3. Historical Changes in Channel Geomorphology

3.1 Introduction

The Santa Cruz River has been experiencing degradation over time. Parker (1995) assessed channel changes from 1936 through 1986 along a 70-mile reach of the Santa Cruz River in Pima County, AZ, by using aerial photos, field observations, and published and unpublished geomorphic, topographic, geotechnical, and historical data. He reported that the timing and magnitude of channel change at a particular location are controlled primarily by hydrologic and climatic factors, while the location of channel change and its magnitude are controlled largely by topographic, geologic, hydraulic and artificial factors. He also found that the dominant vertical change was degradation during the study period. For example, the channel elevation was decreased by 2 feet at Cortaro Road during the period from 1956 to 1976. The comparison of the channel location changes in 1978 and 1986 showed that most meanders between Cortaro Rd. and Avra Valley Rd. were destroyed by the flood of 1983, which had a peak discharge of 65,000 cfs. Aerial photographs taken in 1984 indicated that mean width on the reach between Cortaro and Avra Valley Rd. increased from 150 to 270 feet as a result of the 1983 flood. However, by 1986, mean width of the reach had declined to 170 feet as a result of subsequent low-flow incision, in-channel deposition, and revegetation.

The Lower Santa Cruz River has experienced significant bed degradation, especially the reach between Ina Rd and Avra Valley Rd. RFCD surveyed cross sections along the Lower Santa Cruz and compared the bed elevation changes from 1987 to 1999 (RFCD, 1999). The field survey showed that the significant bed degradation within the low-flow channel, especially the reach between Ina Rd and Avra Valley Rd, is primarily caused by the perennial effluent flow discharged from the wastewater treatment plants. Sediment transport modeling was also performed to assess the underlying factors in the degradation process. The modeling was performed for the effluent flow using the computer program IALLUVIAL2, which is the enhanced PC-version of the model IALLUVIAL (Karim and Kennedy, 1982). Both field survey and modeling results indicated that sediment-free, perennial effluent flow from the WTPs at Ina and Roger Rds was the principal cause of degradation/local scour, and that the impact of major floods on streambed degradation was relatively minor.

Large flooding conditions occurred in Tucson on July 31, 2006, primarily as a result of saturated soil conditions after five days of rainfall with a recurrence interval of approximately five years (Griffiths et al. 2009; Magirl et al. 2007). The peak discharge measured on July 31, 2006 was 40,900 cfs at Cortaro Rd. and 27,200 cfs at Trico Rd. Following the flood of 2006, failures of soil cement bank were observed adjacent to effluent flow channels (RFCD, 2008). RFCD submitted disaster relief applications to the Federal Emergency Management Agency (FEMA) for funding of the repair of the bank collapse areas. All failure areas were repaired during the period of September through November of 2007. In addition to repair the bank failures, RFCD assessed the effluent flow channel bed elevation changes from 1999 to 2007 using LiDAR data with an assumption that the effluent channel is 2 feet in depth (RFCD, 2008). The study indicated that the effluent flow channel invert has continued to degrade throughout the majority of the project area from Cortaro Rd. to Avra Valley Rd.

The objective of this chapter is to assess changes in i) effluent flow channel locations, area, length and width, ii) channel bed elevation, and iii) sediment volume.

3.2 Methods

This study assesses the channel morphology changes in the Santa Cruz River from Sweetwater Dr. to Trico Rd. The study reach of the Santa Cruz River was divided into seven reaches. Reach 1 is from Trico Rd. to Sanders Rd., Reach 2 is from Sanders Rd. to Cement Plant Rd., Reach 3 is from Cement Plant Rd. to Twin Peaks Rd., Reach 4 is from Twin Peaks Rd. to Cortaro Rd., Reach 5 is Cortaro Rd. to Ina Rd., Reach 6 is Ina Rd. to Sunset Rd., and Reach 7 is from Sunset Rd. to Sweetwater Dr.

Effluent flow channel area and length were digitized using aerial photos taken in 1998, 2002, 2005, 2008, 2010, and 2011. Aerial photos were taken in April 1998, September 2002, May 2005, March to April 2008, April to June 2010 and April 2011. It should be noted that the 1998 aerial photo is black and white. It is harder to distinguish between flow and others such as vegetation on a black and white photo.

20-foot DEMs were created to evaluate elevation changes and sediment volume changes in effluent flow channels. DEM for 2008 was obtained from 2-ft contour and point data with 30-foot resolution obtained from orthophotos. LiDAR was used to create DEMs for 2005 and 2008. Elevation changes were evaluated by using the 20-ft DEMs. It should be noted that the original topographic data to create DEM for 1998 contains less detail than the one for 2005 and 2008.

In order to assess elevation change in effluent flow channels, effluent flow channel areas in two different periods were used (Fig. 3.1). For example, the elevation change between 1998 and 2002 was assessed by extracting elevation change in areas where effluent flow channel was observed in 1998 and/or 2002. In other words, digitized effluent flow channel areas for both 1998 and 2002 were used to extract elevation change between 1998 and 2002. Elevation changes were divided into 8 classes; more than -3 feet, -3 to -2 feet, -2 to -1 feet, -1 to 0 foot, 0 to 1 foot, 1 to 2 feet, 2 to 3 feet and over 3 feet. It should be noted that there are discussions about the uncertainty of terrain analysis using LiDAR. The accuracy of the LiDAR-derived DEM, which was used in this study, could be affected by possible errors in LiDAR data and data process.

Effluent flow channel width was calculated by dividing channel area by channel length.

Sediment volume was estimated by multiplying a total area of each elevation difference class by middle value of the range of each class. For example, the depth of 2.5 was used for an elevation difference class from -2 to -3 feet. For the classes with the changes more than 3 feet, the depth of 4 feet was used to estimate the changes in sediment volume. Sediment volume was converted to annual average sediment volume change per area in order to compare the changes.

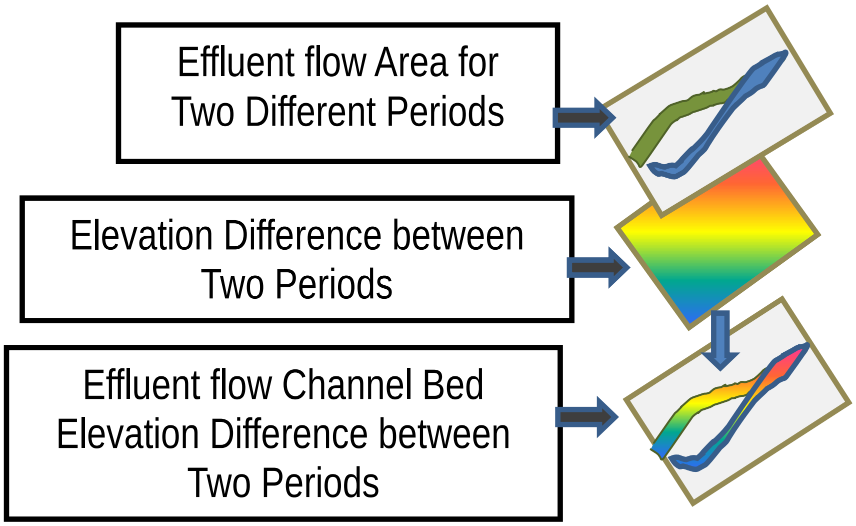

Fig. 3.1 Procedure to Evaluate Elevation Changes in Effluent Flow Channels

3.3 Effluent Flow Channel Location, Area, Length and Width

Exhibit 1.1-1.6 shows effluent flow channel location changes in the Reaches from 1998-2011. Washes with 100-yr flood peak discharge exceeding 2,000 cfs (cubic feet per second) flowing into the Santa Cruz River are shown in Exhibits 1.1-1.6. Figs. 3.2, 3.3 and 3.4 summarize changes in effluent flow channel length, area and width. Tables 3.1 to 3.3 summarize the area, length and width of flow paths observed in 1998, 2002, 2005, 2005 and 2011. Because field measurements taken in 2011 generally indicated narrower widths than those in Table 3.3, the values in the table are considered conservatively high.

Table 3.1 Area of Effluent Flow in Reaches

Reach		Wetted Area (acres)					
		1998	2002	2005	2008	2010	2011
1	Trico-Sanders	32.9	40.6	44.8	37.3	31.8	32.4
2	Sanders-Avra Valley	43.4	31.3	24.1	41.9	41.3	38.2
3	Avra Valley-Cement Plant	21.5	23.9	13.2	14.3	11.1	9.7
4	Cement Plant-Cortaro	14.4	9.2	9.1	18.3	10.8	16.2
5	Cortaro-Ina	19.0	19.6	12.1	15.1	8.3	7.9
6	Ina-Sunset	30.9	13.5	12.1	21.8	22.7	14.4
7	Sunset-Sweetwater	10.4	9.6	9.3	7.0	9.9	8.8
	Total	***172.4***	***147.7***	***124.8***	***155.6***	***135.8***	***127.6***

Table 3.2 Length of Effluent Flow in Reaches

Reach		Length (ft)					
		1998	2002	2005	2008	2010	2011
1	Trico-Sanders	25,291	28,882	31,416	28,987	28,934	28,723
2	Sanders-Avra Valley	38,069	30,176	31,786	37,805	44,299	44,299
3	Avra Valley-Cement Plant	20,117	28,565	16,018	16,315	16,158	15,840
4	Cement Plant-Cortaro	11,141	11,880	11,179	19,853	11,007	17,477
5	Cortaro-Ina	7,973	10,138	8,976	9,926	8,554	10,982
6	Ina-Sunset	21,226	16,104	16,157	16,157	19,166	18,374
7	Sunset-Sweetwater	12,144	14,942	13,622	12,085	12,224	12,197
	Total	***135,960***	***140,686***	***129,154***	***141,128***	***140,342***	***147,893***

Table 3.3 Width of Effluent Flow in Reaches

Reach		Ave Width (ft)					
		1998	2002	2005	2008	2010	2011
1	Trico-Sanders	56.6	61.2	62.2	56.0	47.9	49.2
2	Sanders-Avra Valley	49.6	45.1	33.0	48.3	40.6	37.6
3	Avra Valley-Cement Plant	46.5	36.5	35.9	38.1	29.8	26.6
4	Cement Plant-Cortaro	56.1	33.8	35.3	40.1	42.6	40.3
5	Cortaro-Ina	103.7	84.1	58.9	66.3	42.3	31.4
6	Ina-Sunset	63.5	36.5	32.7	58.8	51.5	34.1
7	Sunset-Sweetwater	37.3	28.0	29.8	25.3	35.3	31.4
	Mean (Length-weighted)	***55.2***	***45.7***	***42.1***	***48.0***	***42.1***	***37.6***

i) Reach 1: Trico Rd. to Sanders Rd.

Throughout the study period from 1998 to 2011, changes in the effluent flow locations, area, length and width are relatively small in Reach 1 (Exhibit 1.1, Figs 3.2, 3.3 and 3.4). The effluent flow channel area, length and width all increased during the period from 1998 to 2002 (Figs. 3.2, 3.3 and 3.4). This is mainly due to a downstream extension of the flow during the period. The flow path did not reach Trico Rd. in 1998, while it ran through the road in 2002. During the period from 2002 to 2005, the effluent flow channel area, length and width all increased but the increase in the width was minor. The increase in the channel area and length can be resulted from a flow split occurred at approximately 9,000 feet downstream of Sanders Rd. During the period from 2005 to 2008, the effluent flow channel area, length and width all decreased. The decrease can be partially because split flows observed in 2005 merged into a single reach during the period. During the period from 2008 to 2010, the effluent flow channel area, length and width all decreased, while the location change of the flow path was minor. This may be because the effluent flow channel width became narrower. There was little change in the effluent flow location, area, length and width between 2010 and 2011.

ii) Reach 2: Sanders Rd. to Avra Valley Rd.

The effluent flow channel area, length and width all decreased between 1998 and 2002 (Exhibit 1.2, Figs. 3.2, 3.3 and 3.4). This can be because the flow split observed at approximately 6,000 feet downstream of Cement Plant Rd. in 1998 became a single reach with less meandering bends by 2002 (Exhibit 1.2). During the period from 2002 to 2005, the flow area and width decreased, while the flow length slightly increased. The increase in the length may be related to a relatively small flow split occurred at approximately 8,500 feet upstream of Sanders Rd. between 2002 and 2005. During the period from 2005 to 2008, the flow area, length and width all substantially increased. The location of the effluent flow channel was substantially changed during the period. The effluent flow channel shifted toward the left bank immediately downstream of Cement Plant Rd. (approximately 1300 feet downstream of Avra Valley Rd.), and minor flow location changes occurred at approximately 9,000 upstream of Sanders Rd (Exhibit 1.2). The increase in the effluent flow area, length and width can be because of flow splits and meandering bends developed during the period (Exhibit 1.2). During the period from 2008 to 2010, the effluent flow channel location was substantially changed at approximately 10,000 feet upstream of Sanders Rd. and relatively minor change in the flow location occurred at approximately 10,000 feet downstream of Cement Plant Rd. The effluent flow channel length substantially increased during the period, while the width decreased. The change in the effluent flow area was minor during the period.

There were minor changes in the location, area, length and width between 2010 and 2011.

iii) Reach 3: Avra Valley Rd. to Cement Plant Rd.

Flow splits and meandering bends were developed at the upstream of Avra Valley Rd. during the period from 1998 to 2002 (Exhibit 1.3). The effluent flow channel area and length increased while its width decreased during the period (Figs 3.2, 3.3 and 3.4). The increase in flow length is relatively large, which can be resulted from the flow splits and meandering bends developed at the upstream of Avra Valley Rd. during the period (Exhibit 1.3). The decrease in the flow width indicates that the effluent flow channel became narrower during the period. During the period from 2002 to 2005, split flows observed in 2002 became a single flow path in 2005. The effluent flow channel in 2005 has less meandering bends, compared to 2002 (Exhibit 1.3). The effluent flow area, length and width decreased between 2002 and 2005. Especially the decrease in the flow length is large during the period, which can be related to the flow merged into a single flow path between 2002 and 2005. Small channel location changes occurred between 2005 and 2008, and the changes in the effluent flow area, length and width were relatively small during the period. During the period from 2008 to 2010, the effluent flow channel location changes were very minor. The effluent flow channel area and width decreased during the period while there was little change in the flow width. These results indicate that the flow path became narrower between 2008 and 2010. During the period from 2010 to 2011, the effluent flow channel location change was very minor with a small decrease in the effluent flow channel area, length and width.

iv) Reach 4: Cement Plant Rd. to Cortaro Rd.

During the period from 1998 to 2002, the flow path shifted approximately 400 feet toward the right bank at around 2,000 feet downstream of Cortaro Rd (Exhibit 1.4). The effluent flow channel area and width decreased while its length slightly increased during the period (Figs. 3.2, 3.3 and 3.4). The decrease in the flow width is relatively large, which indicates that the channel became narrower during the period. There was little change in effluent flow channel location, area, width and length between 2002 and 2005. During the period from 2005 and 2008, two flow splits occurred at immediately downstream of Cortaro Rd. and at 5,000 feet downstream of Cortaro Rd. The effluent flow area, length and width all increased during the period. The increase in the flow length is especially large. The increase in the flow length can be related to the two flow splits developed during the period. During the period from 2008 and 2010, the flow splits observed in 2008 merged into a single flow path, and the effluent flow channel length and area decreased. The decrease in the channel length should be resulted from the flow merged into a single channel. During the period from 2010 to 2011, flow split occurred at the upstream of Twin Peaks Rd., and flow area and length increased as a result of the flow split.

v) Reach 5: Cortaro Rd. to Ina Rd.

During the period from 1998 to 2002, the flow path substantially shifted toward the left bank (1,600 feet at maximum, Exhibit 1.4). Effluent flow channel width largely decreased during the period (Fig. 3.4), which indicates that the flow path became narrower during the period. Flow area and length increased during the period. During the period from 2002 to 2005, the effluent flow channel location change was relatively small but it appears that the flow path in 2005 has less meandering bends than the flow path in 2002. The effluent flow channel area, length and width all decreased. The decrease in the channel width during the period is large. Those results indicate that the effluent flow channel became narrower with less meandering bends between 2002 and 2005. During the period from 2005 to 2008, the split flow was developed and the flow path shifted toward the left bank. The flow area, length and width all slightly increased during the period. During the period from 2008 to 2010, the split flows became a single reach at immediately upstream of Cortaro Rd. The flow area, length and width all decreased during the period. This change can be partially because the flow splits observed in 2008 merged into a single flow path by 2010. During the period from 2010 to 2011, split flows were developed at immediately downstream of Ina Rd., and the flow length increased. The flow area and width decreased during the period, suggesting that the flow path became narrower.

vi) Reach 6: Ina Rd. to Sunset Rd.

During the period from 1998 to 2002, flow splits observed in 1998 became one single flow path with less meandering bends by 2002 (Exhibit 1.5). The effluent flow area, length and width all substantially decreased during the period. During the period from 2002 to 2005, the flow location, area, length and width had very minor change. During the period from 2005 to 2008, the flow path shifted toward the left at approximately 9,600 feet downstream of Sunset Rd. and toward the right bank at approximately 4,000 feet upstream of Sunset Rd. The effluent flow area and width increased during the period, while there was little change in the channel length. Those results indicate that the effluent flow became narrower during the period. During the period from 2008 to 2010, relatively minor flow split occurred at approximately 3,000 feet upstream of Ina Rd. The effluent flow area and length increased while its width decreased during the period. During the period from 2010 to 2011, minor flow split occurred at immediately upstream of Ina Rd. and at approximately 1,600 feet downstream of Sunset Rd., while the split flow observed in 2010 became a single flow path at approximately 4,400 feet upstream of Ina Rd. The effluent flow area, length and width all decreased during the period.

vii) Reach 7: Sunset Rd. to Sweetwater Dr.

Throughout the study period from 1998 to 2011, the effluent flow location changes were minor (Exhibit 1.6). The changes in effluent flow channel area, length and width are also relatively small (Figs. 3.2, 3.3 and 3.4).

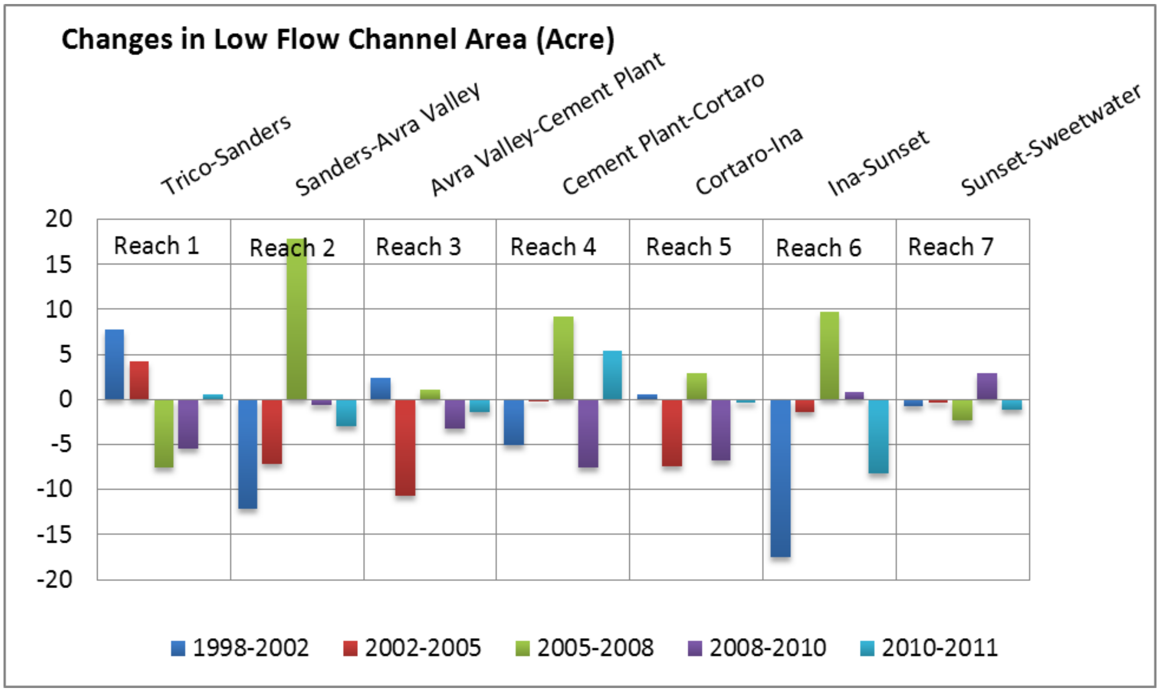

Fig. 3.2 Changes in Effluent Flow Channel Area

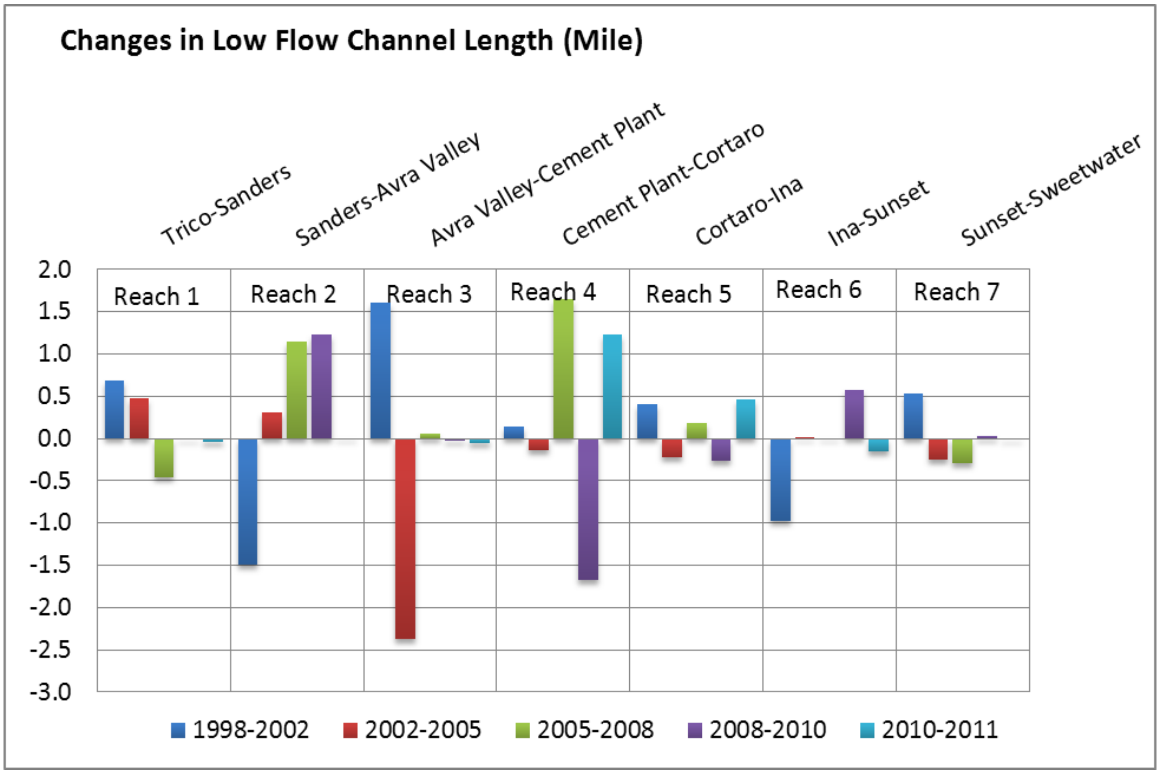

Fig. 3.3 Changes in Effluent Flow Channel Length

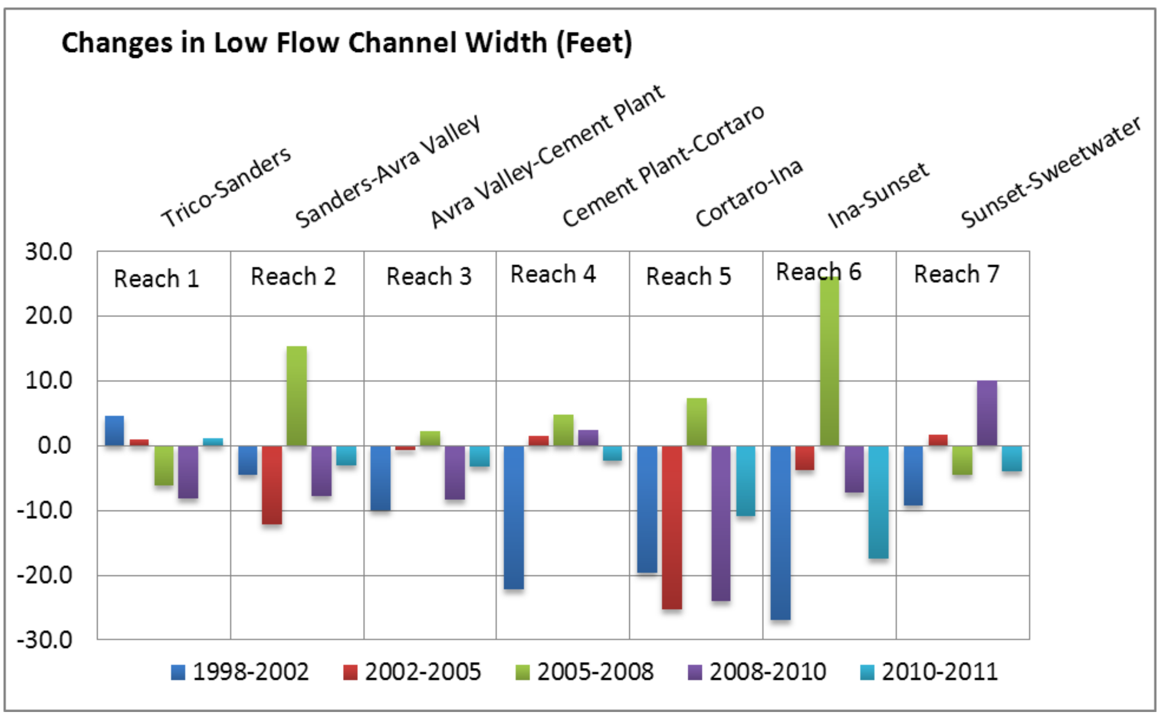

Fig. 3.4 Changes in Effluent Flow Channel Width

3.4 Channel Bed Elevation

3.4.1 Effluent Flow Channel

Exhibits 2.1-2.4 show elevation changes within effluent flow channels in the Reaches 1-7 during the period from 1998 to 2005 and from 2005 to 2008. Figs. 3.5.1 and 3.5.2 show the percentage of area of erosion or deposition separated by erosion or deposition depth. Fig. 3.5.1 show the percentage of area of erosion or deposition between 1998 and 2005, and Fig. 3.5.2 shows the one for the period from 2005 to 2008. Tables 3.4.1 and 3.4.2 summarize the percentage of total area of erosion and deposition in each reach.

i) Reach 1: Trico Rd. to Sanders Rd.

The changes in the effluent flow channel bed elevation were relatively small for the both periods from 1998 to 2005 and from 2005 to 2008 (Exhibit 2.1). Bed elevation changes with depth less than 1 foot (-1 to 0, 0 to 1 foot) occurred at approximately 50% of the effluent flow channel for the both periods (Tables 3.4.1 and 3.4.2). This indicates that relatively shallow erosion or deposition is dominant in the reach for the both periods.

ii) Reach 2: Sanders to Avra Valley Rd.

Severe erosion and deposition with depth exceeding 3 feet occurred between Sanders Rd. and approximately 6,100 feet upstream of the road during the period from 1998 to 2005 (Exhibit 3.3). This is one of the areas where the flow path location substantially changed between 1998 and 2005 (Exhibit 3.3). The severe erosion occurred in the area where new flow path was developed between 1998 and 2005, while the severe deposition occurred in the area where the flow path observed in 1998 was replaced by a new flow path by 2005. During the period from 2005 to 2008, severe erosion exceeding 3 feet occurred at 39% of the effluent flow area (Table 3.1.2). The severe erosion occurred mainly in the area where new flow paths were developed between 2005 and 2008. More erosion occurred in the reach between 2005 and 2008 (Table 3.4.2). Approximately 77% of the effluent flow channel area experienced erosion during the period (Table 3.4.2).

iii) Reach 3: Avra Valley Rd. to Cement Plant Rd.

Severe erosion and deposition with depth exceeding 3 feet occurred between Cement Plant Rd. and approximately 5,200 feet upstream of the road during the period from 1998 to 2005 (Exhibit 2.3). Severe erosion occurred in the area where a new flow path was developed between 1998 and 2005, while severe deposition occurred in the area where the flow path observed in 1998 was replaced by a new flow path by 2005. During the period from 2005 to 2008, severe deposition with depth exceeding 3 feet occurred between Cement Plant Rd. and approximately 7,000 feet upstream of the road (Exhibit 2.3). The severe deposition occurred in the area where the flow path observed in 2005 was replaced by a new flow path by 2008. Approximately 61% of the effluent flow channel area experienced erosion during the period (Table 3.4.2).

iv) Reach 4: Cement Plant Rd. to Cortaro Rd.

Severe erosion with depth exceeding 3 feet occurred immediately upstream of Twin Peaks Rd. between 1998 and 2005 (Exhibit 2.3). More erosion occurred between 2005 and 2008, compared to the period from 1998 to 2005 (Tables 3.4.1 and 3.4.2). Approximately 56% of the effluent flow channel experienced erosion during the period from 1998 to 2005 (Table 3.1.1), while approximately 77% of the effluent flow channel area experienced erosion during the period from 2005 to 2008 (Table 3.4.2). During the period from 2005 to 2008, severe erosion occurred at approximately 28% of the effluent flow channel area where a new flow path was developed during the period.

v) Reach 5: Cortaro Rd. to Ina Rd.

Majority of change between 1998 and 2005 was severe erosion with depth exceeding 3 feet (Table 3.4.1). Approximately 48% of the effluent flow channel experienced the severe erosion during the period. The severe erosion occurred in a effluent flow channel where a flow path substantially shifted toward the left bank (Exhibits 1.4 and 2.3). During the period from 2005 and 2008, severe erosion occurred at the left flow path of the effluent flow channel, while major deposition occurred at the right flow path (Exhibit 2.3). The deposition occurred at the location where the flow path observed in 2005 was replaced by a new flow path by 2008.

vi) Reach 6: Ina Rd. to Sunset Rd.

Deposition occurred at more than 60% of the effluent flow channel area between 1998 and 2005 (Table 3.4.1). Major deposition occurred at locations where the flow path observed in 1998 was replaced by a new flow path by 2005 (Exhibits 1.5 and 2.4). During the period from 2005 to 2008, severe erosion with depth exceeding 3 feet occurred at locations where effluent flow channel observed in 2005 was replaced by newly developed flow paths by 2008 (Exhibit 2.4). The severe erosion occurred at more than 33% of the effluent flow channel during the period (Table 3.4.2).

vii) Reach 7: Sunset Rd. to Sweetwater Dr.

Severe erosion with depth exceeding 3 feet occurred at more than 50% of the effluent flow channel area between 1998 and 2005 (Table 3.4.1). Deep deposition with depth exceeding 3 feet occurred at more than 30% of the effluent flow channel area during the period (Table 3.4.1). Deep deposition occurred between Camino del Cerro and Curtis Rd during the period, while deep erosion occurred most of the rest of the effluent flow channel area (Exhibit 2.4). During the period from 2005 to 2008, severe erosion occurred between Camino del Cerro and Curtis Rd where deep deposition occurred between 1998 and 2005. The severe erosion occurred at approximately 39% of the effluent flow channel during the period (Table 3.4.2). Approximately 70% of the effluent flow channel area experienced erosion during the period (Table 3.4.2).

Table 3.4.1 Percentage of Total Area of Erosion and Deposition between 1998 and 2005

Elevation Change (feet)	Percentage of Total Area						
	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5	Reach 6	Reach 7
	Trico-Sanders	Sanders-Avra Valley	Avra Valley-Cement Plant	Cement Plant-Cortaro	Cortaro-Ina	Ina-Sunset	Sunset-Sweetwater
< -3	4.6	25.7	17.1	16.5	48.0	13.1	53.6
-3 - -2	4.9	7.6	6.4	8.3	4.7	6.9	4.2
-2 - -1	15.7	11.0	8.6	13.8	4.3	8.4	4.2
-1 - 0	29.9	13.5	11.2	17.7	4.6	10.7	2.7
0 - 1	21.2	12.6	14.6	17.0	9.9	12.7	2.6
1 - 2	13.4	12.4	15.7	13.0	12.7	13.0	1.4
2 - 3	6.6	8.3	15.5	9.7	10.3	16.2	1.2
> 3	3.8	9.0	10.9	4.0	5.5	19.0	30.3
Erosion	55.1	57.8	43.3	56.3	61.6	39.1	64.6
Deposition	44.9	42.2	56.7	43.7	38.4	60.9	35.4

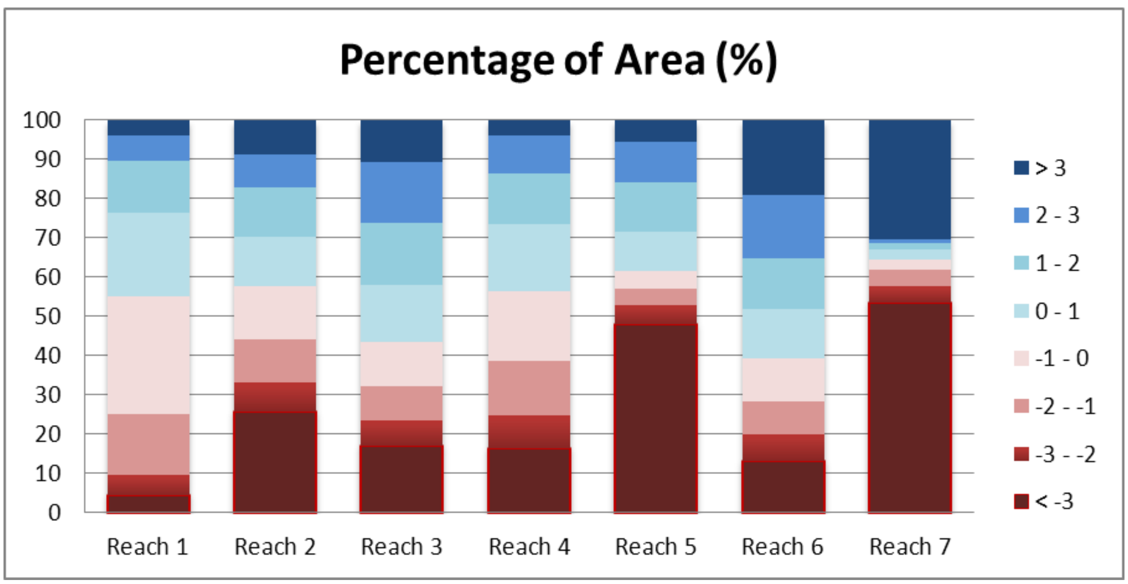

Fig. 3.5.1 Percentage of Total Area of Erosion and Deposition between 1998 and 2005

Table 3.4.2 Percentage of Total Area of Erosion and Deposition between 2005 and 2008

Elevation Change (feet)	Percentage of Total Area						
	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5	Reach 6	Reach 7
	Trico-Sanders	Sanders-Avra Valley	Avra Valley-Cement Plant	Cement Plant-Cortaro	Cortaro-Ina	Ina-Sunset	Sunset-Sweetwater
< -3	7.2	39.1	20.7	28.3	21.7	33.6	38.9
-3 - -2	8.2	13.5	10.3	19.7	3.3	10.7	4.9
-2 - -1	13.4	12.3	14.0	16.2	6.2	10.8	12.9
-1 - 0	24.7	11.6	15.7	12.7	7.6	13.3	13.6
0 - 1	20.8	7.7	11.3	8.6	7.7	11.5	9.9
1 - 2	10.8	6.4	9.3	4.7	9.9	7.1	9.7
2 - 3	6.1	4.8	7.1	3.4	17.3	4.8	3.9
> 3	8.9	4.6	11.5	6.2	26.3	8.3	6.2
Erosion	53.4	76.6	60.8	77.0	38.8	68.3	70.3
Deposition	46.6	23.4	39.2	23.0	61.2	31.7	29.7

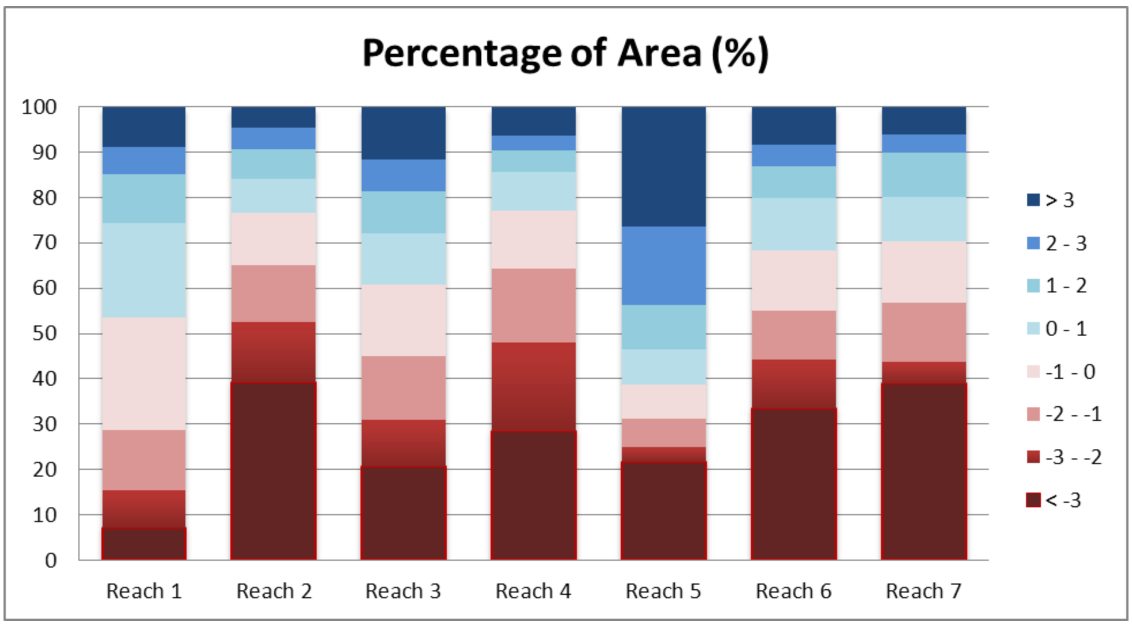

Fig. 3.5.2 Percentage of Total Area of Erosion and Deposition between 2005 and 2008

3.4.2 Floodplain

Exhibits A1 and A2 show elevation changes occurred within a floodplain including overbank of effluent flow channels between 1998 and 2005 or between 2005 and 2008. The floodplain was determined based on a FEMA floodplain, Zone AE. Artificial impacts such as gravel pits along the Santa Cruz River were removed from the floodplain. As shown in Exhibits A1 and A2, the floodplain near Trico Rd. is narrower than the FEMA Zone AE. The floodplain near Trico Rd. was determined using the aerial photo taken in 2011, instead of using the FEMA Zone AE boundary.

Figs. 3.6.1 and 3.6.2 show percentages of total area of erosion and deposition separated by depth in a floodplain of each reach.

During the period between 1998 and 2005, deep erosion with depth exceeding 3 feet occurred in the Reach 5, while deep deposition occurred in the Reach 7 (Exhibit A1 and Fig. 3.6.1). An opposite change occurred in those reaches during the period from 2005 and 2008. Deep deposition occurred in the Reach 5, while deep erosion occurred in the Reach 7 (Exhibit A2 and Fig. 3.6.2). A comparison of Figs. 3.6.1 and 3.6.2 indicates that more deposition occurred in a floodplain of the study reaches during the period between 2005 and 2008.

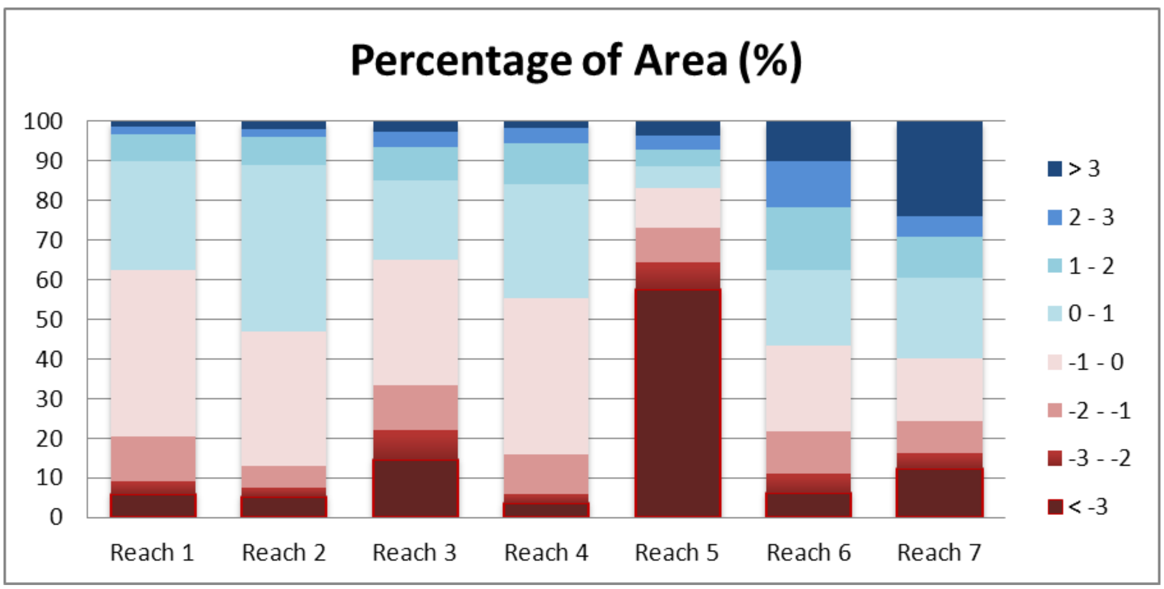

Fig. 3.6.1 Percentage of Total Area of Erosion and Deposition in a Floodplain between 1998 and 2005

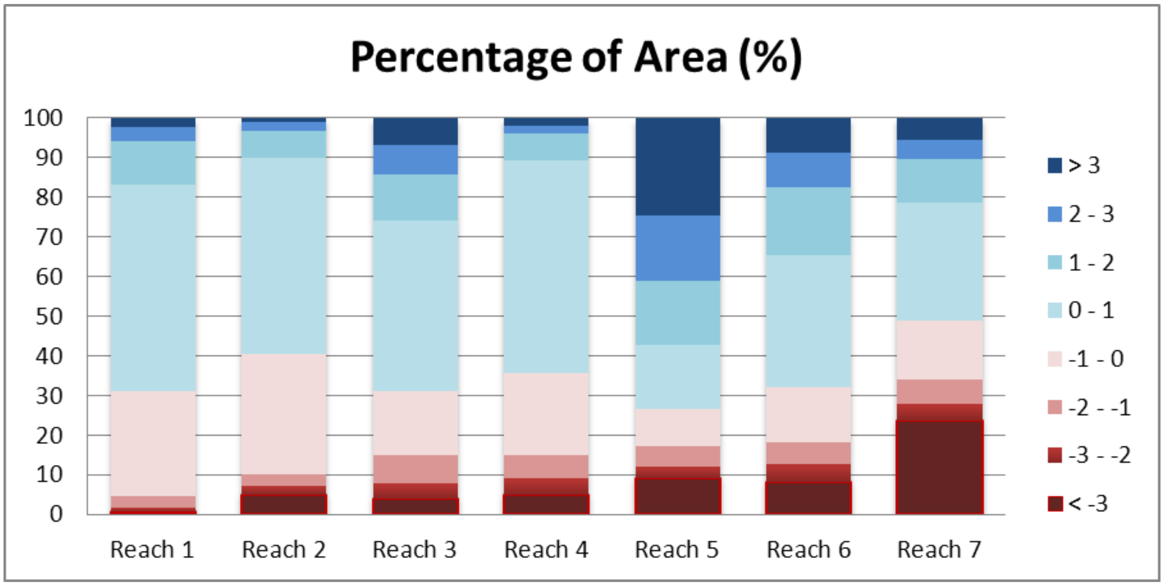

Fig. 3.6.2 Percentage of Total Area of Erosion and Deposition in a Floodplain between 2005 and 2008

3.5 Sediment Volume

3.5.1 Effluent Flow Channel

Fig. 3.7 shows the annual average of sediment volume changes per area in effluent channels between 1998-2005 and 2005-2008. Negative sediment volume change means that erosion is a dominant process in an effluent flow channel during a period. Positive sediment volume change means that deposition is dominant.

Annual average of sediment volume change per area in the Reach 1 was substantially smaller than the other reaches in both periods (Fig. 3.7). As mentioned previously, approximately 50% of the effluent flow channel area in the Reach 1 experienced less than 1 foot erosion or deposition in the both periods (Tables 3.1.1 and 3.1.2). This indicates that the effluent flow channel in the Reach 1 is relatively stable without major location or elevation changes for the periods from 1998 to 2008.

Relatively large sediment volume changes occurred in the effluent flow channel of the Reach 2, and erosion is dominant in the effluent flow channels of the reach for the both periods. Sediment volume change per area in the Reach 3 is relatively small for the both periods. Annual average of sediment volume changes per area between 1998 and 2005 are relatively small in the Reaches 4 and 6. The changes per area are relatively large in the both Reaches 4 and 6 between 2005 and 2008, and erosion is dominant in the both reaches during the period. The annual average of eroded sediment volume per area in the Reach 5 between 1998 and 2005 is close to the annual average of deposited sediment volume per area in the reach between 2005 and 2008. This indicates that overall sediment volume change for the entire study period from 1998 to 2008 is small in an effluent flow channel of the Reach 5. Annual average of sediment volume change per area in the Reach 7 is relatively large between 2005 and 2008. As mentioned previously, more than 40% of the effluent flow channel of the Reach 7 experienced severe erosion with depth exceeding 3 feet (Tables 3.2.1 and 3.2.2), while the location, area, and width changes were minor in the Reach 7 for the entire study period (Exhibits 1.6). This indicates that channel bed degradation occurred in the effluent flow of the Reach 7, particularly between 2005 and 2008.

Overall sediment volume changes shown in Fig. 3.7 indicate that erosion is a dominant process in most of the effluent flow channels in the study reaches for the period from 1998 to 2008. Annual average of eroded sediment volume per area is substantially larger during the period between 2005 and 2008, compared to the period between 1998 and 2005. Annual average erosion depth is also larger during the period between 2005 and 2008. These trends are particularly clear in the Reaches 2, 4, 6 and 7.

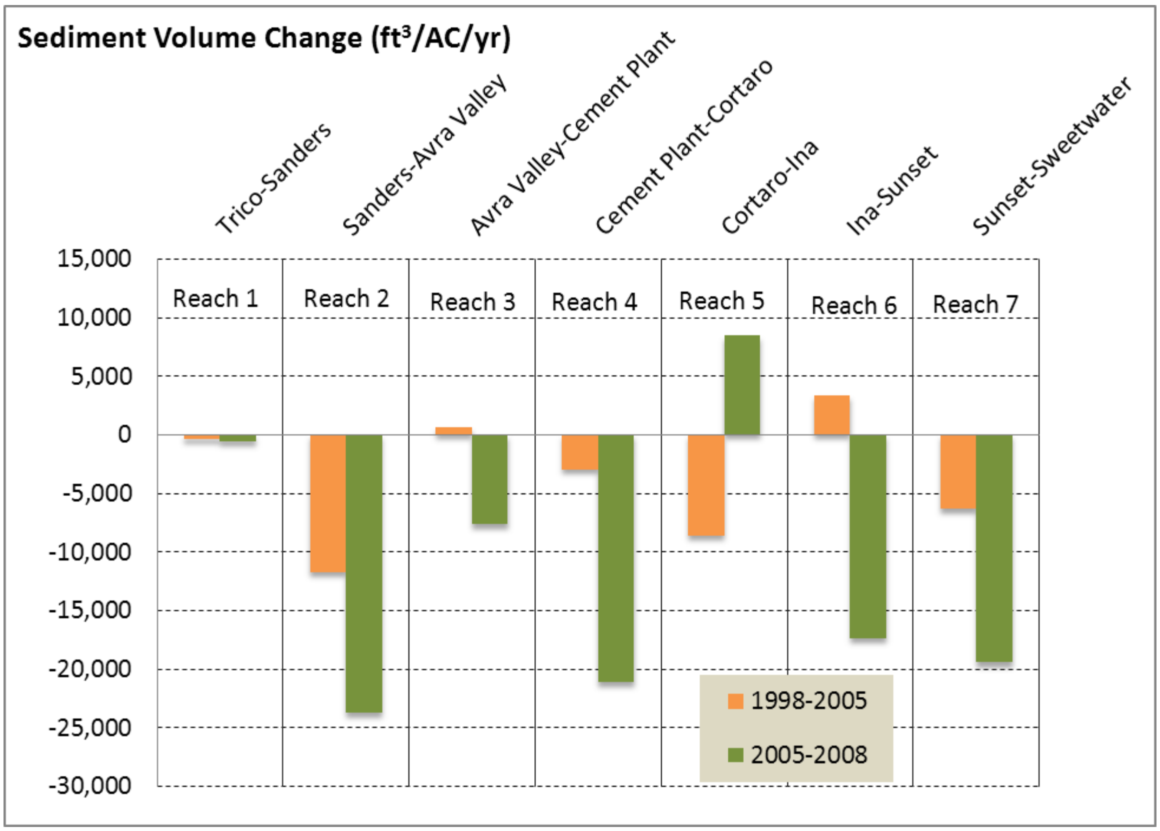

Fig. 3.7 Sediment Volume Changes in Effluent Flow Channel between 1998-2005 and 2005-2008

3.5.2 Floodplain

Fig. 3.8 shows the annual average of sediment volume changes per area in a floodplain between 1998-2005 and 2005-2008. The result indicates that, on average, erosion is dominant in a floodplain of the study reaches between 1998 and 2005, while deposition is dominant between 2005 and 2008. As previously mentioned, more erosion or degradation occurred in effluent flow channels between 2005 and 2008. These results suggest that eroded sediment in effluent flow channels could be transported to overbank during the period.

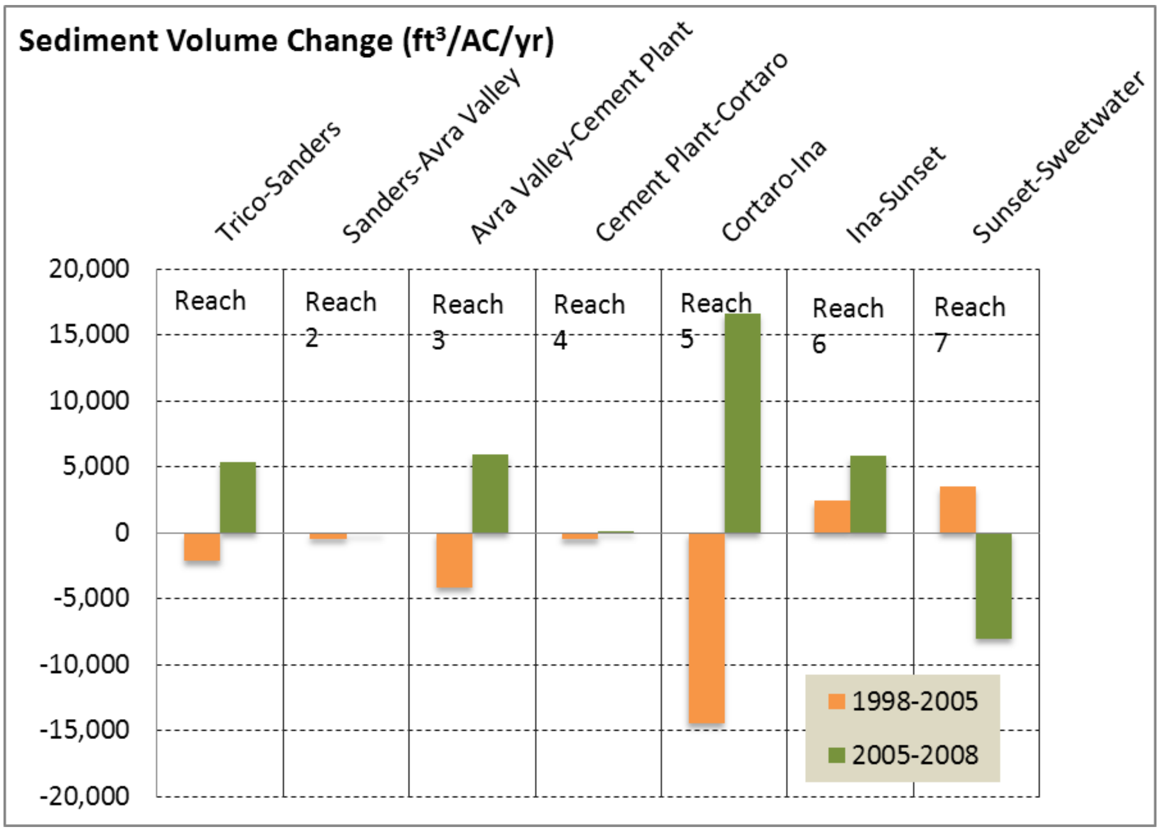

Fig. 3.8 Sediment Volume Changes in Floodplain between 1998-2005 and 2005-2008

3.6 Historical Floods and Scouring Daily Discharge

Tables 3.5.1 and 3.5.2 summarize the largest peak discharge of the year recorded at USGS gages at Cortaro Rd. and Trico Rd. The flood occurred on July 31, 2006 was the largest at both Cortato and Trico gages during the study period (Tables 3.5.1 and 3.5.2). The flood of record on most streams in northeastern Pima County on July 31, 2006 was caused by a rare meso-scale convective storm, that had a duration of about 6-hours (Griffiths et al. 2009). Rainfall depth with a recurrence interval of about five years caused the floods on July 31, 2006 that exceeded the 100-year estimates, largely as a result of saturated soil conditions after five days of rainfall (Griffiths et al., 2009; Magirl et al., 2007).

Lacher (1996) reported that infiltration rate in the Santa Cruz River sharply decreased after the storms with mean daily discharge exceeding 2,200 cfs. She concluded that a flow of approximately 3,000 cfs average daily discharge at Cortaro Rd. was a conservative estimate for the threshold magnitude of storm flow required to achieve significant increase in infiltration of the effluent stream channel. The significant increase in infiltration rate was most likely resulted from scour in channels. Therefore, we assumed that average daily discharge exceeding 2,200 or 3,000 cfs (for a conservative estimate) could trigger scour in effluent flow channels of the Santa Cruz River.

Tables 3.6.1 and 3.6.2 summarize mean daily discharge exceeding 2,000 cfs during the study period from 1998 to 2011. Flow with mean daily discharge exceeding 3,000 cfs occurred three times at both Cortaro and Trico Rds. between 1998 and 2005. During the period from 2005 to 2008, flow with mean daily discharge exceeding 3,000 cfs occurred three times at Cortaro Rd. and four times at Trico Rd. Since the duration between 2005 and 2008 is shorter than the period from 1998 to 2005, the frequency of the flow resulting in scour in an effluent flow channel is higher during the period between 2005 and 2008.

As mentioned before, LiDAR data was collected in April 1998, May 2005 and March to April 2008. This means that the 2005 LiDAR data was collected before the largest flood event in 2005. As shown in Figs. 3.7 and 3.8, annual average of eroded sediment volume per area is higher between May 2005 and April 2008 in the most reaches, compared to the period from 1998 to 2005. This may be caused by i) higher flood peak during the period from May 2005 to April 2008 (Tables 3.5.1 and 3.5.2), and ii) more frequent flows causing scour during the period (Tables 3.6.1 and 3.6.2).

Table 3.5.1 Largest Flood Peak at Cortaro Rd.

Year	Date	Peak Discharge (cfs)
1998	Feb-18	4,600
1999	Jul-15	13,700
2000	Jul-23	1,560
2001	Nov-07	10,000
2002	Aug-05	8,340
2003	Aug-26	9,000
2004	Aug-14	5,420
2005	Aug-23	16,300
2006	Jul-31	40,900
2007	Jul-31	11,400
2008	Jan-28	4,270
2009	Jul-04	2,130
2010	Jul-31	16,800
2011	Sep-10	12,000

Table 3.5.2 Largest Flood Peak at Trico Rd.

Year	Date	Peak Discharge (cfs)
1998	Feb-18	6,510
1999	Jul-15	10,600
2000	Jun-30	644
2001	Oct-23	8,270
2002	Aug-06	3,440
2003	Aug-27	5,490
2004	Aug-14	1,780
2005	Aug-23	15,000
2006	Jul-31	27,200
2007	Jul-28	10,900
2008	Jan-28	5,080
2009	Jul-04	2,360
2010	Jul-31	9,450
2011	Sep-11	6,630

Table 3.6.1 Mean Daily Discharge Exceeding 2,000 cfs at Cortaro Rd.

Year	Date	Mean Daily Discharge (cfs)
1999	Jul-15	3,700
2000	Oct-23	6,900
2000	Oct-24	2,720
2000	Nov-07	3,140
2005	Feb-12	2,000
2005	Aug-23	4,230
2006	Jul-29	5,450
2006	Jul-30	2,340
2006	Jul-31	11,700
2007	Jul-28	2,440
2010	Jul-31	3,350

Table 3.6.2 Mean Daily Discharge Exceeding 2,000 cfs at Trico Rd.

Year	Date	Mean Daily Discharge (cfs)
1998	Feb-18	3,970
1999	Jul-15	2,750
2000	Oct-23	4,350
2000	Oct-24	3,020
2005	Aug-23	3,670
2005	Aug-24	2,120
2006	Jul-29	6,510
2006	Jul-30	3,070
2006	Jul-31	10,500
2008	Jan-28	2,020
2010	Jul-31	2,720

3.7 Summary and Conclusion

Table 3.7 summarizes the results of the historical changes in channel geomorphology, focusing on the effluent flow channels location, area, length and width and channel elevation and sediment volume. There were no substantial location changes occurred in the Reaches 1 and 7 during the study period. Relatively small sediment volume change occurred in the Reach 1, resulting from bed elevation changes with scour or deposition depth less than 1 foot in a effluent flow channel. Meanwhile, large volume of sediment was eroded in the Reach 7, resulting from severe scour with depth exceeding 3 feet in a effluent flow channel. These results indicate that channel degradation occurred especially in effluent flow channels of the Reach 7 during the study period, and that effluent flow channels of the Reach 1 are relatively stable with no major channel incision or location change. Table 3.7 also shows that the changes in location, area and volume of effluent flow channels were relatively large in the Reaches 2 and 6, suggesting that effluent channels in those reaches were relatively unstable during the study period. There are three washes with 100-yr flood peak discharge exceeding 2,000 cfs flowing into the Reach 6 (Rillito River, Canada del Oro Wash and East Idel Hour Wash). Rillito River and Canada del Oro Wash are major washes with 100-yr peak discharge exceeding 10,000 cfs at the confluence with the Santa Cruz River. The instability of the Reach 6 can be resulted from inflow from those two major washes.

Previous studies (Parker, 1995; RFCD, 1999; 2008) reported that effluent channels continued to degrade over time. This study also showed that the overall trend has been toward degradation in both effluent channels and a floodplain over the period from 1998 to 2008. More degradation occurred between 2005 and 2008, compared to the period between 1998 and 2005.

Table 3.7 Summary of Results (*Red means "major" change, Blue means "minor" change, and No-Color means "moderate" change.)*

	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5	Reach 6	Reach 7
	Trico-Sanders	Sanders-Avra Valley	Avra Valley-Cement Plant	Cement Plant-Cortaro	Cortaro-Ina	Ina-Sunset	Sunset-Sweetwater
Location Change							
Area Change							
Volume Change	Erosion	Erosion	Erosion/Deposition	Erosion	Erosion/ Deposition	Erosion/ Deposition	Erosion

3.8 Reference

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