Section 1: Project Goals

The project has three tasks: 1) collect and analyze flow, cross section geometry, suspended sediment and bed load samples: Samples and data will be collected at each sampling site identified (5 sampling sites); 2) develop a sediment rating curve: Sediment rating curve will be developed and implemented into HEC-RAS and SRH1D models to validate the performances of various sediment equations; 3) prepare a report including a summary of the monitoring and modeling results, monitoring data and photographs, appropriate GIS files and associated metadata in the Pima County Projection, and HEC-RAS and SRH1D models including a sediment rating curve
Section 2: Monitoring Base Flow Channel

2.1. Background

Data collection was initiated in Dec 2012. The original purpose is to collect data of bed elevation change to verify the HEC-RAS sediment transport model. In Dec 2012, we began to measure bed elevation change by using erosion pin and scour chain. After the winter monsoon season, the scour chain was buried by deposition, and scour bars were covered by vegetation (Fig.1). Neither method gave us accurate readings of bed elevation change. Therefore, we decided to choose several fixed locations and conduct periodic cross section survey using a total station.

![Fig.1 Scour bar with debris](image)

For sediment transport modeling study, we sampled bed sediment on Dec 17\(^{th}\), 2012 at nine accessible locations, named Sed_1 to Sed_9 as shown in Fig.2. Those sites are located near Sweetwater Road, Ruthrauff Road, Sunset Road, Ina Road, Twin Peak Road, Avra Valley Road, Among those sites, five accessible sites, Sed_1, Sed_3, Sed_5, Sed_8, and Sed_9, which are nearly uniformly distributed along the study reach, were selected to conduct monthly measurements of flow, sediment load, and cross sectional changes.

The monthly survey was conducted on March 26\(^{th}\), April 25\(^{th}\), May 29\(^{th}\), June 25\(^{th}\), August 7\(^{th}\), and September 3\(^{rd}\) in 2013. We used the Nikon DTM series total station. Two or more permanent marks are installed at both banks of each cross section. Those marks are located at very high banks to ensure no flow can reach there. The bed elevations are measured at 2 feet intervals at each cross section. About 15-40 survey points are needed to complete the measurement at one cross section. The changes of those cross sections can be identified by comparing the measurements. Since Sept 3\(^{rd}\) 2013, our survey interval was changed to quarterly. This periodic survey has continued for the past two years until June 2015.
In addition to survey cross sections, bed load sediment was first measured on Feb 27th, 2013 using a 6-inch Helley-Smith bed load sampler at Sweetwater, Ina and Sanders sites. Suspended sediment was measured at the same locations using USGS DH48 suspended sediment sampler. The sampled water was filtered, dried, and weighted in the soil laboratory at UA. As we monitor the cross sections, we see the needs to measure flow and sediment load simultaneously. Therefore, starting May 29th, 2013, we also measured flow and sediment load at each cross section. Flow velocity field was measured using ADV-based flow tracker at 2 feet interval at each cross section. The measured flow depths and velocity were used to calculate flow discharge at each cross section. The changes of cross section, flow discharge, and sediment load from 2013 to 2015 are summarized below:
2.2. Changes of Cross Sections from 2013 to 2015

To be concise, only selected survey results of the base flow channel were shown in Fig.3-8. All the survey data are contained in an excel file, “Fig.3-8.cross section summary.xls”. In general, this reach is experiencing minor erosion (< 0.5 ft) from effluent base flow in 2013, and this erosion became moderate (>1.0 ft) at the reach near Sanders and Trico Road in 2014. During the winter/summer monsoon seasons, moderate sand deposition were found upstream from Sanders Road. Those depositions (< 1.0 ft) were eroded away by the base flow.

Figure 3 showed the Sweetwater reach is relative stable, sand deposition always occurs after storm events, but was washed away by the continuous base flow. Channel bed elevation slightly degraded in 2015, and remains nearly unchanged.
Figure 4 showed the meandering loop passing through the Ina Road section is more active in 2014 than in 2013, and relatively stable in 2015. The meandering loop is migrating to the East bank. There is moderate incision (< 1.0 ft) after Sept 2014.

Figure 5 Twin Peak Section
Figure 5 showed the Twin Peak reach is aggregated from 2013 to 2015, perhaps due to the mild slope. The base flow channel is migrating to the East.

![Sanders Road Cross Section](image)

**Fig.6 Sanders Cross Section**

Figure 6 showed significant lateral migration and bed incision in Sanders location, upstream from the Sanders Bridge. The thalweg of base flow channel has been lowered about 2.0 feet since March 2013, and the East bank has shifted about 20 feet to the East. Before 2014 summer monsoon season, the base flow channel only slightly incised (about 0.5 ft). After the monsoon season, the channel section was shifted 20 ft to the East, and eroded 1.5-2.0 ft vertically. This phenomena has been observed in effluent dominant channels, such as the Las Vegas Wash. Because base flow is clear water, erosion will commence in the base flow channel. Those base flow induced incision will cause steeper banks, which consequently cause bank erosion and associated meandering migrations during storm flows. This will result in deeper and wider base flow channel. Consequently, the groundwater level in the riparian area will drop,
which can cause dehydration of shallow rooted plants, such as cottonwoods. This was observed in the lower Rio Grande River.

![Trico Road](image)

**Fig.7 Trico Cross Section**

Figure 7 showed the similar thalweg incision (1.7 ft) and lateral migration to the East (about 10 ft) after 2014 summer. The base flow remain the same during 2015 survey. This is due to the similar causes as those in the Sanders location.

The changes of cross sections indicated that the channel becomes more active in 2014 than in 2013, and the summer monsoon causes more erosions than it was before. In 2015 survey before the monsoon season, the cross sections remain the same as in 2014. This may indicate the incision within the base flow channel at the lower reach of the Santa Cruz River. However, these five cross sections are just snapshots of the entire reach. At the Ina section, channel has actively migrated to the East, and no significant incision was observed. Incision and lateral migration were observed downstream from the Twin Peak location, and the base flow channel is actively migrating to the East.
2.3. Flow Discharge

Flow discharges were measured during most cross sectional surveys except for the days when there is no flow in the channel. In 2014, two complete flow measurements were obtained: one is on June 6th (Fig.9), and the other on Dec 14th (Fig.10). On Sept 26th, 2014, we only observed flow at the Ina location in the morning (9:15am). No flow were seen at other locations. In 2015, we have completed two flow measurements on March 28th (Fig.11) and June 2nd (Fig.12). During both surveys, no flow were seen at the Sanders and Trico Road locations.

Flow were measured simultaneously at four locations downstream from the Ina Bridge at four different times. For measurements in June, flow is reducing along the reach before noon. In the afternoon, some irrigation return flows were observed downstream from the Ina section. Therefore, discharge was increased slightly. On Dec 14th, 2014, discharge is reducing along the reach. No additional flow was observed. This indicated that flow is reducing along the reach if without irrigation return flows. Irrigation flow only appears in the summer time.

Fig.9 Flow discharge on June 6th, 2014
(Note: Sweetwater was not measured, and Trico has no flow)
Fig. 10 Flow discharge on Dec 14th, 2014
(Note: Sweetwater was not measured)

Fig. 11 Flow discharge on March 28th, 2015
(Note: Sweetwater was not measured, no flow at Sanders and Trico)
**Fig. 12** Flow discharge on June 2\textsuperscript{nd}, 2015

(Note: No flow at Sanders and Trico)
Section 3: Sediment Load Rating Curve

3.1. Bed Load and Suspended Load Rating Curve

The sediment rating curve is the empirical relation between sediment transport rate and flow discharge. For the study reach, the relation curve was developed based on measured bed load and suspended load during base flow periods.

Both bed load and suspended load were measured since Feb 2013. Bed load transport rate (lbs/ft/sec) were plotted vs flow discharge (cfs) in Fig. 13a, while the dimensionless transport rate is plotted vs dimensionless bed shear stress in Fig. 13b. The dimensionless bed shear stress is the grain shear stress contributing to bed load transport. The shear velocity corresponding to grain resistance is calculated by Eq. (1) (Sturm 2011).

\[ u^{*} = V / 5.75 \log (12R / 3d_{90}) \]  

where \( u^{*} \) is the shear velocity corresponding to grain resistance, \( V \) is the averaged velocity, \( R \) is hydraulic radius, and \( d_{90} \) is the size that 90\% of sediment is finer than this size. The dimensionless grain shear stress is calculated as:

\[ \tau^{*} = u^{*2} / [(SG - 1)g d_{50}] \]  

where \( SG \) is the specific gravity, \( g \) is gravitational acceleration, \( d_{50} \) is sediment size that 50\% is finer than this size. The dimensionless bed load transport rate is calculated as:

\[ Q_{b^{*}} = Q_{b} / \sqrt{(SG - 1)gd_{50}^{2}} \]  

where \( Q_{b^{*}} \) is the dimensionless bed load transport rate, and \( Q_{b} \) is bed load transport rate in ft\(^2\)/s. Both figures showed bed load transport rate is increasing with flow discharge or bed shear stress. The correlation coefficient is higher using dimensionless transport rate (R=0.2419). In Fig. 13b, the critical shear stress is subtracted from the measured shear stress. The critical shear stress is the flow with nearly zero bed transport rate. This flow was observed on June 2\(^{nd}\) at Sweetwater site. The flow discharge is 0.43 cfs. This relation is used as the sediment rating curve in HEC-RAS sediment model.

Suspended sediment concentration (ppm) were plotted versus flow discharge (cfs) in Fig. 14a, and the dimensionless concentration versus dimensionless shear stress was shown in Fig. 14b. Neither figures showed meaningful correlation between suspended sediment concentration and
flow properties. Therefore, we believe suspended sediment concentration is supply dependent, and varies based on the upstream sediment concentration.

![Graph showing Bed load transport rate vs flow discharge and bed shear stress](image)

**Fig.13** Bed load transport rate vs flow discharge and bed shear stress
Fig. 14 Suspended sediment concentration versus flow discharge and bed shear stress.

(a) $y = 20.928x^{0.2208}$
$R^2 = 0.0102$

(b) $y = 0.005e^{-3.277x}$
$R^2 = 0.0059$
3.2. Changes of Bed Load with Time

Bed load sediment transport rate versus sampling date was plotted in Fig.15. In general, bed load transport rate is decreased at the Sweetwater and Ina sites, but increased at Twin Peak, Sanders, and Trico sites in 2014 and 2015 except for the dates without data. This means more active bed load transport downstream from Twin Peak site, and this observation is consistent with the changes of cross section.

Note: No measurement on June 6th, 2014
Note: No flow at this site on Sept 30th, 2014

Note: No flow at this site on Sept 30th, 2014
Note: No flow at this site on Sept 30th, 2014, and March 28th, and June 2nd, 2015

![Graph 1](image1.png)

**Fig.15** Bed Load transport rate changes with time

Note: No flow at this site on June 6th and Sept 30th, 2014, and March 28th, and June 2nd, 2015

![Graph 2](image2.png)
3.3. Changes of Suspended Sediment Concentration with Time

For suspended load, the change of suspended sediment concentration were plotted versus time in Fig.16. Suspended sediment was not measured at the Sweetwater site on June 6\textsuperscript{th}, 2014, and no flow at Ina, Twin Peak, Sanders, and Trico sites on Sept 30\textsuperscript{th}, 2014. Figure 16 showed reduced suspended sediment concentration comparing to data measured in 2013. This may indicate clearer flow after the operation of new treatment plant. However, suspended sediment concentration highly depends on the upstream supplies. This data series may not be sufficient to make this conclusion.
Fig. 16 Suspended sediment concentration changes with time
Section 4: Sediment Transport Analysis using HEC-RAS Model

4.1. Model Parameter

Seven different sediment transport functions are available in HEC-RAS (Brunner, 2010). They are:

- Ackers and White (1973)
- Engelund and Hansen (1972)
- Copeland’s form of Laursen (1990)
- Meyer-Peter and Muller (1948)
- Toffaleti
- Yang
- Wilcock

To evaluate the performances of different sediment transport equations, simulations were performed by using these seven different equations while keeping the boundary conditions, the allowable maximum erodible depth, fall velocity method, and sediment sorting method the same. The calibration run selected the reach from the Cortaro Road to the Trico Road along the Santa Cruz River, which is about 16.4 miles long.

There are two USGS gauges, Cortaro gauge and Trico gauge, located within the study reach. The flood event on 09/08/2014 was selected for calibration run because there are survey cross sectional changes near the Twin Peaks, Sanders, and Trico Road. This flood event lasted from 09/08/2014 to 09/10/2014 totaling 49 hours, with a peak flow of 21,200 cfs recorded at the Cortaro gauge at 14:45 PM on 09/08/2014. The observed flow at the Cortaro gauge was used as the upstream boundary condition. The downstream boundary condition is normal depth having a bed slope of 0.003.

Cross sections were measured on 06/04/2014 and 09/26/2014 in the main channel at the Twin Peak, Sanders, and Cortaro Road within the study reach. Measured cross sectional changes were used to calibrate the model.

The maximum allowable erodible depth was set as 50 ft. which is much greater than the observed maximum depth of erosion. Report 12 method was selected to calculate sediment fall velocity. As to the mobile bed layer, the method of “active layer” doesn’t account for sediment sorting in vertical direction, consequently no explicit armoring factor. On the other hand, the Exner
5 method is designed to account for the influences of static armoring, which is applicable to most sand-gravel bed channels. Therefore, Exner 5 method was selected as the sorting method for all the simulation runs.

The sediment rating curve described in the previous section was used as upstream and downstream sediment boundary conditions. The gradation character of the sediment loads must also be specified for both upstream and downstream boundary conditions. The gradation character is the grain class fractions/weight or the incremental percentage or fractions. The average of the gradation character for the sediment loads at the Cortaro and Trico locations were used as the upstream and downstream sediment grading boundary conditions respectively, as shown in Table 1.

<table>
<thead>
<tr>
<th>Grain Classes</th>
<th>Grain Class Fractions/Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upstream (Cortaro)</td>
</tr>
<tr>
<td>Fine Sand</td>
<td>0.107</td>
</tr>
<tr>
<td>Medium Sand</td>
<td>0.136</td>
</tr>
<tr>
<td>Course Sand</td>
<td>0.232</td>
</tr>
<tr>
<td>Very Course Sand</td>
<td>0.174</td>
</tr>
<tr>
<td>Very Fine Gravel</td>
<td>0.059</td>
</tr>
<tr>
<td>Fine Gravel</td>
<td>0.037</td>
</tr>
<tr>
<td>Medium Gravel</td>
<td>0.053</td>
</tr>
<tr>
<td>Coarse Gravel</td>
<td>0.074</td>
</tr>
</tbody>
</table>

4.2. Simulation Result

Table 2 compared the simulated cross sectional area changes with the measurements at Twin Peak, Sanders, and Trico sites. Ackers-White, Meyer-Peter, and Yang equations yielded the best results. Using the sediment rating curve, the results are not better than those from the three equations. This attributes to the fact that sediment rating curve is developed primarily based on low flow data. At high flow discharges, sediment transport rate does not follow the trend from low flow data. Therefore, these three sediment transport equations are considered as the best for the sediment transport analysis in this study reach.
Table 2 Total cross sectional area changes using different sediment equations

<table>
<thead>
<tr>
<th>Sediment Equations</th>
<th>Change of cross sectional area (square feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Twin Peak</td>
</tr>
<tr>
<td><strong>Measured</strong></td>
<td>26.33</td>
</tr>
<tr>
<td><strong>Sediment Rating Curve</strong></td>
<td>7.01</td>
</tr>
<tr>
<td>Ackers-White</td>
<td>26.81</td>
</tr>
<tr>
<td>Engelund-Hansen</td>
<td>7.38</td>
</tr>
<tr>
<td>Laursen</td>
<td>-180.11</td>
</tr>
<tr>
<td><strong>Meyer-Peter</strong></td>
<td>53.57</td>
</tr>
<tr>
<td>Toffaleti</td>
<td>-0.30</td>
</tr>
<tr>
<td><strong>Yang</strong></td>
<td>16.93</td>
</tr>
<tr>
<td>Wilcock</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Among four methods for calculating the fall velocity, Ruby’s and Report 12 methods are most commonly used. Ruby’s method indirectly takes the effect of temperature into account, while American Society of Civil Engineers (ASCE) recommends Report 12 method that includes the effect of temperature, and is applicable to a wide range of sediment sizes. To evaluate the performances of these two methods, the sediment transport analyses were conducted by using these two fall velocity methods, while using Acker-White, Meyer-Peter, and Yang sediment transport equations. All the runs kept the same boundary conditions, maximum erodible depth, and sediment sorting method. Table 3 summarized the simulated cross sectional changes at selected sites using different fall velocity methods. The changes of cross sectional areas remain the same (or approximately the same) for Report 12 and Ruby’s method when using Ackers-White and Meyer-Peter equations, while Report 12 gives better results for Yang equation. Report 12 was selected in sediment analysis.

Table 3 Changes of cross sectional areas (ft$^2$) using different methods for fall velocity

<table>
<thead>
<tr>
<th>Sediment Equation</th>
<th>Fall Velocity Method</th>
<th>Twin Peak</th>
<th>Sanders</th>
<th>Trico</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Measured</strong></td>
<td>Report 12</td>
<td><strong>26.33</strong></td>
<td><strong>-88.30</strong></td>
<td><strong>-36.63</strong></td>
</tr>
<tr>
<td>Ackers-White</td>
<td>Report 12</td>
<td>26.81</td>
<td>-118.86</td>
<td>-69.48</td>
</tr>
<tr>
<td></td>
<td>Ruby</td>
<td>26.81</td>
<td>-118.67</td>
<td>-69.48</td>
</tr>
<tr>
<td>Meyer-Peter</td>
<td>Report 12</td>
<td>53.57</td>
<td>-48.77</td>
<td>-54.72</td>
</tr>
<tr>
<td></td>
<td>Ruby</td>
<td>53.57</td>
<td>-48.77</td>
<td>-54.72</td>
</tr>
<tr>
<td>Yang</td>
<td>Report 12</td>
<td>16.93</td>
<td>-71.02</td>
<td>-63.56</td>
</tr>
<tr>
<td></td>
<td>Ruby</td>
<td>12.94</td>
<td>-32.61</td>
<td>-58.93</td>
</tr>
</tbody>
</table>
Section 5: Conclusion

This report summarized the results from field monitoring of the lower Santa Cruz River base flow channel since March 2013. Five monitoring cross sections were surveyed periodically. Minor cross sectional changes were observed at Sweetwater section. Moderate changes were observed at Twin Peak section, while Ina Road section is actively migrating to the East. At both Sanders and Trico Road section, considerable lateral migration and incision were observed. This indicates that the base flow channel is more active than it was in 2013.

Measurements showed that bed load transport rate is increasing with flow discharge or bed shear stress. However, the best correlation was found between dimensionless bed load transport rate and the dimensionless grain shear stress. The correlation coefficient is R=0.2419, which indicates the data are still weakly correlated. Furthermore, the suspended sediment concentration is poorly correlated with flow properties, which indicates it’s supply dependent, and varies based on the upstream sediment concentration.

Since the treatment upgrade, bed load transport rate has decreased at the Sweetwater and Ina sites, but increased at Twin Peak, Sanders, and Trico sites in 2014 and 2015 except for the dates without data. This means more active bed load transport downstream from Twin Peak site, and this observation is consistent with the changes of cross section. Additionally, suspended sediment concentration tends to decrease. Because suspended sediment concentration is upstream supply dependent, this conclusion needs further verification.

Sediment transport analysis using HEC-RAS quasi-unsteady flow model showed the sediment rating curve generated by using the low flow data did not improve the modeling results. Rather, Ackers-White, Meyer-Peter, and Yang equations yielded the best results for the study reach. Using the Report 12 fall velocity method also yielded close matches with the observed cross section changes. Therefore, Ackers-White, Meyer-Peter, and Yang equations together with Report 12 method are recommended for analyzing sediment transport in this reach.
Reference
