Cotton)

Figure 8. 1955 Aerial photograph (Cotton)

Photo 12 - Aerial Image 6, July 2007

Figure 9. 2007 Aerial photograph (Cotton)

As evidenced by this sequence of aerial photographs, a period of significant establishment and expansion of riparian vegetation on the sandy soils surrounding the creek has occurred in recent years. It is surmised that the increase in groundwater levels and more consistent baseflows in the lower reaches of Cherry Creek, combined with the available supply of seeds and root stock from herbaceous and woody riparian vegetation, has contributed to this growth in vegetation. In the past, when the seeds germinated, it is likely that few plants survived the relatively hot, dry summers when their roots could not grow fast enough to tap into a lower groundwater level. Now, with a higher groundwater table and more consistent baseflows, there is sufficient water available a short distance below the ground that supports the survival of greater percentages of the available seeds that germinate on the soil surface.

Seedlings are susceptible to being removed due to scour and other phenomena if high flow events occur frequently enough, and are powerful enough, to remove the seedlings while they are young. Once cottonwoods or willows reach an age of about 3 to 4 years, they are very difficult to remove by virtually any flow scenario (some removal can occur by sustained high flow events over periods of weeks or months). The dominant pattern of sustained low flows and infrequent high flow events of very short duration has provided excellent conditions for the germination, survival, growth, and expansion of woody riparian vegetation onto much of the sandy soil that is not actually inundated by water during the spring and summer (which prevents germination only on these limited areas of inundation). Thus, the current active channel has concentrated into a relatively narrow width of the former active channel as Cherry Creek is dominated by low flows and high water table supporting woody riparian vegetation.

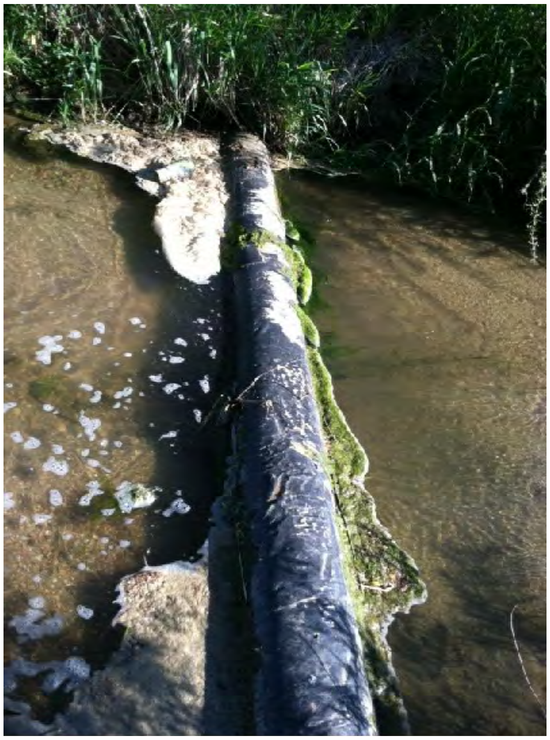
The expansion of woody riparian vegetation on the floodplain has significantly increased the resistance to flow on this portion of the channel. Figure 10 shows an example of this riparian vegetation.

Figure 10. Woody Riparian Vegetation on the Floodplain Surrounding Active Channel (Muller)

Based on experience with woody riparian vegetation, given the currently high groundwater table and consistent baseflows along the study reach coupled with the fact that the vegetation has been established for longer than four years, it is likely that the vegetation will remain for the foreseeable future. Experience on the Platte River with the same issue indicates that well-established woody vegetation experienced only limited removal with high flows in excess of 20,000 cfs flowing over long periods of time. Based on the flow record, most floods that have occurred on Cherry Creek have been of extremely short duration (typically less than one day) and likely would not, if they occurred today, result in significant removal of vegetation. As a result, during future high flow events, less sediment will likely be eroded from the floodplain and higher resistance to flow over significant areas will reduce sediment transport and induce further deposition of sediment on the floodplain compared to the calibration periods used by Cotton for sediment transport equation selection. Thus, the total sediment transport rate in the corridor will likely be less than predicted based on sediment transport equations calibrated using high flows and significantly less riparian vegetation.

The complex interaction between sediment transport and vegetation can be analyzed in more detail using approaches developed on the Platte River (Simons & Associates: "Physical Process Computer Model of Channel Width and Woodland Changes on the North Platte, South Platte and Platte Rivers," 1990; "Modeling of Sediment Transport and Vegetation Processes Along the Platte River in Nebraska – Initial Calibration Fixed Bed Version," 2000; "Sediment-Vegetation Model Testing, Calibration, Verification, and Evaluation," 2002)

Observation of Cherry Creek in June 2011 provided some insights into current trends. Areas of recent sediment deposition in areas of riparian vegetation on the floodplain were observed. Signs of active channel degradation were also observed, including water flowing under a pipeline that had been undercut. It appears, based on these observations, that at least under 2011 conditions in the study reach, the active channel has been degrading while the floodplain has been aggrading. While these may not represent permanent trends, it appears that for now, Cherry Creek is characterized by significant woody riparian vegetation that will slow the velocity of flow on the floodplain, and a relatively narrow active sand-bed channel that concentrates flows and elevates velocities to a level that can erode and transport sediment.



Figures 11 and 12. Aggradation on Floodplain Adjacent to Active Channel, and Undercut Pipeline Showing Evidence of Degradation in Active Channel (Muller)

Sediment Transport

For the sediment transport aspect of the work ("Cherry Creek Sedimentation Study, Reservoir to Pine Lane – Sediment Transport Equation Calibration," January 2011), Cotton used HEC-RAS and calibrated the sediment transport portion of the model by using the various sediment transport equations over two time periods bounded by sedimentation surveys in Cherry Creek Reservoir. The sediment transport equation that provided the best result in terms of the most accurate quantity of sediment delivered to the reservoir compared to surveyed changes in sedimentation within the reservoir was then selected. The two time periods utilized were 1950-1961 and 1961-1965. The latter time period included the very large 1965 flood event, but both these time periods were decades ago, before significant expansion of woody riparian vegetation onto the floodplain. The time periods for calibration were selected, at least partially, due to the fact that there were issues with the other more recent sedimentation surveys in Cherry Creek which did not provide accurate information on the quantity of sediment deposited in the reservoir.

Based on Cotton's analysis the sediment transport equation which, when coupled with the historic flow regime over the calibration periods, resulted in the best match to the quantity of sediment deposited in Cherry Creek Reservoir was the Engelund – Hansen equation (see Appendix B). As shown in the graphics below, the transport equation was simplified to a power function (Gb = aQ^b) and plotted as a function of flow for easy application (Gb is the sediment transport rate in tons/day).

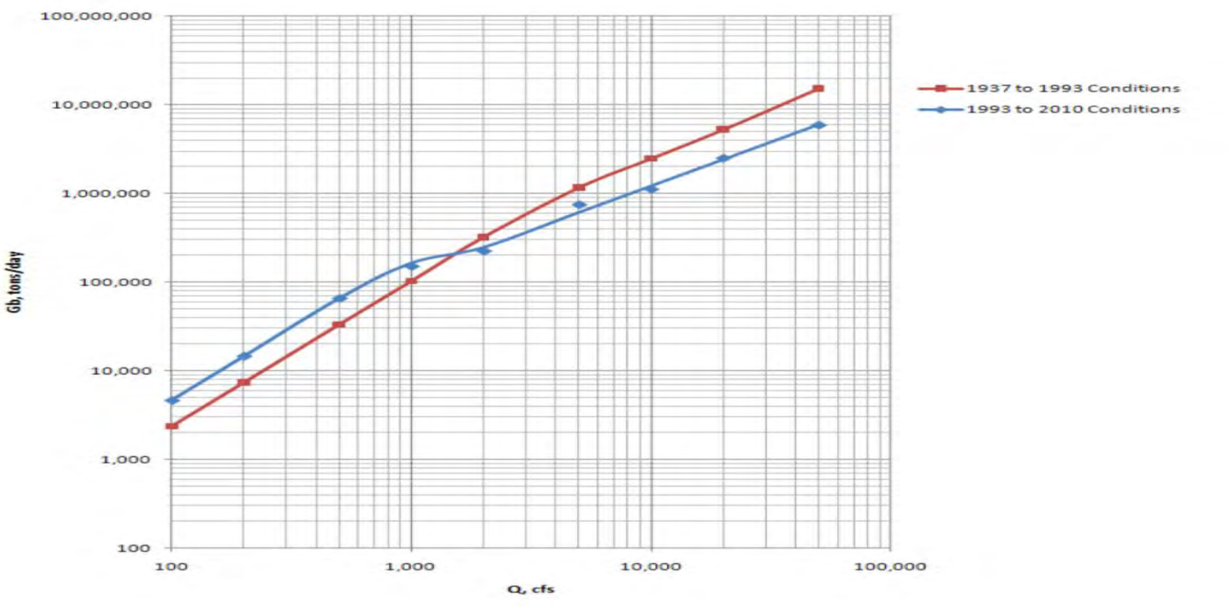
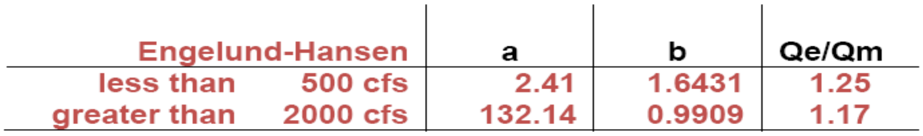


Figure 14. Revised Site #1 Sediment Rating Curve

Table 5. Power functions of Sediment Transport Capacity – 2010 Conditions



Engelund-Hansen		a	b	Qe/Qm
less than	500 cfs	2.41	1.6431	1.25
greater than	2000 cfs	132.14	0.9909	1.17

Figure 13. Graphics Summarizing Best-Match Sediment Transport Relationship (Cotton)

Since the calibration periods reflected the greater availability of sediment on the floodplain 50 to 60 years ago prior to the expansion of riparian vegetation, and included one of the largest floods ever experienced in Colorado (1965), the results are perhaps somewhat skewed towards high flows and high sediment compared to the predominant conditions of today.

Calculations of the sediment concentration associated with the predicted sediment loads were made in an attempt to evaluate the reasonableness of the information. Table 1 presents the results of these calculations for a range of flows.

Table 1 Sediment concentrations computed from selected transport equation

Flow (cfs)	**Sediment Transport (tons per day)**	**Sediment Concentration (parts per million)**
100	4,100	15,000
1000	140,000	49,000
10000	1,050,000	37,000
50000	6,000,000	43,000

These computed sediment concentrations appear to be excessively high. As discussed previously, this could be due to the fact that the calibration periods were from decades ago before significant establishment of riparian vegetation, and could also be influenced by the extreme magnitude of the 1965 flood that occurred during one of the calibration periods. The author has measured sediment concentrations from many rivers worldwide and has only experienced concentrations of this magnitude twice: once when specifically sampling in areas of collapsing river banks associated with intense boat wave activity (Connecticut River with localized concentrations during bank collapse in the 10,000 to 20,000 mg/l range), and the other associated with a mining activity when tailings were discharged into a river at a rate of up to several hundred thousand tons per day from the world's largest gold mine -- in addition to the natural sediment load (Otomona River, Irian Jaya with concentrations in the 10,000 to 20,000 mg/l range). The author's opinion is that the sediment concentrations shown in Table 1 are not realistic given the current condition of a floodplain that is densely vegetated with woody riparian vegetation.

A memorandum from William Ruzzo to the Urban Drainage and Flood Control District (updated 3/31/2005) included a summary of suspended sediment data collected by Halepaska (John C. Halepaska & Associates, Inc., April 2003. *2002 Annual Report Baseline Water Quality Data Collection Study for the Upper Cherry Creek Basin*.). A summary of data from the memo is included as follows:

	TP (mg/l)	TSS (mg/l)	Flow (cfs)
Data points =	66	59	92
Average =	0.29	91	14.3
Median =	0.27	39	8.2
Maximum =	1.20	1400	120.0
Minimum =	0.16	0	0
Standard deviation =	0.149	202	21.5

The maximum concentration was 1400 mg/l at a flow of 120 cfs. This is only about $1/10^{th}$ the magnitude of the sediment concentration for a similar flow event as developed by Cotton, calibrated to the USACE sedimentation data. It appears that the USACE sedimentation data cause the sediment transport equations to produce sediment concentrations that are higher than those indicated by actual TSS data (although these data are on the relatively low end of the flow spectrum and do not include bedload transport). The low end of the flow spectrum occurs a great percentage of the time and bedload typically is not likely to be 10 times the suspended sediment load. Collection of sediment transport data including both suspended and bedload over a range of flows would be very useful in developing a better understanding of these issues.

Effective or dominant discharge

An analysis of what has been termed "effective discharge" or "dominant discharge" was conducted by Cotton (Cherry Creek Sedimentation Study, Reservoir to Pine Lane, Scenario Development and Evaluation, May 2011). This type of analysis combines the sediment transport rating curve with a flow duration curve to determine what magnitude of flow transports the greatest amount of sediment. Of course, very high flows transport the most sediment but occur infrequently such that over the long term the high flow events don't actually transport the most sediment. Low flows don't transport much sediment but they occur frequently, typically resulting in a potentially significant quantity of sediment – but not the maximum amount. Frequently, a flow in the mid-range transports the greatest amount of sediment because they transport a moderate rate of sediment and occur just frequently enough to create a maximum value of sediment transport in this type of analysis. Results of the effective discharge analysis from Cotton (May 2011, summarized in Appendix D) are presented in graphic form below.

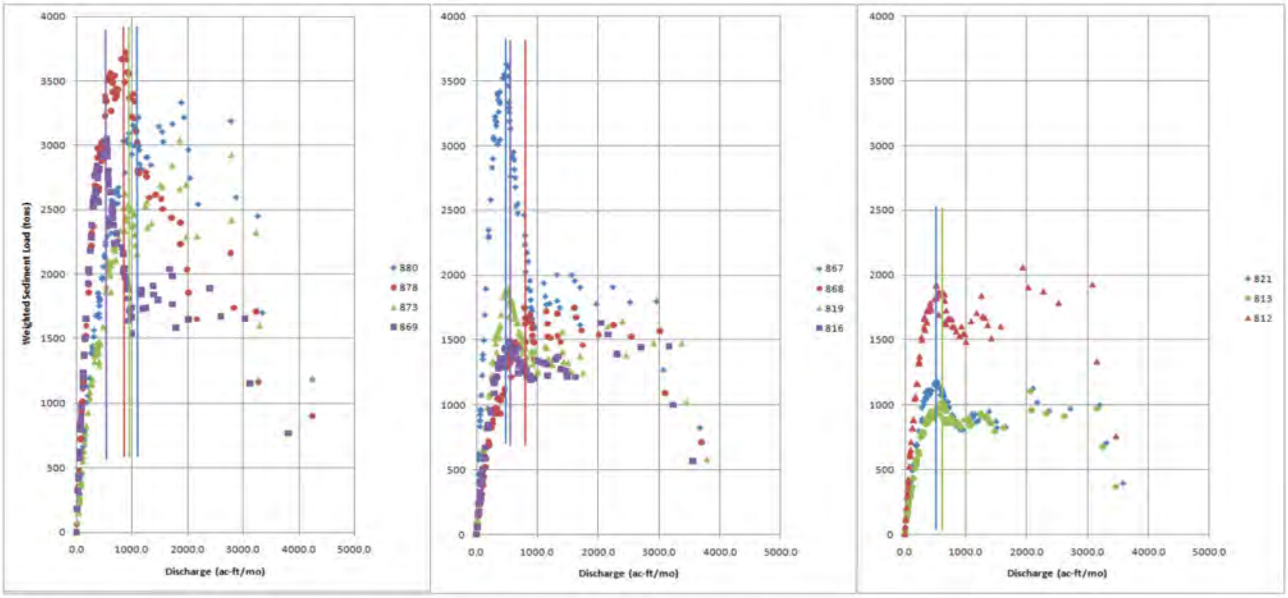


Figure 3 Shows plots of dominant discharge calculation as computed by sub-reach for the CCBWQA simulation. The vertical lines show the approximate location of the first peak in weighted sediment loading, i.e. the dominant discharge for the sub-reach (ac-ft/month). The vertical axis is the probability weighted sediment transport in tons.

Figure 14. Graphics Summarizing Effective Discharge Analysis (Cotton).

The Cotton study suggests using scaled 2-year flows ranging from 1555 cfs in the upstream reaches down to 1064 cfs farther downstream (based on major drainageway study existing conditions). The dominant discharge analysis, however, appears to be less than conclusive without producing an obvious dominant discharge (except for one section which shows a relatively sharp peak while the rest of the curve remains relatively flat across the top). Due to the potential issues with the sediment transport relations, the dominance of low flows, and the fact that the above curves show relatively flat or ill-defined peaks, some of which occur at quite low flows, suggests that perhaps the dominant discharge is significantly lower than the major drainageway study 2-year flow.

Previous effective discharge analyses on other streams from the available scientific literature have shown that the maximum effective discharge frequently occurs somewhere around the 2-year frequency, which is typically the bankfull flow on many streams. This happy coincidence has led many to believe that bankfull flow and effective discharge are important factors in determining channel size. While this may be true of channels that are not experiencing significant effects of riparian vegetation expansion and where large flows are more frequent and of longer duration, it may not be as relevant in the case of Cherry Creek.

Equilibrium Slope

Cotton ("Cherry Creek Sedimentation Study Reservoir to Pine Lane Scenario Development and Evaluation," May 2011) and CH2M HILL ("Cherry Creek at 12-Mile Park DRAFT FINAL Site Assessment Report," November 2010) focused some attention on the concept of equilibrium slope. Equilibrium slope is based on the concept that if a channel is set on a slope that produces a velocity that can transport the sediment load delivered to it from upstream; the channel bed will be in equilibrium because the quantity of sediment coming into the reach will be transported out -- hence no net aggradation or degradation. This is perhaps a corollary to the concept of an equilibrium channel in the geomorphic literature. Unfortunately, even in the most simple of situations and assuming a channel is in a state of so-called "equilibrium," the reality of an equilibrium channel flowing over an equilibrium slope leaves room for significant channel dynamics.

In discussing the concept of equilibrium in an ideal channel, Leopold, Wolman and Miller (Fluvial Processes in Geomorphology, 1964) state the following:

> *This analysis brings out an essential point. In the simplest stable natural channel with movable bed and banks, two conditions must be satisfied simultaneously – the transmission of the flow and the stability of the banks. Such a channel has been called "threshold" (Henderson, 1961, p. 112), describing the fact that each point on the perimeter is at the threshold of movement. In this hypothetical condition a channel could not transport sediment because the required increase in stress would cause erosion of the banks. In actuality a natural channel not only carries sediment but migrates laterally by erosion of one bank, maintaining on the average a constant channel cross section by deposition at the opposite bank. In this case the condition of no bank erosion is replaced by an equilibrium between erosion and deposition.*

> *The form of the cross section is "stable," meaning constant, but position of the channel is not.*

Likewise, Schumm (1977, The Fluvial System) discusses that rivers generally change position, shape, and pattern and "*are subject to constant changes as a normal part of their morphological evolution.*" Thus, an ideal natural channel in equilibrium essentially means that the channel size generally retains an overall unchanging average size, with erosion in one place balanced by deposition in another, resulting in a channel that changes its position over time. Changing position, even while retaining overall average channel geometry, necessarily means riverbank erosion occurs even in such channels that are considered to be in equilibrium. The Leopold, Wolman and Miller textbook is replete with examples of rivers that have historically experienced significant changes.

In the author's opinion, the concept of equilibrium must also allow for some dynamic adjustment not only in channel banks and position, but also in channel slope. In reality, it is not possible for a channel to remain in a static state with no adjustment in any way. In addition, it is unlikely to be so clever as to actually determine an exact slope or width of channel that will remain in a state of true equilibrium despite the natural (and unnatural) variations in hydrology and sediment delivery from an upstream watershed. Any such determinations must be put in perspective that considers complex factors that control river response. For many channels, and particularly Cherry Creek (due to the trends in changing hydrology, development, and watershed conditions), a concept of a range in slopes and widths within some significant dynamic range of "equilibrium" is to be expected.

The previous determinations of an equilibrium slope for Cherry Creek, while based on recognized concepts and technical approaches, unfortunately suffer from the lack of actual and complete (suspended and bedload) sediment transport data, and the techniques do not necessarily reflect the very real effect of riparian vegetation dynamics on geomorphology. Unfortunately, these relatively simple analysis techniques do not adequately represent these complex interacting phenomena. It is likely that the previously estimated equilibrium slopes are in the ballpark for one point in the possible range of conditions, but because of the complexities of Cherry Creek and the dynamics that must be considered in any "equilibrium" type of analysis, these slopes will vary from reach to reach and over time as the stream responds to variable hydrology and variable sediment input.

The overall longitudinal slope of Cherry Creek is approximately 0.4 percent (Cotton, May 2011). The equilibrium slope was computed by Cotton (for Scenario 3) and CH2M HILL to be essentially the same value. The stable slope analysis conducted by CH2M HILL utilized the 2-year flow (both existing and developed conditions) in their computations. CH2M HILL states the following in discussing the concept of a stable slope:

> *The stable slope analysis using the stable sediment transport rate for Cherry Creek at 12-Mile Park suggests that the stable slope along the historic flow path is approximately 0.4%. It must be understood that the concepts used for the computation of sediment transport innately include a margin of error and in general,*

> *the methods used in this analysis result in a slope that will reduce the degradation and aggradation of the main channel.*

The main concerns with previous analyses of stable channel slope or equilibrium slope are that they are based on very limited, if any, actual sediment transport data, they are based on flows that only occur a fraction of the time and ignore the dominant regime of low flows, and they don't specifically reflect the effect of riparian vegetation dynamics.

There appear to be a number of issues to be considered with any equilibrium slope analysis along Cherry Creek as indicated in the points below:

- A significant percentage of the bed of the active channel of Cherry Creek upstream of the reservoir appears to be currently in a mode of degradation, which would likely not be the case if the equilibrium slope were 0.4%.
- Reference reaches assumed to be stable in the various analyses may not actually be stable.
- Several reaches of Cherry Creek show bed slopes approaching 0.0% (based on surveys conducted by Muller).
- Reaches that are currently not degrading are generally located downstream of reaches that are degrading and producing higher sediment loads to these "quasi-stable" reaches.

Cherry Creek in the lower reaches (upstream of the reservoir) is becoming progressively locked into a relatively narrower active channel by processes of riparian vegetation dynamics due to high ground water and a dominant low-flow regime. While the slope may tend towards the value suggested by Cotton and CH2M HILL during higher flows that occur only a fraction of time, in some reaches of the stream, the slope has decreased due to bed erosion to a slope of essentially 0.0%. Absent significant upstream sediment input from the watershed as a result of large flow events, or if a sediment basin was built (as addressed by Tetra Tech – Design of the Cherry Creek Sediment Basin and Stream Stabilization Measures, 2006); it is reasonable to expect the bed in certain reaches to approach an essentially zero slope. This has also occurred on reaches of Cherry Creek downstream of the dam.

In general, Cherry Creek is not in equilibrium and it is unlikely that it will reach, or can be held in equilibrium given the current hydrologic and watershed conditions. So far, equilibrium slopes computed in prior studies tend to be developed around flow conditions that rarely occur and are in conflict with the dominant hydrologic regime. Such an equilibrium slope is not real or sustainable since it is developed around conditions that do not occur frequently enough to actually maintain such a slope. In other words, an equilibrium slope that is computed based on flow events that occur infrequently and for very short durations ignores the channel forming flows that actually do occur on a frequent basis.

Because high sediment loads during infrequent and very short duration high flow events may tend to temporarily steepen the slope, and the dominant low flow regime may tend to flatten the slope, any channel improvement designs must account for potential variability in bed slope and a stream that is not in a "fixed" equilibrium condition.

Discussion of Issues and Alternatives

Historically, Cherry Creek has experienced a few large flood events including the extreme 1965 flood event which reached a peak of approximately 58,000 cfs entering the reservoir (1977 USACE hydrograph as shown in Cotton, January 2011). Hydrologic analysis based on the historic record results in a prediction of peak flows into the thousands and tens of thousands of cfs for the typical range of return periods. Thus, significant flood events have historically occurred and will occur in the future. The flood conveyance capacity of Cherry Creek has decreased, and the flood stage has increased for a given flood discharge because of the expansion of woody riparian vegetation onto the formerly active channel which has significantly increased the resistance to flow. Because the active channel is now narrower than it was decades ago, the sediment transport capacity has decreased. Sediment that is being conveyed with the flow over the floodplain has a tendency to deposit because of the lower velocities. Conversely, some reaches of the narrow, active channel are experiencing scour and channel bed degradation because the dominant low flows have a sufficient velocity to erode and transport sediment downstream towards the reservoir. This has resulted in undermining of utility crossings and flatter channel bed slopes.

A wider active channel on a relatively steeper slope (consistent with the overall longitudinal slope of the stream) would undoubtedly provide increased flood conveyance and sediment transport capacity. Such channel geometry could be developed for reaches of Cherry Creek. However, this channel geometry will not be maintained by the flow and would require continual maintenance by external processes (vegetation removal and/or replacement with alternative vegetation that does not increase resistance to flow, drop structures, etc.). Any channel that is "too" wide will tend to "narrow" as woody riparian vegetation expands onto whatever portion of the channel isn't active and inundated during the seed germination season (mid-May to mid-July). Seeds do not germinate on the portion of the channel where water is actually flowing, and therefore seedlings will not establish on this portion of the active channel bed. Rather, they will tend to germinate and establish on portions of the sand bed where water is not flowing during the germination season. Once the woody vegetation reaches three to four years of age, their root system may be sufficient to resist all but the highest and most erosive flows. Their roots can become firmly tapped into the groundwater, enabling the vegetation to survive surface water droughts (again, except perhaps in the most extreme cases). The active channel width then tends to be dictated by the frequently occurring flows that occur during the germination season.

Larger channel widths will tend to experience expansion of woody riparian vegetation and narrowing of the active channel as long as there is not a predominance of large flows that would maintain a wider cross-sectional geometry. At the lower flows typical of recent years, the sediment supply from upper reaches is likely to be quite small and a narrower, somewhat incised channel will tend to form within whatever cross-section might be initially set, resulting in a narrower channel with vegetation expanding onto the remainder of the cross-section. Unless the vegetation expansion process could be eliminated by intense maintenance or a grassed floodplain, it will be very difficult to develop and maintain anything other than a relatively narrow active channel within a floodplain covered with woody riparian vegetation.

The vegetation expansion processes are dominating and appear to be inconsistent with the concept of dominant discharge or effective discharge related to maximum sediment discharge and channel forming or channel maintaining processes as discussed in the report entitled, "Scenario Development & Evaluation," May 2011. In other words, the most effective channel from the perspective of sediment transport may be in conflict with the vegetation processes at work in a channel that has experienced a shift from the drier environment of the 1950s and 1960s to a wetter environment that now supports extensive riparian vegetation. This is further complicated by the possibility that the upper watershed may remain in a somewhat drier environment with less vegetation, and can potentially produce larger volumes of sediment during major storms than can readily be transported by the lower part of the channel system. These potential conflicts complicate the design of a stable channel that works under the range of potential flooding scenarios. Based on current observations and the large differences between resistance to flow between the active channel and the floodplain, the author expects aggradation on the floodplain with either aggradation or degradation in the active channel being determined by the sediment transport capacity of the active channel as compared to the sediment inflow into the active channel. Cherry Creek therefore presents a complex geomorphic response to a modified hydrologic regime.

The current hydrologic condition in Cherry Creek (domination by low flows, losing water in the downstream direction, and high groundwater levels – all supporting the increase in riparian vegetation) leads to a dilemma in developing plans related to channel stability and future floods. Rare large flood events can transport significant sediment loads that will have a tendency to deposit as they spread onto the vegetated floodplain. On the other hand, more frequent and sustained low flows tend to erode the channel bed, leading to degradation. The small active channel that has formed as a response to the dominant low-flow regime cannot fully convey the larger flood events, nor all of the sediment load transported during such events, since a portion of the sediment will spread to the overbanks.

It is not seen as practical or desirable to remove the existing riparian vegetation and attempt to re-create a wide, open, sandy floodplain along Cherry Creek that may be able to convey the rare floods and associated sediment load without significant deposition. A sandy floodplain, left on its own with the existing seed and root stock supply and a favorable hydrology, would quickly become re-vegetated with woody riparian vegetation.

Given the likelihood that Cherry Creek in the study reach will continue to be characterized by a relatively narrow active channel flanked by woody riparian vegetation, another design approach is to address each of these portions of the floodplain separately. The active channel is expected to experience degradational tendencies during the dominant periods of low flow that could, at times, flatten the slope to near zero. To keep the channel bottom from incising deep below the adjacent floodplain benches (concentrating flood flows, increasing velocities and erosion, and drying out and stressing the overbank vegetation), small, relatively frequent grade control structures are recommended. In larger flow events conveying higher sediment loads, the active channel slope is expected to steepen. Small, frequent drops can handle a wide variability in sediment load, transport and slope. Steeper slopes will simply reduce the height of the drops or even bury the drops for a time until lower flows carry away some of the deposited sand, again flattening the slope and re-exposing the drop.

The densely vegetated overbanks adjacent to the active channel are inherently less able to adjust to variability in flow rate and sediment transport, since they generally only have aggradational, not degradational, tendencies. During periods of low flow and low sediment transport, the overbanks will essentially remain in their existing condition, since little or no sediment is carried to the overbanks. During flood events conveying substantial sediment loads, the vegetated overbanks will tend to aggrade, perhaps preferentially in the zone nearest the active channel where sediment concentrations are highest. Since this aggradation seems difficult to eliminate altogether, the design objectives may need to shift to *minimizing* the rate and total depth of accumulation, and to *reducing* the impacts of the aggradation, realizing that periodic removal of the accumulation may be required. Measures that may help to achieve these objectives could include the following:

- Continue to implement projects to stabilize badly degrading reaches of upstream Cherry Creek and its tributaries to reduce the associated high sediment loads (these loads appear to dominate the current loading of sediment from the watershed).

- In areas of new development along Cherry Creek, set lowest floor elevations well above the minimum freeboard requirements over 100-year floodplain elevations, creating an allowance, or safety factor, for future sediment accumulation.

- Since a number of residential structures along the study reach are in close proximity to the existing 100-year floodplain, consider conveyance improvements along the Cherry Creek corridor to lower flood elevations and create an allowance for future sediment accumulation.

- Consider the feasibility of creating preferential deposition zones in the overbanks to reduce sediment accumulation in downstream overbanks and perhaps to focus, or isolate, sediment removal operations that may become warranted in the future.

- Periodically monitor channel cross-sections and floodplain elevations to allow evaluation of when potential aggradation reaches a point that might require some maintenance so that flood elevations are controlled within design limits.

Sediment Basin

As a result of concern over phosphorous loading into Cherry Creek Reservoir and potential aggradation of sediment on the bed and floodplain of Cherry Creek, a sediment basin has been suggested to trap sediment and reduce associated phosphorous loading downstream. A study was conducted by Tetra Tech RMC ("Design of the Cherry Creek Sediment Basin and Stream Stabilization Measures," 2006) to evaluate this concept. The analysis seems to be consistent with a feasibility or preliminary level of analysis suitable as an initial evaluation, but did not include detailed hydraulic, sediment transport modeling or quantitative geomorphic analysis of the effects of the sediment basin on Cherry Creek. The quantity of sediment potentially trapped in the basin was estimated using sedimentation surveys from the U.S. Army Corps of Engineers periodic studies of Cherry Creek reservoir sedimentation as well as suspended sediment sampling data from Halepaska. Unfortunately, the two approaches provide dramatically different and inconsistent results (3,600 to 36,000 cubic yards per year). The reservoir sediment surveys should provide a reasonable estimate of the total sediment load flowing down Cherry Creek and into the reservoir, but do not isolate sediment coming from Piney Creek, a significant source of sediment delivered to the lower reaches of Cherry Creek upstream of the reservoir but downstream of the proposed location of the sediment basin (at Arapahoe Road).

This estimate of sediment transport, as discussed previously, suggests much higher sediment loads by an order of magnitude compared to the suspended sediment sampling. The suspended sediment sampling data produce an estimate of sediment transport into the sediment pond that is therefore much less than that based on the reservoir sedimentation survey analysis. The suspended sediment data do not include bedload transport and therefore underestimates the total sediment transport down Cherry Creek and into the sediment basin, but it is likely much closer to reality than the reservoir survey data.

While a discussion of the effect of the sediment basin on the geomorphology of Cherry Creek was included in the Tetra Tech report, no sediment transport modeling was conducted to quantify potential effects of the basin on the creek. Without such an analysis, it is difficult to evaluate and quantify the impact of the basin on the creek. Qualitatively, the sediment basin would reduce sediment loads and potential aggradation below the basin, but would likely cause degradation of the downstream channel bed. Given the potential deficiencies in the reliability and accuracy of the sediment transport data available to Tetra Tech for their evaluation, the results of the analysis are less than adequate to quantitatively evaluate the impact of the sediment basin on Cherry Creek. If such a basin were to be considered to be potentially beneficial, a more detailed quantitative analysis with new sediment transport data (including bedload) modeling should be conducted to quantify the effects of the basin on the creek and to adequately evaluate the potential benefits. This is consistent with the following recommendation by Cotton: *"It is highly recommended that detailed moveable-bed modeling be conducted for major floods in the study reach to determine the potential damage to downstream channel improvements,"* May 2011.

Given the author's opinion that the sediment transport is likely closer to the low end of the spectrum and that downstream reaches of Cherry Creek are degrading rather than aggrading, the potential benefits of such a basin are likely to be minimal in terms of reducing sediment and phosphorous loading, and the impact of the basin on the degradation of downstream reaches that are already experiencing such a response may be large. As a result, proceeding with the concept of an on-stream sediment basin does not seem to be adequately supported without further analysis as discussed above. On the other hand, sediment basins that could potentially reduce overbank aggradation may be beneficial, and may warrant further consideration.

Conclusions and Recommendations

Cherry Creek in the several mile reach upstream of the reservoir, including the reach between Piney Creek and Arapahoe Road, has experienced significant changes in hydrology that has triggered a geomorphic response in channel geometry and riparian vegetation. As a result of imported water and urbanization, combined with reduced alluvial pumping following changes in water rights administration, there have been more consistent low flows and a higher water table to support the establishment and growth of woody riparian vegetation. This vegetation, which has become well established on the floodplain benches adjacent to the active channel, plays a significant role in defining active channel widths.

Various analyses have been conducted to better understand the dynamics of Cherry Creek using best available data and acceptable techniques. However, because of the limited and sometimes conflicting data and complexities associated with the riparian vegetation dynamics, the results of these analyses are limited in their application. Based on the author's review and evaluation of the available data and analyses, and an independent site visit and evaluation of this stream, the following statements provide a summary of key points.

1. Cherry Creek remains in a state of dynamic response, and adjustments in slope will occur due to variations in hydrology and sediment supply. Therefore, considering a range of probable slopes is seen as more appropriate than designing for a single slope associated with a single set of assumed stream conditions.

2. The equilibrium slope analysis is affected by the selection of a sediment transport equation and a reference reach that is assumed to be stable. There are significant disparities in the previous studies in the selected sediment transport equation and reference reaches, and it is not necessarily the case that these reaches are stable.

3. The use of the 2-year return period master plan flows in equilibrium slope calculations is not well-supported by the dominant discharge analysis, the predominance of low flows, and the short duration of high flows. Computed equilibrium slopes, therefore, do not represent the dominant flow conditions.

4. The sediment transport analysis conducted by Cotton using the reservoir sedimentation surveys in the 1950s and 1960s were based on data collected when the Cherry Creek channel was wider and drier with more sediment exposed to potential transport, and before significant expansion of woody riparian vegetation. The resulting sediment transport rates seem excessively high, yielding sediment concentrations in the several tens of thousands of parts per million, whereas the available TSS data collected by the Cherry Creek Basin Water Quality Authority ranges from a few milligrams per liter (mg/l) to a maximum of 1400 mg/l.

5. Some sediment transport comes from the upstream watershed and some is derived from erosion of the channel. The distinction and quantification between natural sediment loading from the upstream watershed as compared to the eroding channel is not evident. Since many of the degrading reaches of Cherry Creek have been, or are in the process of being stabilized, sediment transport rates will likely decrease in the future.

6. If the predominant equilibrium slope in the active channel of Cherry Creek were 0.4%, as suggested in two prior studies, this would suggest that the channel would tend to run at the same overall valley slope without significant aggradation or degradation, thereby requiring few, if any, grade control structures. The observation that approximately 70% of the 17 master planned miles upstream of the reservoir have shown evidence of degradation indicates a trend toward a flatter slope and a need for grade control structures along the study reach.

7. Current slopes of the active channel in two selected reaches of Cherry Creek subject to watershed sediment loading, but not subject to high sediment loads from an eroding upstream reach, have been surveyed at essentially a flat slope that has developed over recent years.

8. Because of the dominant low-flow regime and potential for channel bed degradation and relatively flat slopes, it is recommended that frequent, low drops or bed stabilization riffles utilizing coarse material be used to increase the stability of the active channel.

9. Channel widths that are currently being maintained free of vegetation should be used to guide the design of the active channel in the study reach, since riparian vegetation will likely continue to control channel width (based on flows during germination season -- typically mid-May through mid-July -- that inundate the width of active channel where germination and establishment of vegetation is prevented).

10. Woody riparian vegetation is generally doing well and will provide some degree of channel bank stability. However, frequent low-height drop structures will be required to prevent significant degradation of the channel bed and undercutting of banks. Absent channel bed

degradation, no significant channel bank erosion is anticipated because of the resistance to erosion provided by this type of vegetation.

11. The need for a sediment basin to reduce aggradation of sediment along the channel bed has not been established. However, some form of a sediment trap or preferential deposition zone could be investigated further as a means of managing overbank aggradation.

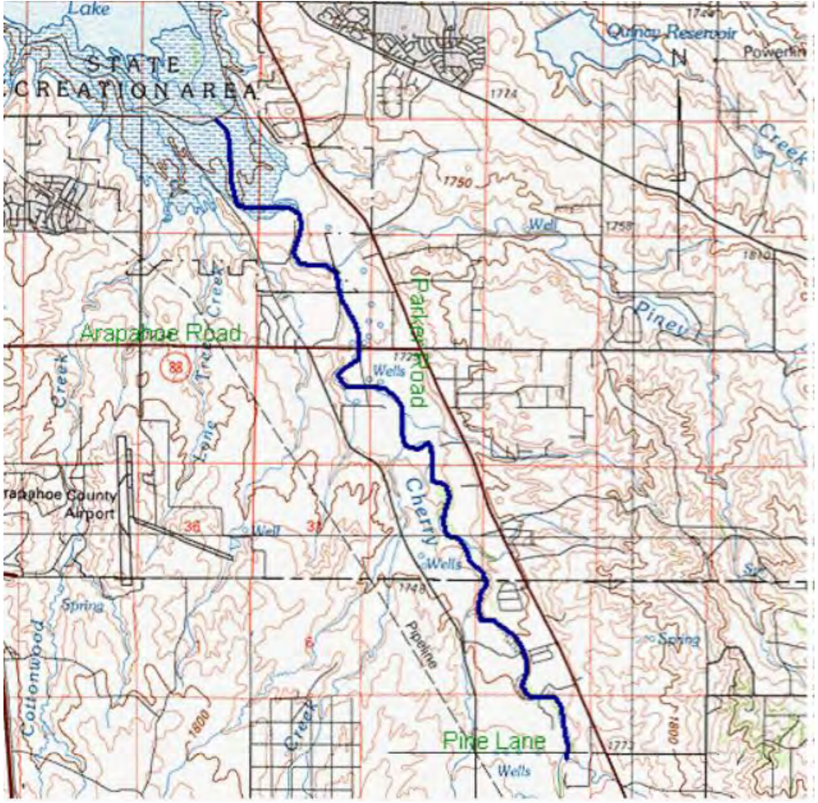
12. Collection of suspended and bedload transport data over a range of flows, bed mobility sediment transport modeling, and riparian vegetation analysis would be useful in better understanding the complex geomorphic issues of Cherry Creek. Such analyses would quantify sediment transport rates and could help predict channel bed response to a range of hydrologic and sediment conditions.

Cherry Creek continues to adjust geomorphically to changing hydrologic and sediment inflow conditions, as well as to the further expansion of and interaction with woody riparian vegetation. These factors need to be carefully considered in the evaluation and design of channel stabilization measures.

Appendix A

Review of: “Cherry Creek Sedimentation Study, Reservoir to Pine Lane, Project Data and Evaluation,” November 2010, prepared for Southeast Metropolitan Stormwater Authority by GK Cotton Consulting

Study Reach: Reservoir to Pine Lane

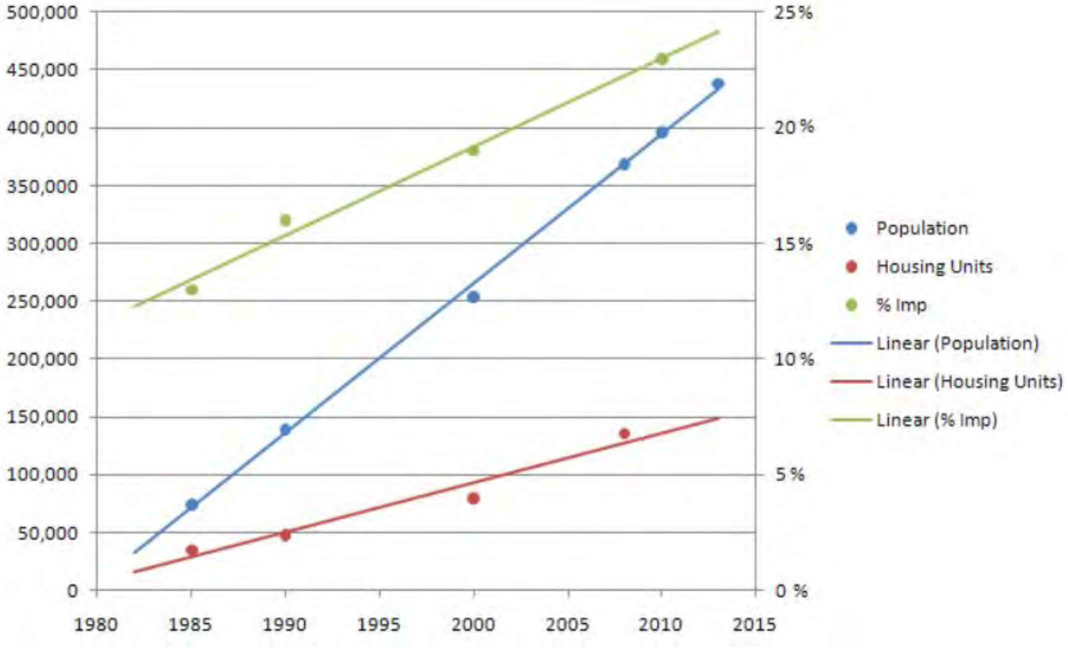


Period of hydrologic record: 1940 to present
Major droughts in 1930s and 1950s combined with groundwater pumping adversely affected riparian vegetation.

Major tributaries: Piney Creek, Happy Canyon Creek, and Baldwin Gulch / Newlin Gulch
Drainage Area: Cherry Creek at the Baldwin Gulch = 310 square miles, at reservoir = 360 square miles

Geology: east side of valley - aeolian (wind-blown) sands (Qes), west side of valley - colluvial deposits derived from erosion of the Castle Rock conglomerate (Tkr) and Denver formation (Tkd). The Louviers alluvium (Qlo) borders much of the west valley and forms a gravelly terrace that is about 60 feet above the modern valley of the Cherry Creek. mostly coarse sands with some gravel sediments + Aeolian sands

Population and % Impervious Trends:



Flood Peaks and Volumes:

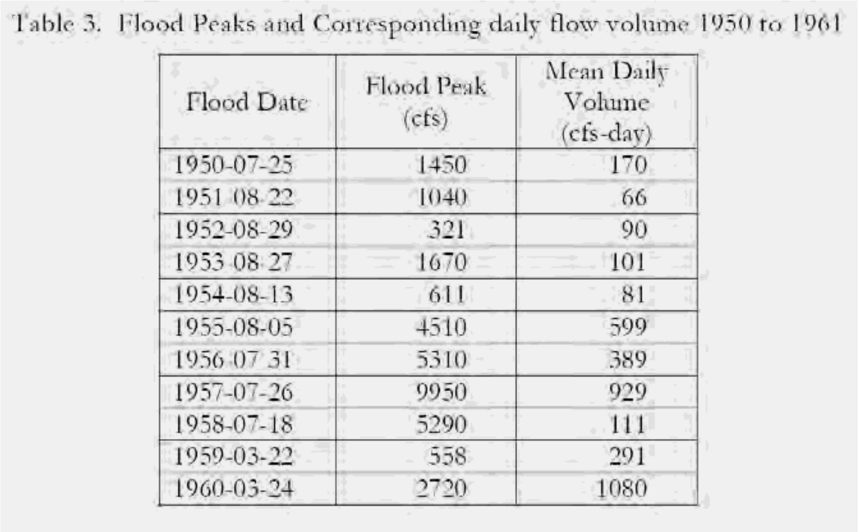
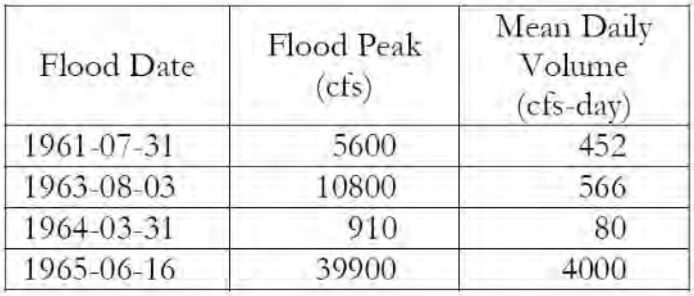


Table 3. Flood Peaks and Corresponding daily flow volume 1950 to 1961

Flood Date	Flood Peak (cfs)	Mean Daily Volume (cfs-day)
1950-07-25	1450	170
1951-08-22	1040	66
1952-08-29	321	90
1953-08-27	1670	101
1954-08-13	611	81
1955-08-05	4510	599
1956-07-31	5310	389
1957-07-26	9950	929
1958-07-18	5290	111
1959-03-22	558	291
1960-03-24	2720	1080

Table 4. Flood Peaks and Corresponding daily flow volume 1961 to 1965

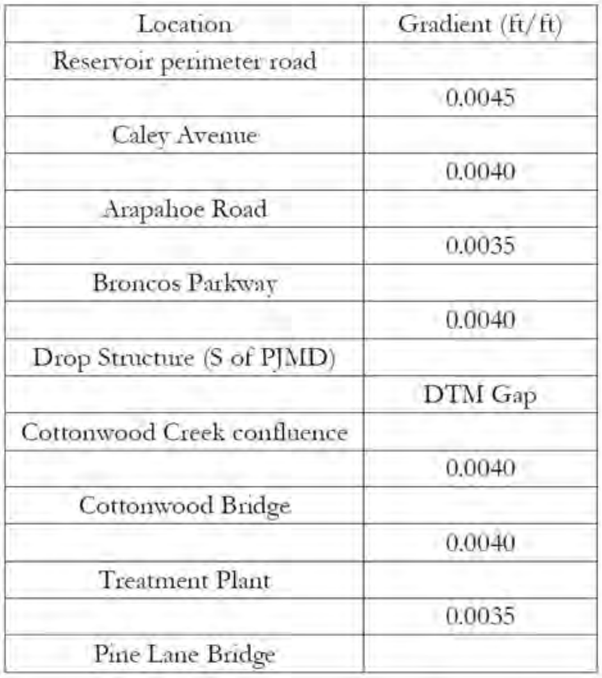


Flood Date	Flood Peak (cfs)	Mean Daily Volume (cfs-day)
1961-07-31	5600	452
1963-08-03	10800	566
1964-03-31	910	80
1965-06-16	39900	4000

Channel Geometry

Longitudinal Slope:

Table 5. Longitudinal Slope of the Cherry Creek



Location	Gradient (ft/ft)
Reservoir perimeter road	
	0.0045
Caley Avenue	
	0.0040
Arapahoe Road	
	0.0035
Broncos Parkway	
	0.0040
Drop Structure (S of PJMD)	
	DTM Gap
Cottonwood Creek confluence	
	0.0040
Cottonwood Bridge	
	0.0040
Treatment Plant	
	0.0035
Pine Lane Bridge	

Channel Width:

Table 6. Observed Active Channel Width

Site #1 (in State Park)	25.0 feet
Site #2 (at Valley Country Club)	41.0 feet
Site #3 (on Piney Creek)	19.5 feet
Site #4 (at Broncos Parkway)	21.0 feet
Site #5 (Happy Canyon Creek)	30.3 feet
Site #6 (above Broncos trailhead)	29.0 feet
Site #7 (above PJMD drop structure)	35.0 feet
Site #8 (at Pine Drive bridge)	10.0 feet

Bed Material:

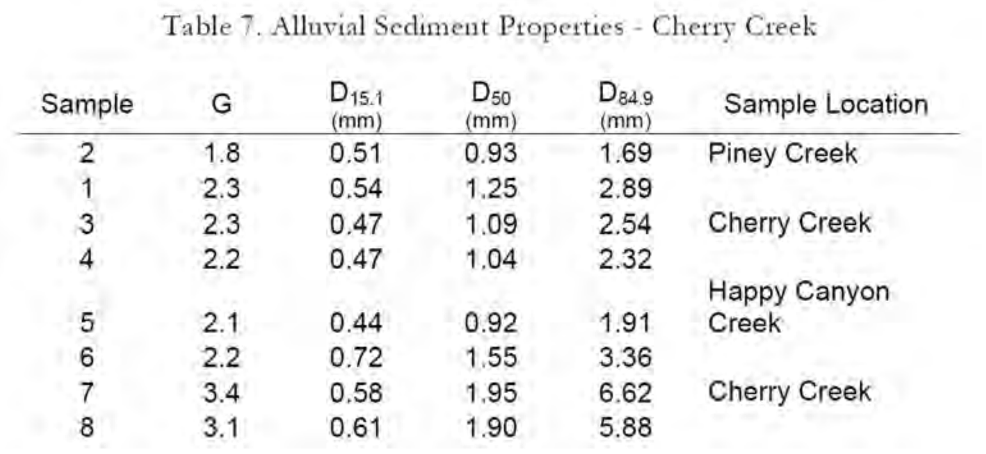


Table 7. Alluvial Sediment Properties - Cherry Creek

Sample	G	$D_{15.1}$ (mm)	D_{50} (mm)	$D_{84.9}$ (mm)	Sample Location
2	1.8	0.51	0.93	1.69	Piney Creek
1	2.3	0.54	1.25	2.89	
3	2.3	0.47	1.09	2.54	Cherry Creek
4	2.2	0.47	1.04	2.32	
5	2.1	0.44	0.92	1.91	Happy Canyon Creek
6	2.2	0.72	1.55	3.36	
7	3.4	0.58	1.95	6.62	Cherry Creek
8	3.1	0.61	1.90	5.88	

Table 8. Average Properties of Alluvial Sediments

Sample	G	$D_{15.1}$ (mm)	D_{50} (mm)	$D_{84.9}$ (mm)	Reach
2	1.8	0.51	0.93	1.69	Piney Cr.
1 3 4 5 6	2.2	0.53	1.17	2.60	Cherry Cr. below 17 Mile House Drop Structure and Happy Canyon Cr.
7 8	3.2	0.60	1.93	6.25	Cherry Cr. above 17 Mile House Drop Structure

Reservoir Sedimentation:

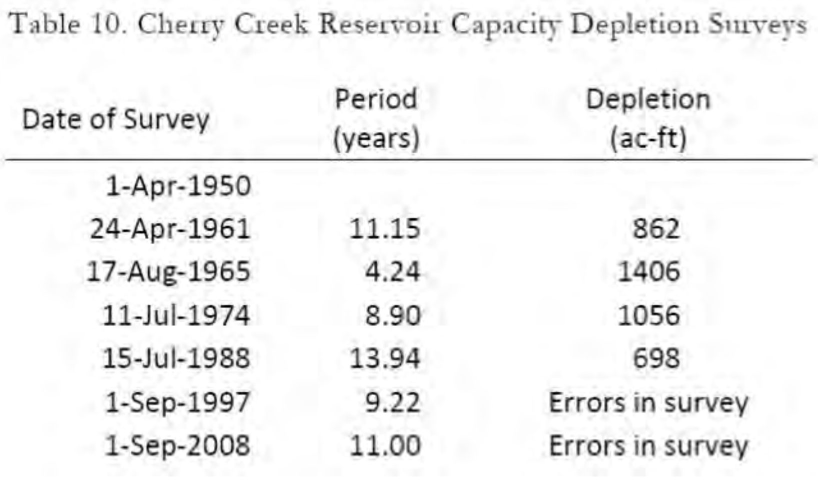


Table 10. Cherry Creek Reservoir Capacity Depletion Surveys

Date of Survey	Period (years)	Depletion (ac-ft)
1-Apr-1950		
24-Apr-1961	11.15	862
17-Aug-1965	4.24	1406
11-Jul-1974	8.90	1056
15-Jul-1988	13.94	698
1-Sep-1997	9.22	Errors in survey
1-Sep-2008	11.00	Errors in survey

Channel Erosion:

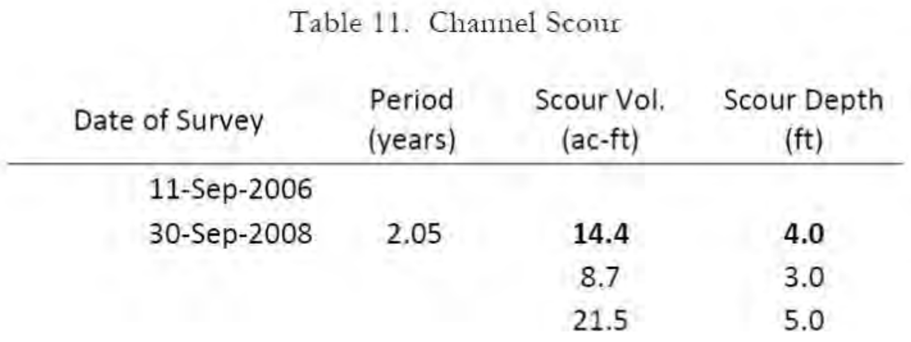


Table 11. Channel Scour

Date of Survey	Period (years)	Scour Vol. (ac-ft)	Scour Depth (ft)
11-Sep-2006			
30-Sep-2008	2.05	**14.4**	**4.0**
		8.7	3.0
		21.5	5.0

Appendix B

Summary of: Cherry Creek Sedimentation Study, Reservoir to Pine Lane – Sediment Transport Equation Calibration, GK Cotton, January 2011

HEC-RAS:

equation alone. The HEC-RAS sediment routines solve the sediment continuity equation (also known at the Exner equation):

$$(1-\lambda_p)\,\gamma_s\,B\,\frac{\delta z}{\delta t} = -\frac{\delta G_s}{\delta x} \text{ .... Equation 1}$$

where: B is the channel width; z is the channel elevation; λ_p is the active layer porosity; γ_s is the dry unit weight of sediment; t is time; x is distance; and, G_s is the transported sediment load.

Melvin Gage Locations:

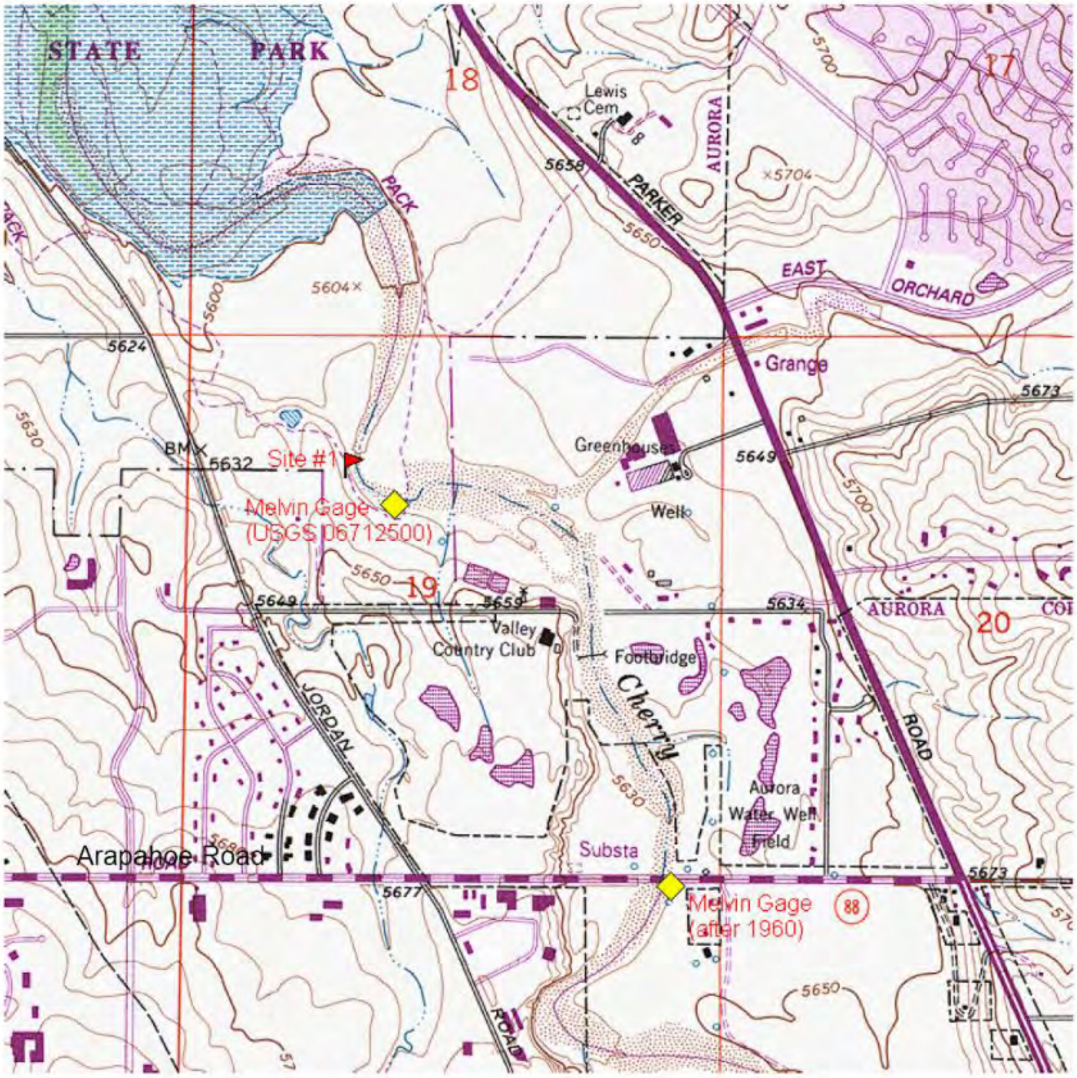
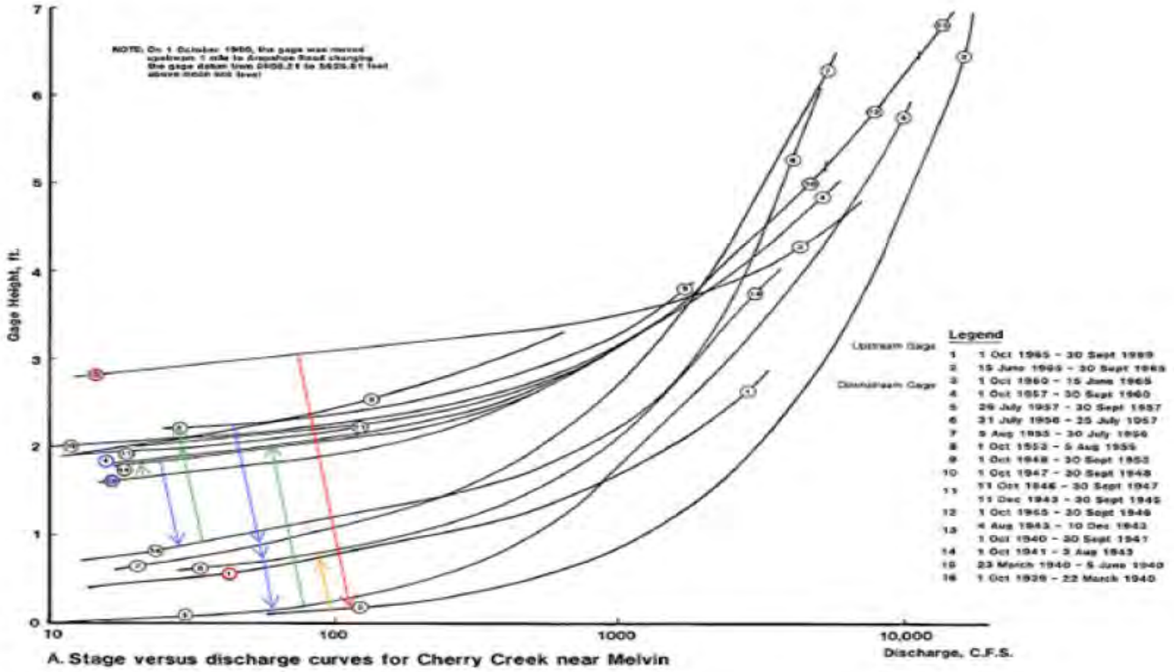


Figure 1. Location of sediment sampling site 1 and the Melvin Gage locations

Melvin Gage History:



A. Stage versus discharge curves for Cherry Creek near Melvin

A cycle of about 14 years (crest to crest of trough
to trough) can be seen in the shift history. A brief period of scour is followed by a longer period of aggradation. After the gage was relocated in 1960, there was a period of aggradation that abruptly ended with scour during the 1965 flood.

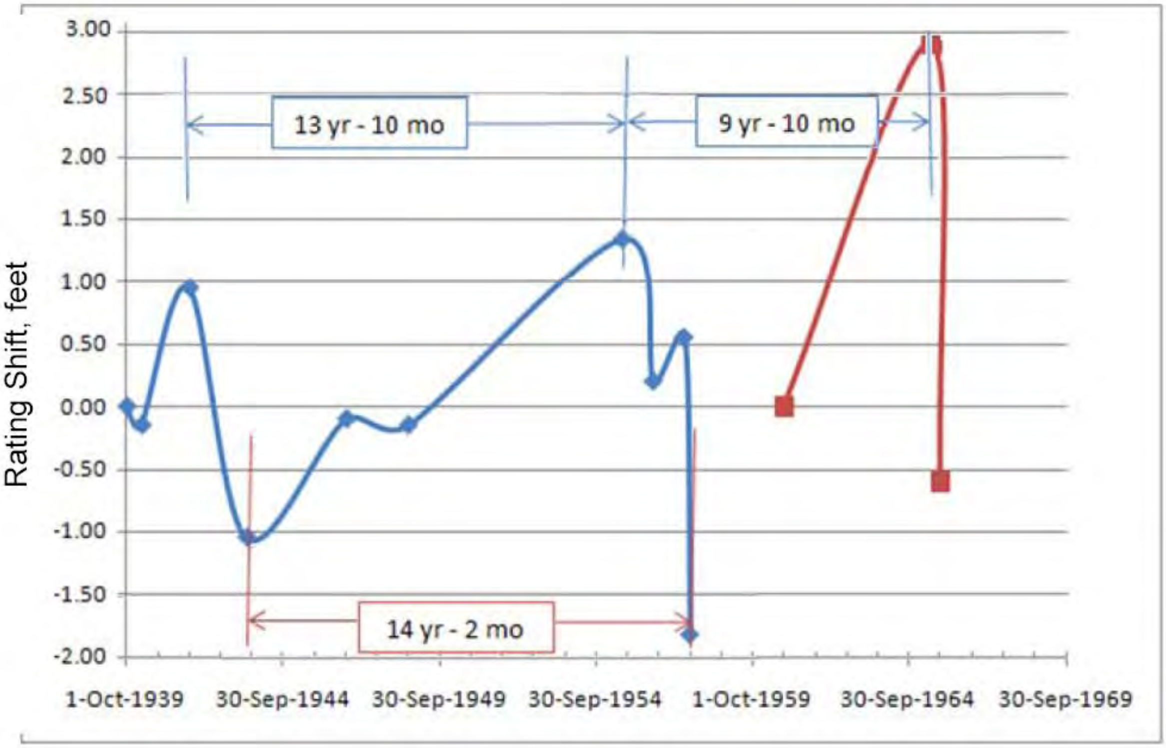


Figure 9. Melvin Gage History

Sediment Gradation (finer pre 1993):

Table 1. Site #1 Bed-Material Gradation (pre-1993)

Size, mm	% Finer
0.25	15.1
0.50	41.5
1.00	72.7
2.00	92.2
4.00	98.7
8.00	99.9
16.00	100.0

Channel Roughness:

From the aerial photographs it is observed that the active channel was unvegetated from 1937 to 1993 and that overbanks were vegetated with grasses, shrubs and a sparse number of cottonwood trees. The sand-bed channel has a low resistance characteristic of dunes or anti-dunes. An n-value of 0.025 was used for the active channel.

Table 2. Site #1 Channel Overbank n-values

Overbank Depth (ft)	Overbank Left	Right
0.6	0.311	0.336
1.6	0.311	0.166
2.7	0.146	0.091
4.5	0.076	0.068
5.8	0.064	0.061
7.5	0.057	0.056
10.6	0.049	0.048

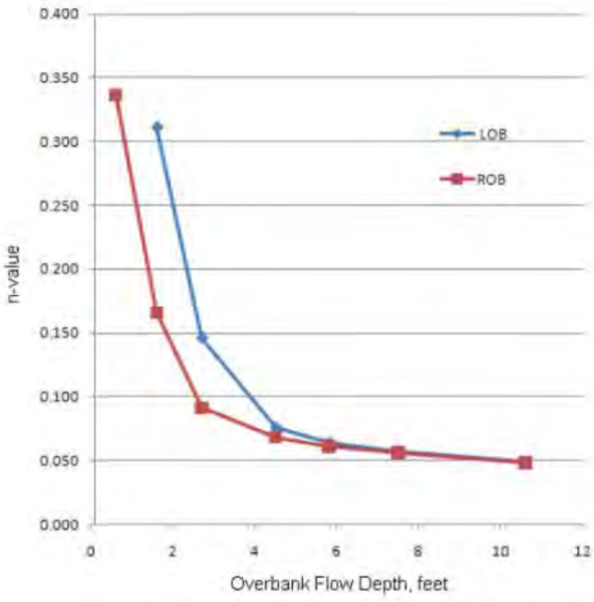


Figure 11. Overbank n-value

Sediment Transport Capacity Rating Curves:

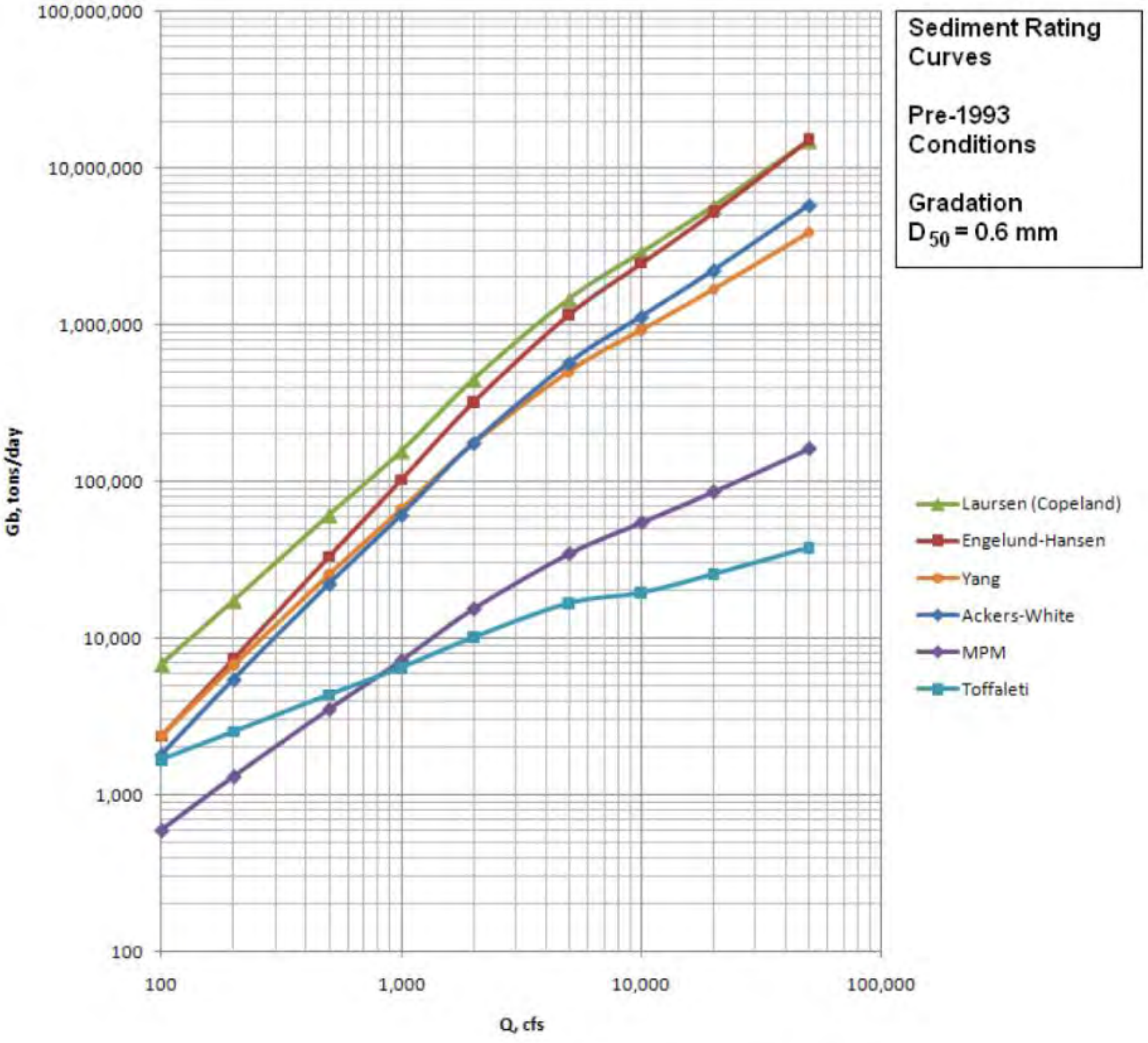


Figure 12. HEC-RAS derived sediment transport capacity rating curves

Rating Curves as Power Functions:

$$G_b = a\,Q^b \quad \text{Equation 2}$$

Table 3. Power functions of Sediment Transport Capacity

Transport Equation	a	b
Laursen (Copeland) (<2000 cfs)	11.04	1.3897
Laursen (Copeland) (>5000 cfs)	262.19	1.0111
Engelund-Hansen (<2000 cfs)	1.2357	1.6401
Engelund-Hansen (>5000 cfs)	86.235	1.1149
Ackers-White (<2000 cfs)	1.6184	1.5269
Ackers-White (>5000 cfs)	106.76	1.0065

These transport relationships are specifically for the channel geometry and bed-material conditions at Site #1 for the period from 1937 to 1993.

1965 Flood Hydrograph at Cherry Creek Reservoir:

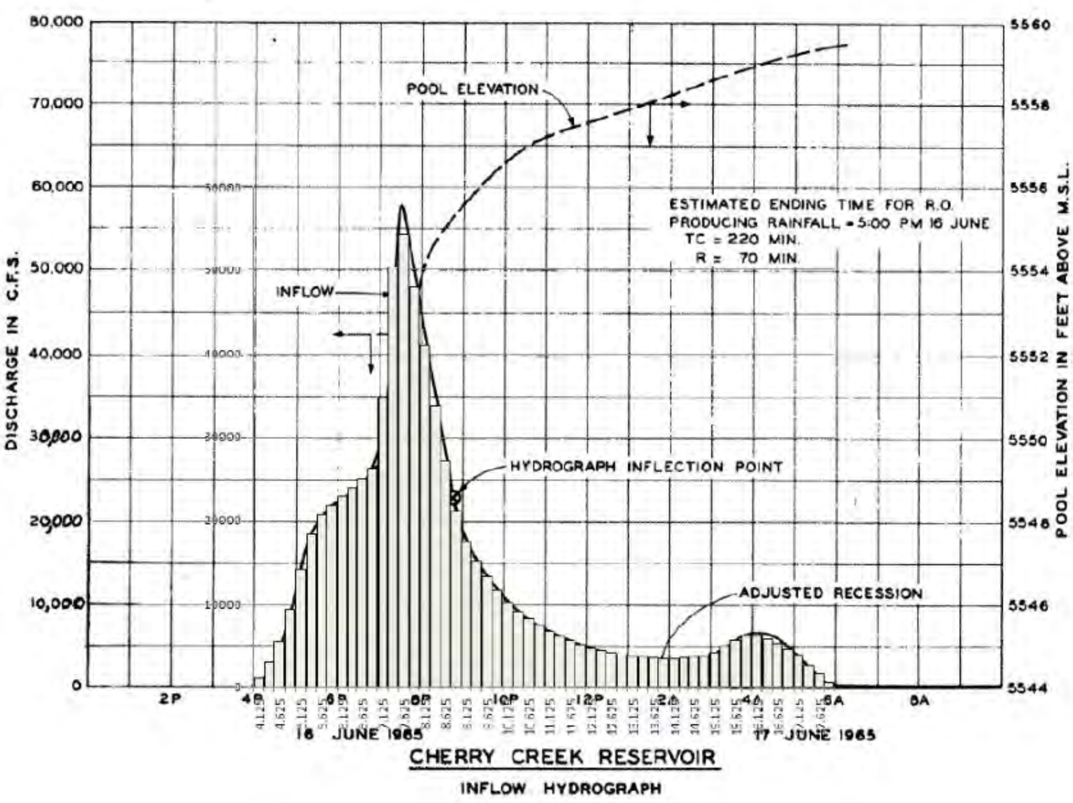


Figure 13. Digitized 1965 Flood Hydrograph at Cherry Creek Reservoir

Sediment Transport Calibration:

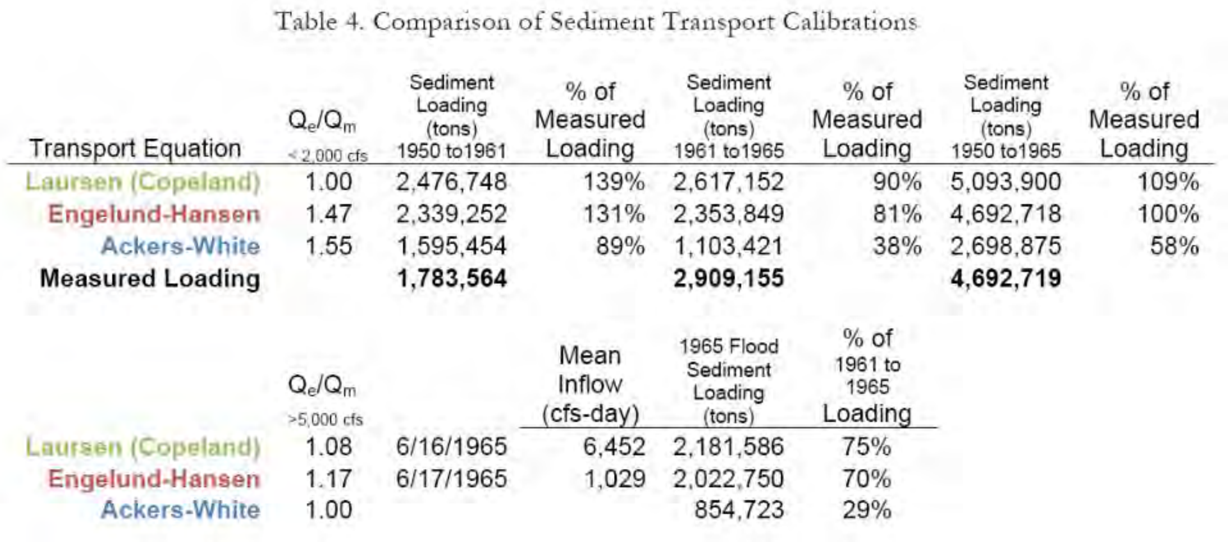


Table 4. Comparison of Sediment Transport Calibrations

Transport Equation	Q_e/Q_m <2,000 cfs	Sediment Loading (tons) 1950 to1961	% of Measured Loading	Sediment Loading (tons) 1961 to1965	% of Measured Loading	Sediment Loading (tons) 1950 to1965	% of Measured Loading
Laursen (Copeland)	1.00	2,476,748	139%	2,617,152	90%	5,093,900	109%
Engelund-Hansen	1.47	2,339,252	131%	2,353,849	81%	4,692,718	100%
Ackers-White	1.55	1,595,454	89%	1,103,421	38%	2,698,875	58%
Measured Loading		**1,783,564**		**2,909,155**		**4,692,719**	

	Q_e/Q_m >5,000 cfs		Mean Inflow (cfs-day)	1965 Flood Sediment Loading (tons)	% of 1961 to 1965 Loading
Laursen (Copeland)	1.08	6/16/1965	6,452	2,181,586	75%
Engelund-Hansen	1.17	6/17/1965	1,029	2,022,750	70%
Ackers-White	1.00			854,723	29%

RECOMMENDED TRANSPORT EQUATION

The Engelund-Hansen sediment transport equation is recommended for use on the Cherry Creek. Reasons for selecting the equation include:

1. The ability to accurately estimate sediment loading to Cherry Creek reservoir over two sedimentation survey periods.
2. Provides a reasonable value for the mean daily discharge scaling factor, which is consistent with the historic storm runoff character of inflows at the Melvin gage over the two sedimentation survey periods.
3. The equation provides a reasonable estimate of sediment loading during the 1965 flood, while also being able to provide a reasonable estimate of sediment loading from lower flows. The rating curve for the equation shows increased transport for high discharges that approach transport rates for Laursen (Copeland) but are between the rating for Laursen (Copeland) and Ackers-White.

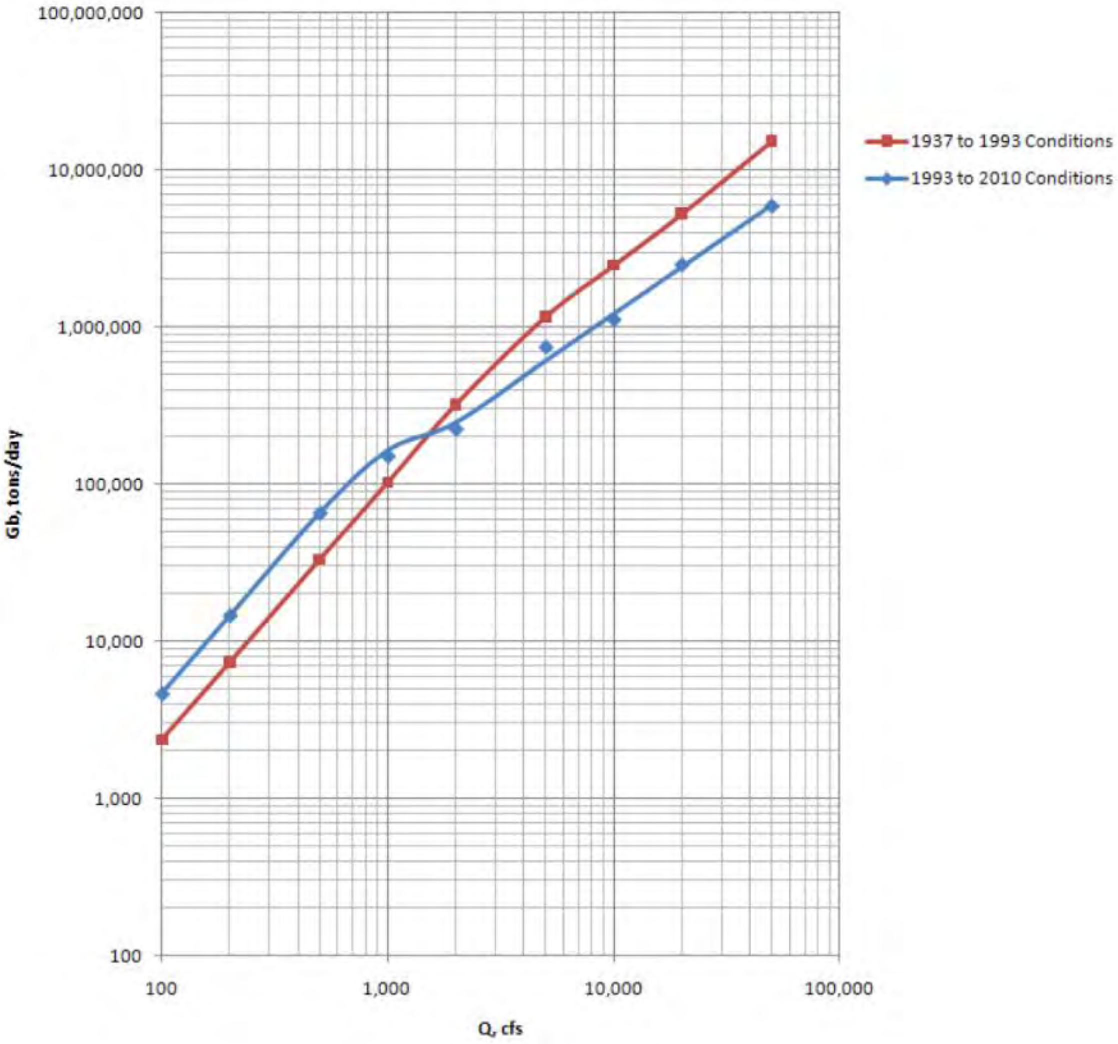
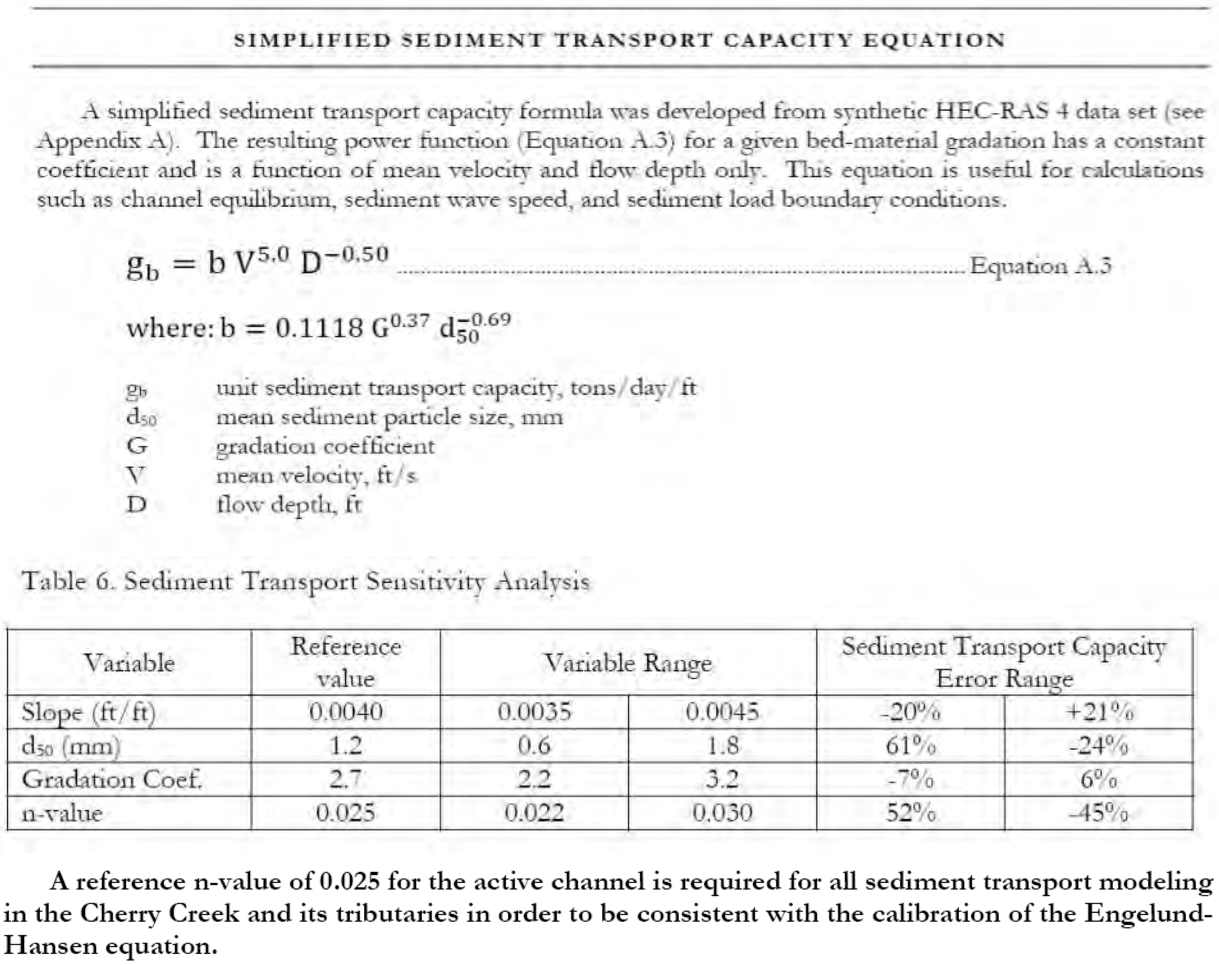


Figure 14. Revised Site #1 Sediment Rating Curve



SIMPLIFIED SEDIMENT TRANSPORT CAPACITY EQUATION

A simplified sediment transport capacity formula was developed from synthetic HEC-RAS 4 data set (see Appendix A). The resulting power function (Equation A.3) for a given bed-material gradation has a constant coefficient and is a function of mean velocity and flow depth only. This equation is useful for calculations such as channel equilibrium, sediment wave speed, and sediment load boundary conditions.

$$g_b = b\,V^{5.0}\,D^{-0.50} \quad \text{Equation A.3}$$

$$\text{where: } b = 0.1118\,G^{0.37}\,d_{50}^{-0.69}$$

g_b	unit sediment transport capacity, tons/day/ft
d_{50}	mean sediment particle size, mm
G	gradation coefficient
V	mean velocity, ft/s
D	flow depth, ft

Table 6. Sediment Transport Sensitivity Analysis

Variable	Reference value	Variable Range		Sediment Transport Capacity Error Range	
Slope (ft/ft)	0.0040	0.0035	0.0045	-20%	+21%
d_{50} (mm)	1.2	0.6	1.8	61%	-24%
Gradation Coef.	2.7	2.2	3.2	-7%	6%
n-value	0.025	0.022	0.030	52%	-45%

A reference n-value of 0.025 for the active channel is required for all sediment transport modeling in the Cherry Creek and its tributaries in order to be consistent with the calibration of the Engelund-Hansen equation.

SUMMARY OF RESULTS

From study field reconnaissance, and review of Google Earth images (from 1937 to 2010) it was determined that the stream segment of the Cherry Creek near Site #1 had a relatively stable cross section between 1937 to 1993. Using a cross section at Site #1 derived from 2008 aerial lidar data and adjusting for lateral erosion and scour that had occurred since 1993, the historic stream cross section was reconstructed. Historic sediment gradation was estimated from 1985 and 2010 samples of the Cherry Creek stream bed. The channel roughness was estimated based on the observed unvegetated width of channel and estimated vegetation coverage. The channel hydraulic conditions were computed over a range of discharges using a vertical change in roughness to simulated the affected of vegetation on the overbank.

Using HEC-RAS 4's hydraulic design tools, six sediment transport capacity rating curves were developed for the historic conditions. Of these three equations were selected for further evaluation: Laursen (Copeland), Engelund-Hansen, and Ackers-White. For more convenient computation, the rating curves were converted to power functions.

The sediment transport equations were compared to measured sediment deposition in Cherry Creek reservoir for two periods (1950 to 1961, 1961 to 1965). Sediment load was estimated for the sedimentation periods using the inflow time series at the Melvin stream gage and the 1965 June flood inflow hydrograph. Based on this analysis the Engelund-Hansen equation was found to most closely estimate the sedimentation history from 1950 to 1965.

A simplified version of the Engelund-Hansen sediment transport equation was developed as a power function. A sensitivity analysis was conducted using the power function version of the Engelund-Hansen sediment transport equation that shows the potential affect on sediment transport capacity estimations caused by errors in key hydraulic variables. Other potential uses of the simplified equation include: equilibrium analysis, estimation of sediment wave speed, and estimation of boundary conditions.

E-H SEDIMENT TRANSPORT CAPACITY REGRESSION EQUATION

A sediment transport capacity regression equation was computed by transforming the data set (total bed load, mean velocity, depth, and mean sediment size) to natural log values and then linearly regressing the transformed data set using Excel's LINEST regression function. Since the data set is without error and derived from a fairly simple function it was expected that regression error should be minimal. The r^2 value for the equations was in fact 1.0. The resulting power function formula is

$$g_b = b\, V^{5.0}\, D^{-0.50} \quad \text{.......... Equation A.3}$$

$$\text{where: } b = 0.1118\, G^{0.37}\, d_{50}^{-0.69}$$

The coefficient, b, is constant for a known sediment gradation. For example, current bed-material in the Cherry Creek has the following properties: $d_{50} = 1.2$ and $G = 2.2$, which give a coefficient of $b = 0.132$. Up-valley the bed-material coarsens to $d_{50} = 1.9$ and $G = 3.2$, which give a coefficient of $b = 0.110$ (about a 20% reduction).

Of interest in equation 3 are the two exponents. The velocity exponent of 5.0 can be predicted from equation 2, since $\tau_o \propto U^2$. This indicates that the formula has a very high sensitivity to velocity. The flow depth exponent shows a common behavior of sediment transport, which is a reduction in transport capacity with increasing flow depth.

RANGE OF APPLICABILITY

As with any regression equation, the use of the Engelund-Hansen regression equation should not exceed the range of data from which it was developed. This is particularly true for the properties of the sediment gradation (G and d_{50}). Likewise, when using this regression equation to estimate sediment transport in the active channel of the Cherry Creek, the active channel roughness should always be 0.025 to be consistent with the active-channel roughness that was used to develop this data set.

The ranges are applicable to the hydraulic properties of the active channel of the Cherry Creek and do not necessarily apply to portions of the channel that are outside that boundary where sediment transport is not being calculated.

Variable	Range
Sediment size, d_{50} (mm)	0.6 to 1.9
Gradation Coefficient, G	2.2 to 3.2
Velocity, V (ft/s)	1.8 to 20.8
Depth, D (ft)	0.4 to 13.3
Froude No., Fr	0.4 to 1.2
Unit discharge, q (cfs/ft)	1 to 200
Slope, S (ft/ft)	0.0020 to 0.0060

Appendix C

Summary of: Cherry Creek Sedimentation Study, Reservoir to Pine Lane – Sediment Budget by GK Cotton, March 2011

Sediment transport capacity ratings for the sub-reaches were developed using HEC-RAS 4 design tools with the Engelund-Hansen formula.

Sediment budget was calculated on a monthly basis for each sub-reach and the potential volume of reach aggradation / scour computed.

It was found that the study reach looses stream flow at the rate of about 6.3% per mile relative to inflow at the confluence of Baldwin Gulch (near Parker, CO). Over the simulation period, 32% of inflow is diverted by water suppliers as well as inflows from stormwater runoff and return flows. These diversions occur from the alluvial aquifer of the Cherry Creek valley via well fields that are operated by water providers. As a result, 67% of the sediment supply that enters the study reach is deposited within the study reach. Most of the study sub-reaches are depositional with the exception of the sub-reach below the confluence of Happy Canyon Wash, which is scour prone.

Sustained groundwater elevations in the alluvium will be important to the riparian plant community. So while surface flows may vary significantly, groundwater elevations should ensure that larger riparian plants weather drought conditions in the watershed.

Stream slopes measured for this study were found to be in a narrower range than was reported in the Master Plan, averaging 0.0395 +0.00043 ft/ft compared to 0.00444 +0.0007.

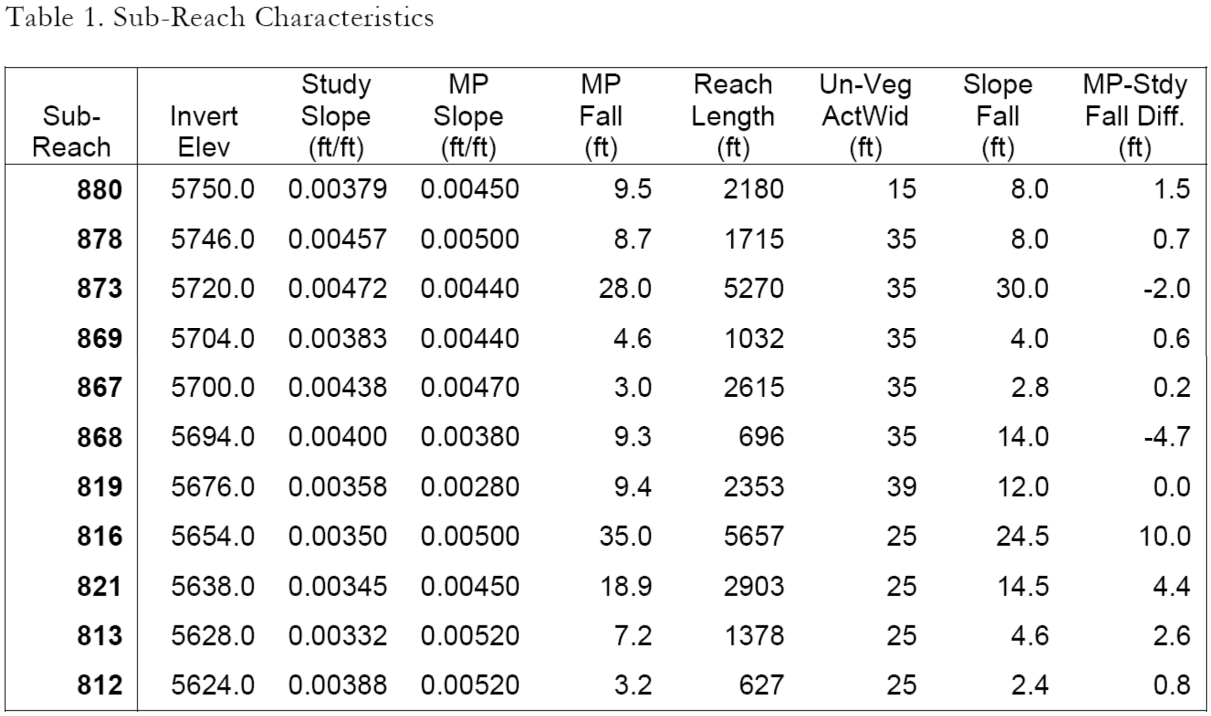


Table 1. Sub-Reach Characteristics

Sub-Reach	Invert Elev	Study Slope (ft/ft)	MP Slope (ft/ft)	MP Fall (ft)	Reach Length (ft)	Un-Veg ActWid (ft)	Slope Fall (ft)	MP-Stdy Fall Diff. (ft)
880	5750.0	0.00379	0.00450	9.5	2180	15	8.0	1.5
878	5746.0	0.00457	0.00500	8.7	1715	35	8.0	0.7
873	5720.0	0.00472	0.00440	28.0	5270	35	30.0	-2.0
869	5704.0	0.00383	0.00440	4.6	1032	35	4.0	0.6
867	5700.0	0.00438	0.00470	3.0	2615	35	2.8	0.2
868	5694.0	0.00400	0.00380	9.3	696	35	14.0	-4.7
819	5676.0	0.00358	0.00280	9.4	2353	39	12.0	0.0
816	5654.0	0.00350	0.00500	35.0	5657	25	24.5	10.0
821	5638.0	0.00345	0.00450	18.9	2903	25	14.5	4.4
813	5628.0	0.00332	0.00520	7.2	1378	25	4.6	2.6
812	5624.0	0.00388	0.00520	3.2	627	25	2.4	0.8

Table 2. Vertical variation in roughness with flow depth

Depth (ft)	n-value		
	Left	Main	Right
0.0	0.311	0.025	0.311
1.0	0.311	0.025	0.311
2.0	0.146	0.025	0.146
4.0	0.076	0.025	0.076
5.0	0.064	0.025	0.064
7.0	0.057	0.025	0.057
10.0	0.049	0.025	0.049

Table 3. Bed material gradation properties

Grain size (mm)	% Finer		
	Left	Main	Right
0.25	15.1	2.5	15.1
0.5	41.5	14.0	41.5
1.0	72.7	42.1	72.7
2.0	92.2	75.2	92.2
4.0	98.7	94.1	98.7
8.0	99.9	99.3	99.9
16.0	100.0	100.0	100.0

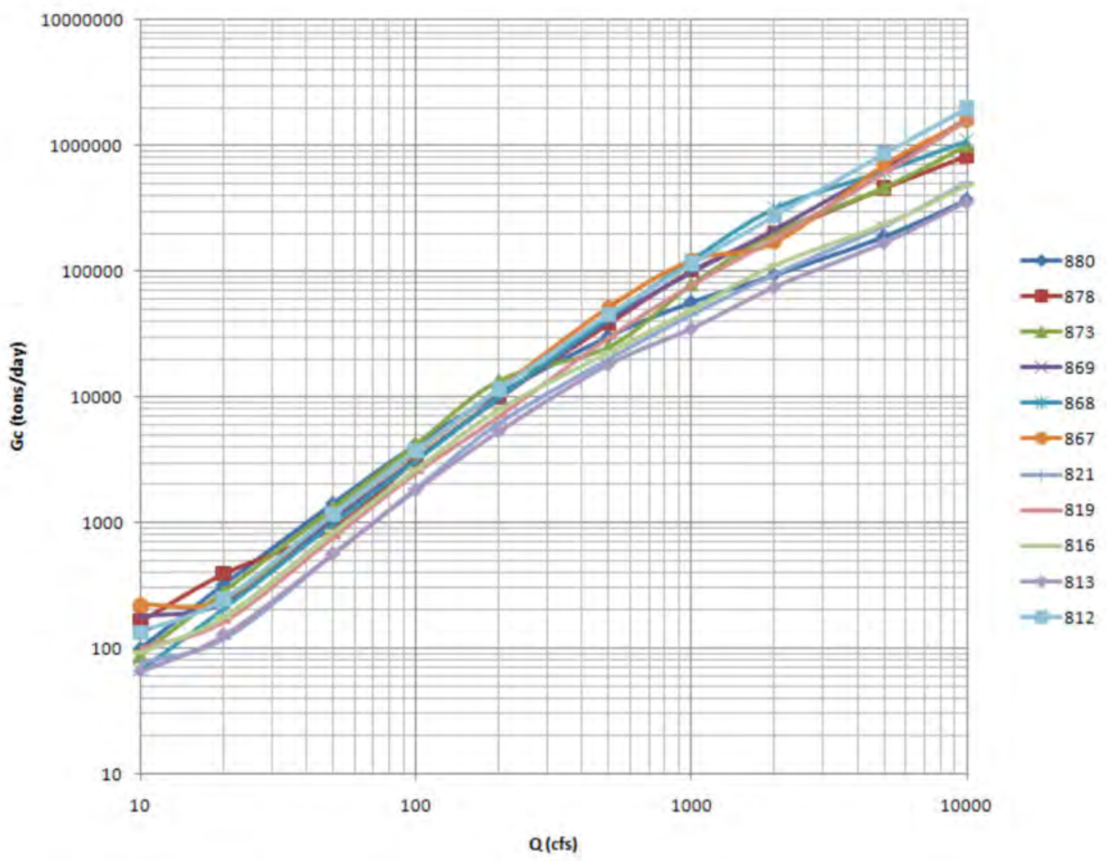


Figure 3. Sub-Reach Sediment Transport Rating Curves

Figure 10 shows the cumulative transport of sediment for the eight year study period. On an annual basis, there is an average of 2.1 tons (1.6 cubic yards) of sediment depositing per foot of stream length per year within the active channel of the Cherry Creek. Relative to the transport capacity of the Cherry Creek at Parker, only 33% of that capacity remains at the most sub-reach 813.

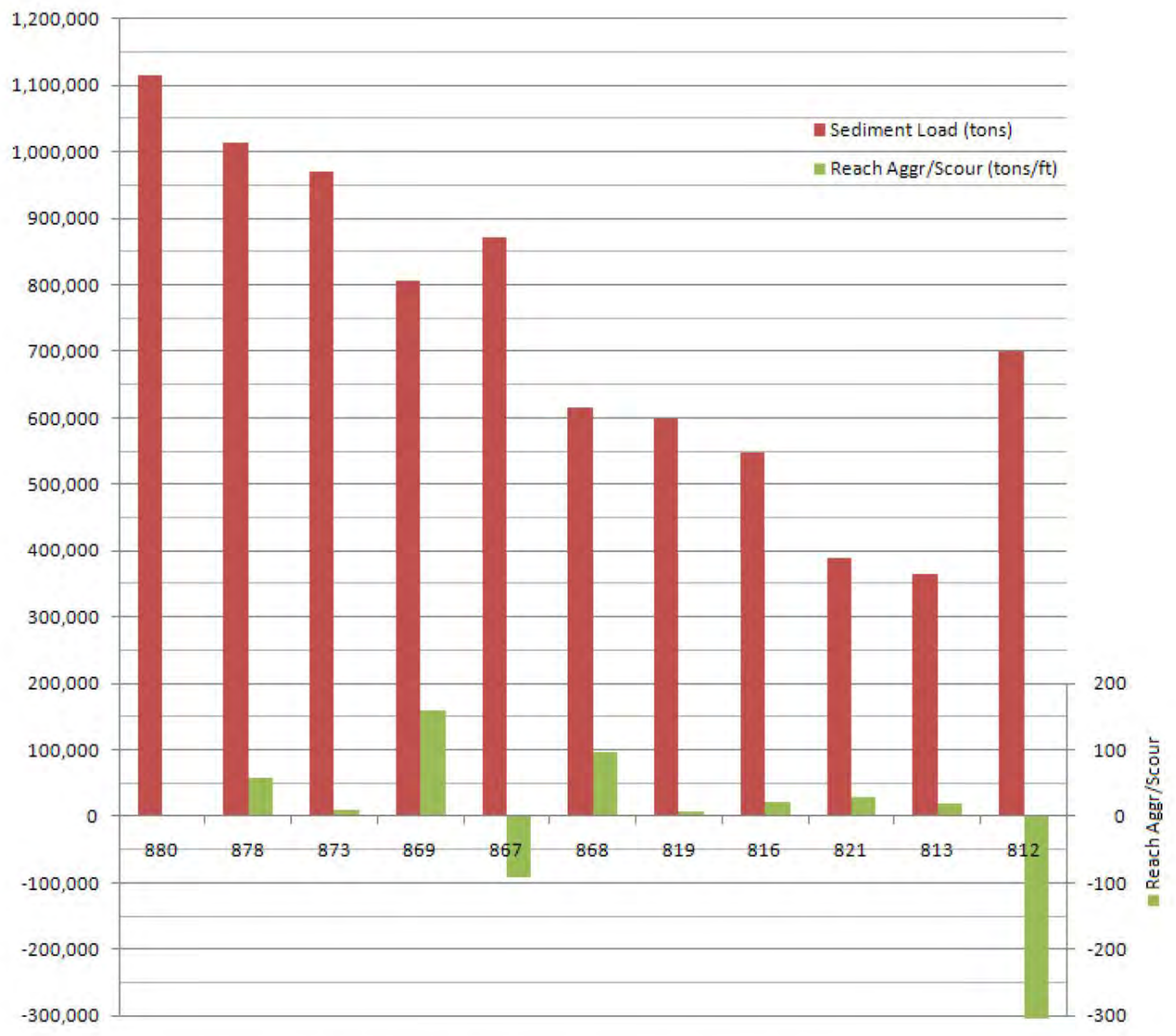


Figure 10. Sediment Budget by Sub-Reach and Potential Aggradation/Scour

As an example of the detailed aggradation/degradation behavior of a sub-reach, reach 867 and 813 are shown in Figure 11. These time series show that while a sub-reach tends to be predominantly aggradational or degradational, there are never-the-less periods where the trend reverses (highlighted in yellow). While a lack of sediment supply to a reach results in channel erosion, erosion still occurs in aggrading reaches as the stream reworks the excess sediment load. Large deposits of sediment in a reach often cause a shift in stream pattern, which can trigger erosion.

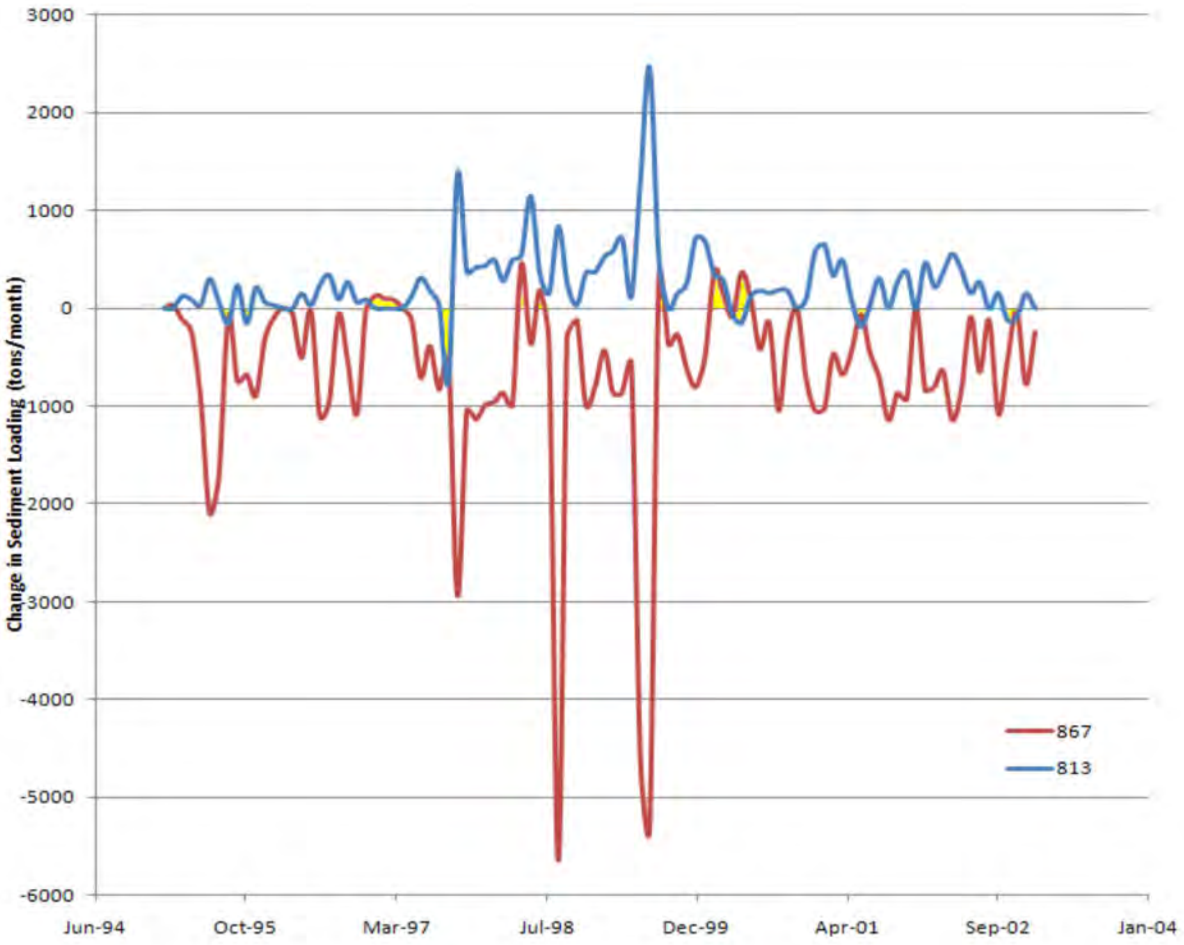


Figure 11. Aggradation / Degradation Time Series for selected sub-reaches (867 and 813), yellow highlights show periods of scour in a predominantly aggrading reach or periods of aggradation in a predominantly scouring reach.

SUMMARY AND FINDINGS

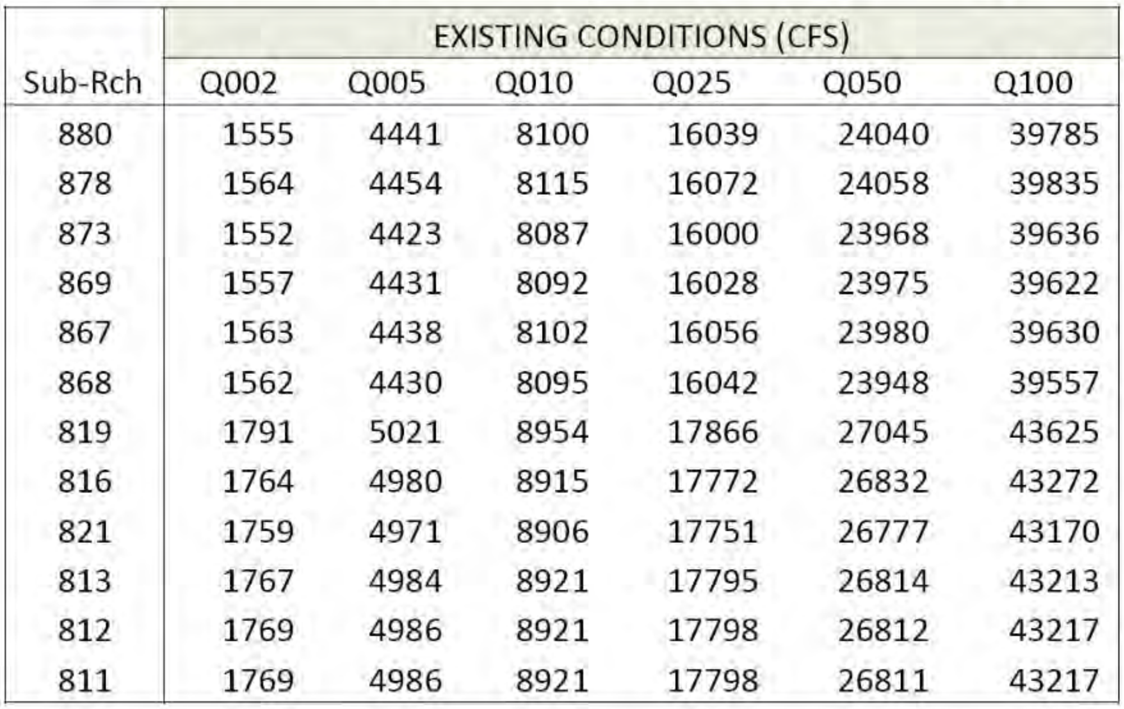
1. The CCBWQA hydrology simulation provided eight years of flow data for the study reach. In addition, the simulation provides detailed routing for 11 sub-reaches following the routing topology that was developed for floodplain master planning (URS, 2002).
2. The hydrology simulation shows that the study reach looses flow to water diversion at the rate of 6.3% per mile. Tributary inflow are quickly diverted and as a result have a fairly localize affect on the water balance.
5. Channel cross-section, stream gradient, and cross section properties (sediment gradations and roughness) were developed for each of the 11 sub-reaches of the study reach.
3. Mean monthly discharge was scaled by a factor of 1.352 for estimation of mean-monthly sediment load. This allowed the use of CCBWQA mean-monthly flow data.
4. The upper sub-reach of the study area (sub-reach 880) was found to be stable and it is recommended as a reliable reach for the estimation of incoming sediment supply to the study reach.
6. The sediment budget for the study sub-reaches shows that transport capacity steadily decreases in the downstream direction. This is directly attributable to the reduction in flow in the Cherry Creek.
Only the sub-reach below Happy Canyon showed a potential for scour.

Appendices include cross-section data, sediment data, and results of modeling

Appendix D

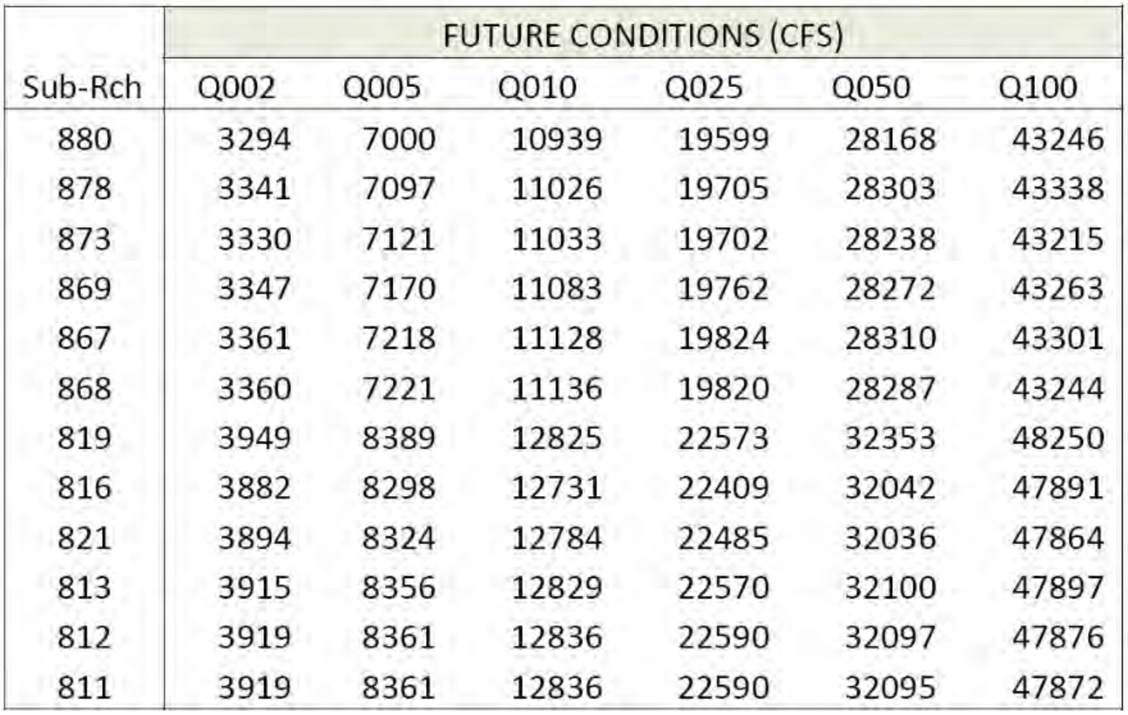
Summary: GKC – Scenario Development & Evaluation, May 2011

Table 3. Peak Flow Summary - Sedimentation Study Reach / Existing Conditions



	EXISTING CONDITIONS (CFS)					
Sub-Rch	Q002	Q005	Q010	Q025	Q050	Q100
880	1555	4441	8100	16039	24040	39785
878	1564	4454	8115	16072	24058	39835
873	1552	4423	8087	16000	23968	39636
869	1557	4431	8092	16028	23975	39622
867	1563	4438	8102	16056	23980	39630
868	1562	4430	8095	16042	23948	39557
819	1791	5021	8954	17866	27045	43625
816	1764	4980	8915	17772	26832	43272
821	1759	4971	8906	17751	26777	43170
813	1767	4984	8921	17795	26814	43213
812	1769	4986	8921	17798	26812	43217
811	1769	4986	8921	17798	26811	43217

Table 4. Peak Flow Summary - Sedimentation Study Reach / Future Conditions



	FUTURE CONDITIONS (CFS)					
Sub-Rch	Q002	Q005	Q010	Q025	Q050	Q100
880	3294	7000	10939	19599	28168	43246
878	3341	7097	11026	19705	28303	43338
873	3330	7121	11033	19702	28238	43215
869	3347	7170	11083	19762	28272	43263
867	3361	7218	11128	19824	28310	43301
868	3360	7221	11136	19820	28287	43244
819	3949	8389	12825	22573	32353	48250
816	3882	8298	12731	22409	32042	47891
821	3894	8324	12784	22485	32036	47864
813	3915	8356	12829	22570	32100	47897
812	3919	8361	12836	22590	32097	47876
811	3919	8361	12836	22590	32095	47872

Dominant discharge analysis:

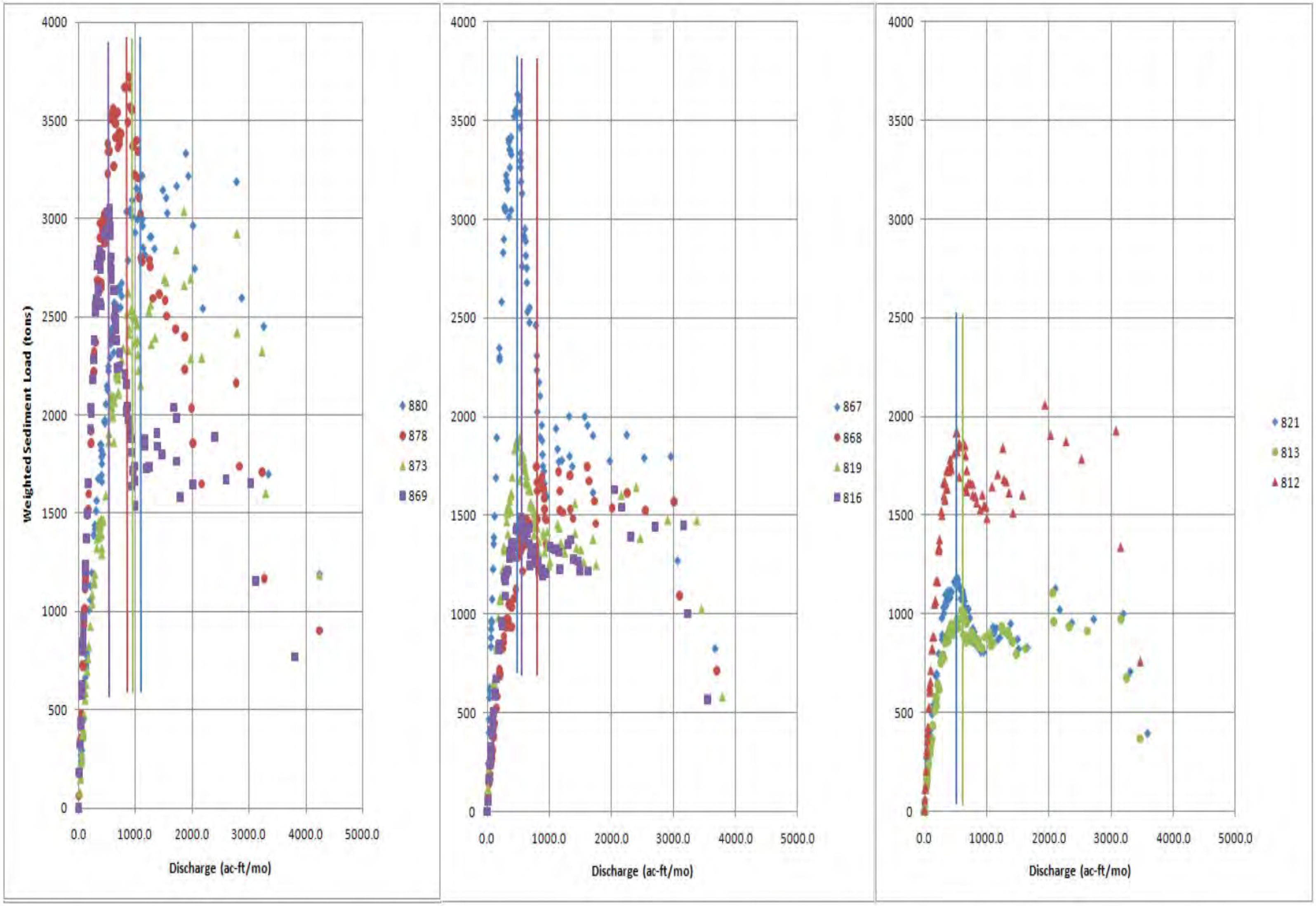


Figure 3 Shows plots of dominant discharge calculation as computed by sub-reach for the CCBWQA simulation. The vertical lines show the approximate location of the first peak in weighted sediment loading, i.e. the dominant discharge for the sub-reach (ac-ft/month). The vertical axis is the probability weighted sediment transport in tons.

SUMMARY AND FINDINGS

1. Water supply development in the Cherry Creek basin results in the reach between Parker and Cherry Creek reservoir being a losing reach. It is expected that on average there will be about 32% less stream flow at the lower end of the study reach compared to inflow at the upper end.

2. An interim approach to the estimation of channel forming flows is proposed that scales the 2-year Major Drainageway Planning flow at sub-reach 880 according to the average loss rates calculated by the CCBWQA model for downstream sub-reaches.

3. It is recommended that a better model of minor floods and low-flows be developed that incorporates elements of the CCBWQA model (i.e. water storage in alluvial aquifers, aquifer flows, and pumping operations for water recovery). The new model should upgrade the Major Drainageway Planning hydrology model that is based on UDSWM to EPA-SWMM 4.

4. The upper sub-reach of the study area (sub-reach 880) was found to be stable and it is recommended as a reliable proxy reach for the estimation of incoming sediment supply to the study reach.

5. The equilibrium index method was applied to evaluate three channel design scenarios. It was found that recent improvements to the channel are not in equilibrium between sediment transport and stream power. This results in the potential for sediment deposition within the channel improvements. This aggradation is expected to be minor for 2-year flows and will require further investigation for major floods.

6. Scenarios #2 and #3 developed in this report can be mixed as needed to meet the needs of the corridor. Scenario #2 comports to prior design and major drainageway planning but may be vulnerable to significant aggradation during major floods. Scenario #3 has a cross-section geometry and profile grade that is similar to the original Cherry Creek channel. It has the advantage of creating a larger vegetated channel width, which would provide a significant water quality benefit.

7. It is highly recommended that detailed moveable-bed modeling be conducted for major floods in the study reach to determine the potential damage to downstream channel improvements.

8. A monitoring program for sedimentation and alluvial groundwater elevations should be started so that stream health can be routinely evaluated in light of very rapid changes occurring to the water supply within the basin and the extensive use of the alluvial aquifers as the means of recycling a large portion of that imported water supply as permitted by Colorado water law.