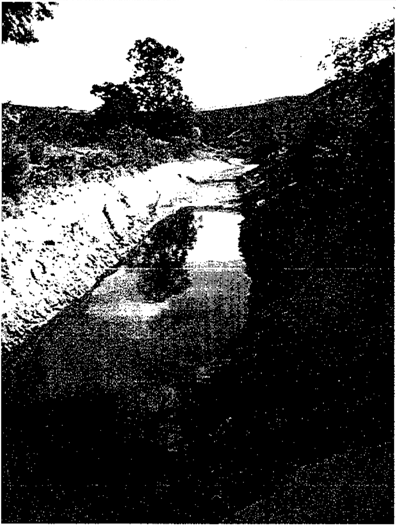

SEDIMENT YIELD ESTIMATE OF THE TIJUANA RIVER

FINAL REPORT

TASK ORDER #38

DOC ID# CSD-RT-12-URS38-02.F

MARCH 6, 2012

CITY OF SAN DIEGO

PREPARED BY URS CORPORATION

3.5.4.1

Doc Scanned On 10/21/13
K. Ruiz Time: 4:06

This page intentionally left blank

Table of Contents

List of Tables, Figures, and Appendices

Tables

Figures

Appendices

List of Acronyms and Abbreviations

A_B	Areas draining to Barrett Dam
A_R	Areas draining to Rodriguez Dam
ac-ft	acre-feet
BMP	Best Management Practice
cfs	cubic feet per second
cm/yr	centimeters per year
IBWC	International Boundary Waters Commission
in	inches
m^3	cubic meters
m^3/s	cubic meters per second
mi^2	square miles
SPA	Sediment Producing Areas
TMDL	total maximum daily load
tons/mi^2/yr	tons per square mile per year
tons/yr	tons per year
U.S.	United States
USGS	U.S. Geological Survey
Valley	Tijuana River Valley

This page intentionally left blank

SECTION 1 BACKGROUND

The Tijuana River watershed is located within the County of San Diego, California in the United States (U.S.) and the state of Baja California in Mexico. It has an area of 1,724 square miles, of which 73% is located in Mexico and 27% is located in the U.S. (see Figure 1-1). The river discharges in the U.S., just north of the border with Mexico, and the estuary portion within the discharge area is an environmentally sensitive and ecologically important area. The Tijuana River Estuary is one of the few salt marshes remaining in southern California, a region where over 90% of wetland habitat has been lost to development. The estuary is an essential breeding, feeding and nesting ground and an important habitat for over 370 species of migratory and native birds, including six endangered species.

It has been determined by the California Regional Water Quality Control Board, San Diego Region (SDRWQCB) that sediment and trash are the major pollutants of concern in the estuary. Consequently, the understanding of the sediment yield at the entrance of the Tijuana River into U.S. territory is of paramount importance in implementing measurements to control the excessive sediment deposition and to restore the natural functioning of the estuary to the maximum extent practicable.

To understand the sediment problem, available data is needed to conduct the analysis. The Tijuana River has a record of 73 years (10/1/1936 – 12/31/2009) of daily peak flow at the upstream end of the Tijuana River Valley (Valley), that is, just downstream of the U.S.-Mexico border. However, no measurements of sediment load are available.

In this technical report, two methodologies used to estimate the sediment yield of the Tijuana River at the entrance to the Valley are described. This study assumed the following: (1) the portions of the watershed currently controlled by dams remain the same, and (2) the portions currently not controlled are assumed to be in a natural or restored condition (equivalent to those analyzed by Dendy and Bolton, see Section 2.1). The objective is to establish a baseline for the determination of future Total Maximum Daily Load (TMDL). However, it is important to note that the return to fully natural conditions is highly unlikely for the following reasons:

(a) Upstream dams will remain since they are necessary for domestic water supply and flood control.

(b) Channelization of the river will remain in the City of Tijuana as it is necessary for flood protection and public safety.

(c) Land uses in the Valley cannot be returned to early 1800s conditions since part of the original estuary is occupied by the City of Imperial Beach and the Imperial Beach Naval Air Station.

(d) Other portions of the watershed are occupied by urban development in the City of Tijuana.

A new restored equilibrium state is envisioned. In order to evaluate the future water-sediment equilibrium required for this restoration, it is necessary to estimate the sediment yield at the entrance to the Valley. One methodology used to estimate the average annual sediment yield is based on the Dendy and Bolton equation. In addition, the Brune sediment trap efficiency graph [1, 18] is used to estimate sediment retention at the two dams with larger contributing area in the watershed: Rodriguez Dam in Mexico and Barrett Dam in the U.S. Given the daily peak flow for the period of record (73 years), a corresponding sediment daily load time series was obtained using a power law equation in which the coefficient is calibrated using the Dendy and Bolton equation.

The fraction of the sediment load deposited in the estuary and adjacent depositional areas was preliminarily estimated using geological depositional rates, experience-based estimates for channel deposition and pre-dam estimates of sediment load.

Once the sediment loads are obtained, they can serve as a basis for TMDL determination. Also, the impracticability of using a sediment basin Best Management Practice (BMP) at the entrance of the Valley to reduce the sediment load of the main river will be explained. Consequently, improving the sediment transport capacity of the river and/or establishing efficient sediment control programs upstream (mainly in Mexico, but potentially in contributing areas located in U.S. territory) may be the only feasible options for sediment control.

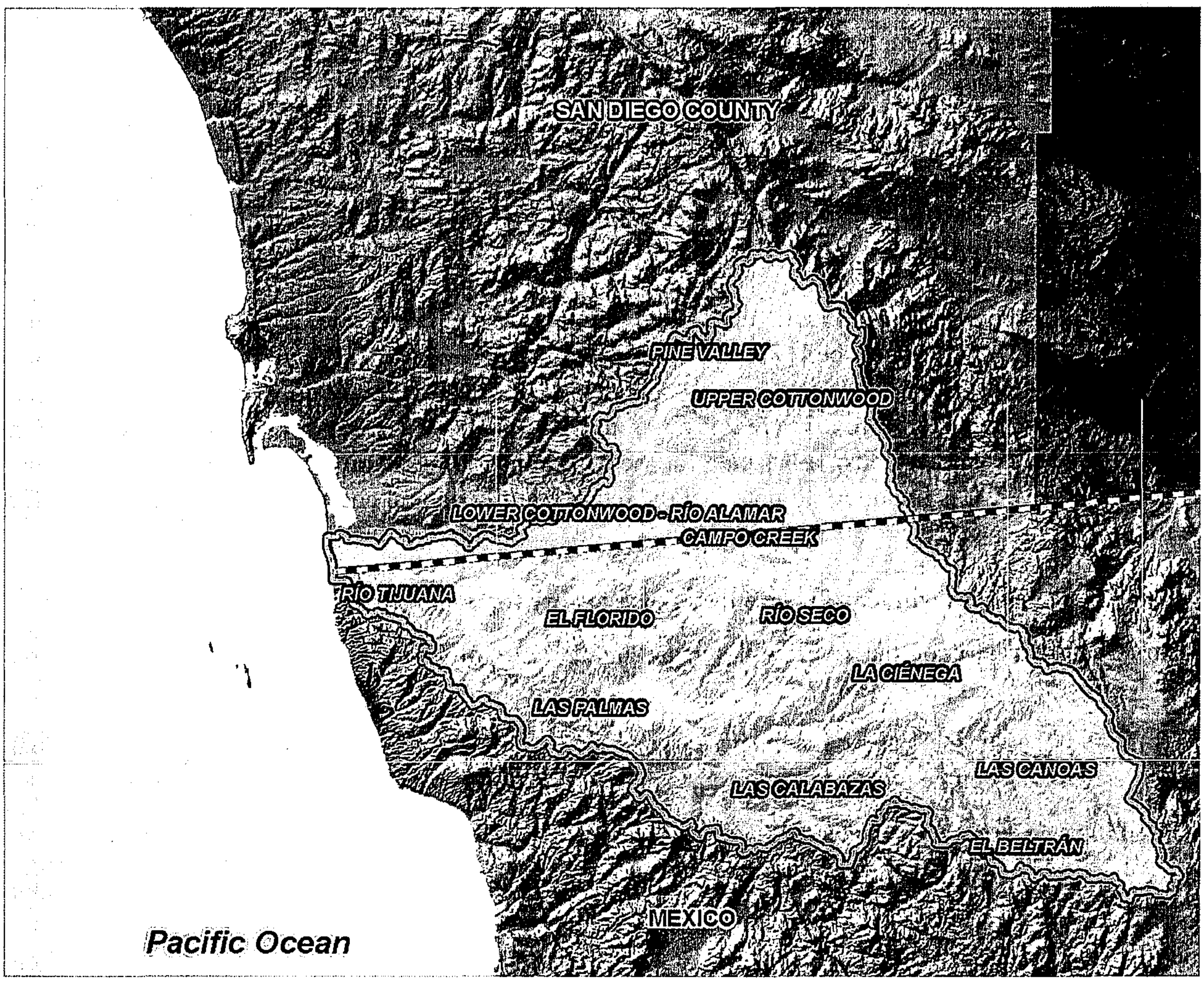

Figure 1-1. Tijuana River Watershed

SECTION 2 DENDY AND BOLTON METHOD AND RESERVOIR TRAPPING EFFICIENCY

Dendy and Bolton studied sedimentation data from 1,500 reservoirs, 505 of which had mean annual runoff data [1]. They established an equation specifically applicable for areas where low runoff depth is expected. Annual sediment yield was shown to increase sharply as the mean annual runoff Q increased from 0 to 2 inches (in). Thereafter, for a mean annual runoff from 2 to 50 in, the annual sediment yield decreased exponentially. Increase of sediment yield with increase of runoff (from 0 to 2 in) is related to the transport capacity of the water to move sediments as the volume of runoff increases in arid areas. Decrease of sediment yield with increase of runoff (from 2 to 50 in) is related to the fact that an increasing amount of vegetation will reduce the sediment detachment in the soil (for large amounts of precipitation, a dense vegetation cover establishes naturally). Therefore, the optimum amount of runoff necessary to maximize sediment yield is about 2 in of runoff per year in natural conditions, below which there is not enough water and above which vegetation overcomes increases in runoff.

The Dendy and Bolton Sediment yield equation for less than 2 in of average annual runoff, which correspond to the Tijuana River watershed is:

$$\frac{S}{S_R} = 1.07\left(\frac{Q}{Q_R}\right)^{0.46}\left[1.43 - 0.26\log\left(\frac{A}{A_{Rf}}\right)\right] \qquad (1)$$

in which S is the sediment yield in tons per square mile per year (ton/mi^2/yr); S_R is the reference sediment yield (equal to 1,645 ton/mi^2/yr); Q is the annual runoff entering the reservoir (in), and Q_R is the reference runoff (2 in). The area of reference A_{Rf} in equation (1) is 1 square mile (mi^2). The Dendy and Bolton analysis of 1,500 reservoirs discarded those with contributing areas smaller than 1 mi^2 as too much variation was found in those cases, and included those with contributing areas in the range 1 mi^2 – 30,000 mi^2 and with runoff in the range 0 in – 50 in.

2.1 LIMITATIONS OF THE DENDY AND BOLTON METHOD

The Dendy and Bolton method provides an estimate for sediment yield for watersheds in natural or close to natural conditions. Therefore, in this report, sediment loads obtained using this method are referred to as natural or restored conditions. The method is not intended to give a good estimate for watersheds affected significantly by anthropogenically accelerated erosion as in the case of the Tijuana River Watershed. Therefore, estimations from this equation are assumed to correspond to natural conditions (when past estimation of sediment load is needed) or to restored conditions (when future estimation of sediment load is desired). Current sediment loads could be higher than expected due to variations in the anthropogenic processes within the watershed and cannot be properly estimated with Dendy and Bolton. Only sediment load measurements could provide reliable estimates of sediment yield under the current altered scenario. However, the Dendy and Bolton method provides a framework to establish a goal of acceptable sediment loads.

2.2 MODELING IN THE TIJUANA RIVER WATERSHED FOR ESTIMATION OF SEDIMENT LOAD

For areas draining into the main Tijuana River from upstream of the U.S.-Mexico border, the Dendy and Bolton equation was applied to the areas identified below, and depicted in Figure 2-1.

(a) Areas draining to Rodriguez Dam (hereafter AR).

(b) Areas draining to Barrett Dam (hereafter AB).

(c) Sediment Producing Areas (hereafter SPA) upstream of the Valley that are not controlled by dams, excluding Smuggler's Gulch, Goat Canyon, Yogurt Canyon, and the Valley itself. The latter areas are also important for sediment load in the Valley, and they will be analyzed in a separate report.

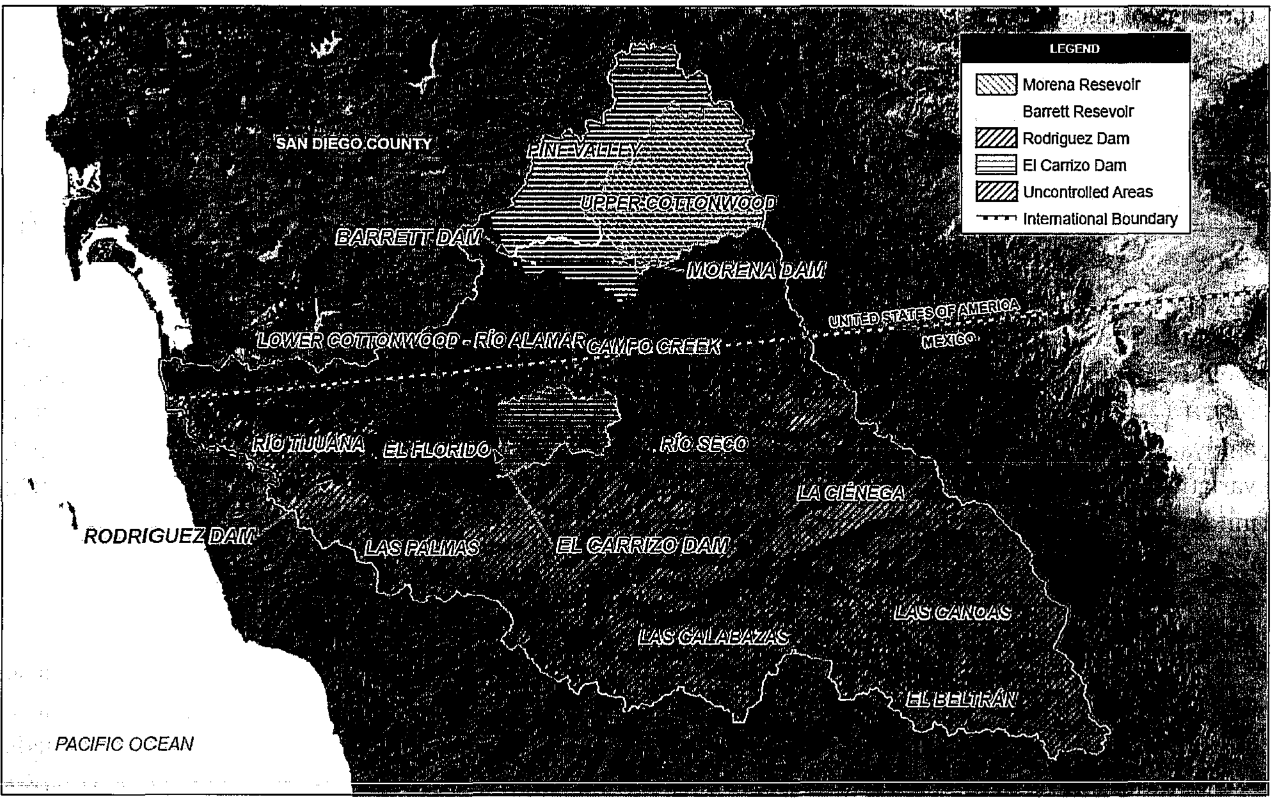

Figure 2-1. Areas Draining to Dams and SPA (in Red) in the Tijuana River Watershed

The reduction in the sediment load due to sediment deposition in the reservoirs was estimated according to the Brune Curve for trap efficiency of reservoirs [1,2]. The sediment entering the Valley from the main river consists of:

(1) sediments leaving the reservoirs,

(2) additional channel erosion from the release of the reservoirs as a result of "hungry water[1]," and

(3) sediments produced by the SPA.

A portion of these sediments will be deposited in the Valley, while a larger fraction will be discharged to the Pacific Ocean at the mouth of the river. The trapping efficiency of the Valley was established by comparing (a) the geologic measurements of sediment deposition in the estuary and the estimated deposition in the main channel areas, with (b) the load entering the channel as approximated by the Dendy and Bolton equation.

2.2.1 Required Data for Analysis

The following data was required for the analysis:

- the three contributing areas: AR, AB, and SPA,
- the average storage capacity of Rodriguez Dam and Barrett Dam (in order to calculate the Reservoir Capacity to Mean Annual Inflow ratio, with which to estimate trap efficiency), and
- the Mean Annual Runoff of the three areas ($Qi_{R\text{-}T}$, $Qi_{B\text{-}T}$, and $Qi_{SPA\text{-}T}$) for the period of record (the letter "i" indicates inflows to the dams).

The mean annual runoff QT of the entire watershed is known for the period of record (73 years) based on U.S. Geological Survey (USGS) and International Boundary and Water Commission (IBWC) measurements [3.4]. The runoff QT satisfies the continuity equation:

$$Q_T = Qo_{R\text{-}T} + Qo_{B\text{-}T} + Qo_{SPA\text{-}T} = 1.636\ m^3/s \qquad (2)$$

where the letter "o" indicates outflow discharge.

Rodriguez Dam and Barrett Dam use a large portion of runoff volume entering into the reservoirs; therefore:

$$Qi_{R\text{-}T} > Qo_{R\text{-}T} \qquad (3a)$$

$$Qi_{B\text{-}T} > Qo_{B\text{-}T}. \qquad (3b)$$

The inflow and outflow for the SPAs is the same; therefore:

$$Qi_{SPA\text{-}T} = Qo_{SPA\text{-}T}. \qquad (4)$$

---

[1] "Hungry water" is defined as water released by dams that has been depleted of sediments.

A portion of the runoff discharged from Barrett Dam may become infiltrated along Cottonwood Creek. However, since the dam discharges runoff only during wet conditions and extreme events, the infiltration percentage is considered to be negligible for the purpose of the present analysis.

Ponce [5] has compiled a list of monthly reservoir levels at Barrett Dam that can help to estimate when the Dam has had significant discharges. However, if the levels reported are assumed equal to mean monthly levels and translated into peak flows from the discharge duration curve provided in [5], it implies that the mean discharge of the dam is many times larger than the measured peak flows downstream where the entire watershed is contributing. Consequently, the analysis performed with Barrett data information suggests that the levels reported could be associated with maximum monthly levels and therefore tied to much lower average discharges. In any case, data collected in [5] is helpful in establishing seasons when Barrett Dam discharged a significant amount of water. Regarding Rodriguez Dam, CONAGUA in Mexico provided information regarding the years during which Rodriguez Dam discharged since 1948 [Daniel Sosa, personal communication], and, based on information provided on the City of Tijuana web page and the history of the dam [6], Rodriguez Dam also had significant discharges in 1941.

At this point, detailed data are not available regarding peak flow discharges from Rodriguez Dam or Barrett Dam for the period studied, nor are data available regarding the incoming flow to the dams. Therefore, certain assumptions must be established in estimating the partitioning of the runoff based on the available data. The following section discusses these assumptions.

2.2.2 Analysis of the Data

In the Tijuana River watershed, a few extreme events account for a significant portion of the total runoff. Furthermore, the water usage and releases of Rodriguez Dam in Mexico and, to a lesser extent, Barrett Dam in the U.S. are essential to understand the water and sediment dynamics in the watershed. Releases from El Carrizo Dam, which controls 2.6% of the watershed, are not included in this analysis because El Carrizo stores water imported from the Colorado River and does not release water.

The daily runoff data associated with the Tijuana River was recorded from October 1, 1936 to December 31, 2009. Data were gathered by the USGS from October 1, 1936 until September 30, 1982 at the Nestor Gauge at the entrance of the estuary, and by the IBWC from January 1, 1962 until December 31, 2009 at a location very close to the old USGS gauge at the entrance to the estuary. During several years (1962 to 1981), both stations collected data. Although the correlation coefficient of the data is extremely good during these years ($R^2 = 0.988$), the IBWC data are preferred because it is more accurate for small flows, and they display a larger mean average daily runoff value for dry years. In particular, 1964 and 1971 have an average flow of 0.00 cubic feet per second (cfs) according to the USGS, and an average flow of 0.17 cfs and 0.21 cfs respectively, according to the IBWC, which appears more realistic. In any case, the large difference in peak flow for small runoff values is of no consequence as small peaks do not contribute significantly to the sediment transport (see Section 2.3).

As Rodriguez Dam and Barrett Dam affect 56.9% and 13.6% of the total watershed, respectively, the data (73 water years starting October 1 and ending September 30) have been separated into five groups, based on the discharge of the dams and the characteristics of the runoff (wet or dry years). These groups are described below.

1) Group 1: Water years with releases of water from Rodriguez Dam and Barrett Dam (1940-41, 1977-78, 1979-80, 1982-83, 1992-93 and 1994-95). During those years, there were three sources of runoff: SPA, AR and AB. Runoff was calculated as follows:

   $Q_{T,1} = Qo_{R,1} + Qo_{B,1} + Qo_{SPA,1}$

   occurring 1,826 days or 6.85% of the time.

2) Group 2: Water years with releases of water from Rodriguez Dam exclusively (only 1977-78). During that water year, Barrett Dam was very low and did not release any water. There were two sources of runoff: SPA and AR. Runoff was calculated as follows:

   $Q_{T,2} = Qo_{R,2} + Qo_{SPA,2}$

   occurring 365 days or 1.37% of the time.

   In this particular water year, the water retained and used by Barrett Dam was above average in order to satisfy continuity constrains. The water usage of Barrett Dam this water year was included with Group 4 to determine the maximum water usage of Barrett Dam during wet years.

3) Group 3: Additional seasons with releases from Barrett Dam, but not releases from Rodriguez Dam (11 seasons in total: 36-37 to 39-40, 41-42 to 44-45, 78-79, 97-98 and 04-05). During those seasons, there were two sources of runoff: SPA and AB. Runoff was calculated as follows:

   $Q_{T,3} = Qo_{B,3} + Qo_{SPA,3}$

   occurring 4,017 days or 15.06% of the time.

   Sub Group 3A: The five wettest water years of Group 3 (Sub-Group 3A, 36-37, 37-38, 43-44, 97-98, 04-05 occurring 1,826 days or 6.85% of the time) were assumed to be representative of the maximum water usage at Rodriguez Dam (for example, information from Mexico indicated that the Dam levels in 1998 and 2005 were very high but Rodriguez Dam did not release water).

4) Group 4: Wet water years with no releases from Barrett Dam (1937-38, 1941-42, 1978-79, 87-88, 90-91, 93-94). It was assumed that, during those years, usage of water from the Barrett Dam watershed was maximized, and those seasons were assumed to be representative of the maximum water usage in Barrett Dam, in combination with Group 2. Runoff was calculated as follows:

   $Q_{T,4} = Qo_{SPA,4}$

   occurring 1,828 days or 6.86% of the time. The only contributing area during those wet seasons was SPA.

5) Group 5: All other 51 water years. As in Group 4, during those water years, there was only one source of runoff, that is, the areas not controlled by dams upstream of the Valley (SPA). Runoff calculated for those seasons is QoSPA, occurring 18,627 days or 69.86% of the time. The difference between Group 5 and Group 4 is that the water years in Group 5 were not wet years and are not considered representative of the maximum water usage of Barrett Dam.

The determination of the mean annual runoff for the three areas is detailed in Appendix A of this report. There are 36 variables, 13 of which can be measured directly from the data, and 23 of which must be calculated using: (a) the continuity equation (6 equations), (b) the proportionality assumptions between mean annual precipitation volume and runoff among all areas (12 equations), and (c) the water usage by the dams (5 equations).

The results of the water balance analysis for all groups and years are shown in Table 2-1 as peak flows in cubic feet per second (cfs) and also in parenthesis as cubic meters per second (m^3/s), and in Table 2-2 as depth of runoff (in).

2.2.3 Application of the Dendy and Bolton Equation

Once the average runoff upstream of the Rodriguez Dam, Barrett Dam and the SPAs had been estimated, the Dendy and Bolton equation was used to estimate the sediment entering the dams (shown in Table 2-3).

Runoff was divided into the different contributing sub-areas of the Tijuana River watershed as the sediment reduction by dams was applied to downstream discharges. However, the application of the Dendy-Bolton equation to the entire watershed area resulted in a determination of the sediment production under natural conditions, that is, in the absence of dams.

2.3 APPLICATION OF SEDIMENT TRAPPING EFFICIENCY BY DAMS

Sediment yields upstream of Rodriguez and Barrett Dams were then reduced downstream to about 2.5% of their incoming value, according to the Brune graph, which is displayed on Fig. 15.17 of [1], based on the average runoff and average capacity of the dams. The resulting sediment yield downstream of Barrett and Rodriguez Dams, as well as the sediment yield of the SPA, was included in Table 2-3. The total sediment yield was obtained by increasing the yield of Barrett Dam to its new equilibrium load, calculated as described in the following section.

2.4 ADDITIONAL CHANNEL AND BANK EROSION DOWNSTREAM OF DAMS

As the water released by the dams was depleted of sediments (i.e., “hungry water”) and did not satisfy the natural water flow – sediment load equilibrium, the potential existed for additional erosion to occur before the water released by Rodriguez and Barrett Dams reached the concrete channel. Sections 2.4.1 and 2.4.2 discuss these discharges, respectively.

2.4.1 Rodriguez Dam

The "hungry water" released by Rodriguez Dam has little chance to pick up additional sediments by means of erosion (see Figure 2-2, on which the distance between the dam discharge and the beginning of the concrete channel is displayed). Therefore, the erosion that can occur immediately downstream of Rodriguez Dam in the main channel was assumed to be negligible and not affecting the sediment load entering into the Tijuana Valley. Erosion from canyons and rivers entering the concrete channel in the city of Tijuana were considered to be part of the SPA.

Figure 2-2. Satellite View of the Tijuana River from Rodriguez Dam to the beginning of the Concrete Channel in the Tijuana River

Table 2-1. Approximate Average Peak Flows Entering and Discharging Rodriguez and Barrett Dams and the SPA

PEAK FLOWS cfs; (m^3/s in parenthesis)	Rodriguez Dam			Barrett Dam			SPA	TOTAL (all areas)	
	IN(1)	OUT	USED	IN(2)	OUT	USED	IN=OUT	IN(3)	OUT(4)
GROUP 1 : 1,826 days	436 (12.34)	*253(5)* *(7.17)(5)*	183(6) (5.17)(6)	180.5 (5.11)	*133* *(3.77)*	47.3(7) (1.34)(7)	*185* *(5.25)*	802 (22.70)	**572** **(16.19)**
GROUP 2(8) : 365 days	189 (5.36)	*6.71* *(0.19)*	183(6) (5.17)(6)	78.4 (2.22)	*0* *(0)*	78.4 (2.22)	*80.5* *(2.28)*	348 (9.86)	**87.2** **(2.47)**
GROUP 3 : 4,017 days	132 (3.75)	*0* *(0)*	132 (3.75)	54.7 (1.55)	*7.42* *(0.21)*	47.3(7) (1.34)(7)	*56.2* *(1.59)*	244 (6.90)	**63.9** **(1.81)**
Sub-Group 3A: *1,826 days*	183 (5.17)	*0* *(0)*	183(6) (5.17)(6)	75.6 (2.14)	*28.3* *(0.8)*	47.3(7) (1.34)(7)	*77.7* *(2.20)*	336 (9.50)	**106** **(3.00)**
GROUP 4 : 1,828 days	99.2 (2.81)	*0* *(0)*	99.2 (2.81)	41.0 (1.16)	*0* *(0)*	41.0 (1.16)	*42.0* *(1.19)*	183 (5.17)	**42.0** **(1.19)**
GROUP 5 : 18,627 days	16.5 (0.468)	*0* *(0)*	16.5 (0.468)	6.9 (0.194)	*0* *(0)*	6.9 (0.194)	*7.0* *(0.199)*	30.4 (0.861)	**7.0** **(0.199)**
TOTAL : 26,663 days	70.6 (2.00)	*17.5* *(0.494)*	(53.3) 1.51	29.3 (0.829)	*10.3* *(0.291)*	19.0 (0.538)	*30.1* *(0.852)*	130 (3.68)	**57.9** **(1.64)**

Notes:

(1) Since inflow is proportional to the volume of precipitation, and volume of precipitation upstream of Rodriguez Dam is about 235% of that occurring over the SPA, this column is approximately 2.35 times larger than the values of the SPA column.

(2) Since inflow is proportional to the volume of precipitation, and volume of precipitation upstream of Barrett Dam is about 97.3% of that occurring over the SPA, this column is approximately 0.973 times larger than the values of the SPA column.

(3) The total inflow corresponds to the approximate average peak flows without Rodriguez and Barrett Dams and the infiltration downstream of Barrett were negligible.

(4) Bold values are the values measured directly from the data, from 10/1/1936 to 9/30/2009. Those values satisfy the continuity equation at each row such that all numbers on italics when added horizontally are equal to the bold values.

(5) Since the maximum runoff retained and used in Rodriguez Dam is assumed to be approximately the average value of the flow incoming to Rodriguez Dam in Sub-Group 3A (5.17 m^3/s). This value corresponds to 12.34 – 5.17 = 7.17 m^3/s

(6) The maximum water usage for Rodriguez Dam was assumed equal to the corresponding water usage for Sub-Group 3A, obtained with the continuity equation, since it is known that Rodriguez Dam did not release water the years represented by Group 3A.

(7) The maximum runoff retained and used by Barrett Dam is approximately the weighted average value of the flow incoming to Barrett Dam in Group 4 (1.16 m^3/s) and Group 2 (2.22 m^3/s). The weighted average is 1.34 m^3/s.

(8) 1977-78 is the only year where the water usage of Barrett is allowed to exceed the average value of 1.34 m^3/s since it is known that such water year is the only one when Rodriguez released water and Barrett did not release water.

Table 2-2. Appropriate Average Annual Depth of Runoff (in) Entering and Discharging Rodriguez and Barrett Dams and the SPA

RUNOFF (in)(1)	Rodriguez Dam			Barrett Dam			SPA	TOTAL (all areas)	
	IN(2)	OUT	USED	IN(3)	OUT	USED	IN=OUT	IN(4)	OUT(4)
GROUP 1 : 1,826 days	6.04	*3.51*	2.53	10.43	*7.70*	2.73	5.76	6.59	4.70
GROUP 2 : 365 days	2.62	*0.09*	2.53	4.53	*0.00*	4.53	2.50	2.86	0.84
GROUP 3 : 4,017 days	1.84	*0.00*	1.84	3.17	*0.44*	2.73	1.75	2.00	1.29
Sub-Group 3A: 1,826 days	2.53	*0.00*	2.53	4.37	*1.64*	2.73	2.41	2.76	2.14
GROUP 4 : 1,828 days	1.37	*0.00*	1.37	2.37	*0.00*	2.37	1.31	1.50	1.31
GROUP 5 : 18,627 days	0.23	*0.00*	0.23	0.40	*0.00*	0.40	0.22	0.25	0.22
TOTAL : 26,663 days	0.98	*0.24*	0.74	1.69	*0.59*	1.10	0.94	1.07	0.48

Notes:

(1) All values in Table 2-2 can be obtained from Table 2-1 by transforming the runoff in m^3/s into in/yr. Total runoff volume (average peak flow of Table 2-1 multiplied by time) divided by contributing area and the result converted into inches is displayed in this table.

(2) Since the average rainfall upstream of Rodriguez Dam is approximately 11 in and in the SPA is approximately 10.5 in, this column is equal to the SPA column multiplied by 11/10.5.

(3) Since the average rainfall upstream of Barrett Dam is approximately 19 in and in the SPA is approximately 10.5 in, this column is equal to the SPA column multiplied by 19/10.5.

(4) Total depth of runoff (both IN and OUT) is equal to the weighted average of runoff with respect to the contributing areas (both IN and OUT for Rodriguez, Barrett and SPA areas)

Table 2-3. Sediment Load of the Tijuana River at the U.S./Mexico Border (Entrance to the Valley) under Restored Conditions

Location where Annual Sediment Load has been Estimated	Sediment Load (ton/yr)
(1) Upstream of Barrett Dam	300,000
(2) Discharge of Barrett Dam	8,000
(3) Discharge of Barrett Dam at junction with concrete channel	70,000
(4) Upstream of Rodriguez Dam	800,000
(5) Discharge of Rodriguez Dam	20,000
(6) SPA (include areas in U.S. and Mexico upstream of border)	400,000
(7) Total Sediment Load (3) + (5) + (6)	500,000
(8) Total Area at Entrance of Valley under Natural Conditions and without considering dam influence	1,300,000

2.4.2 Barrett Dam

Unlike the releases from Rodriguez Dam, releases from Barrett Dam have plenty of opportunity to pick up additional sediments. Cottonwood Creek tries to reach its sediment-water equilibrium state as the flow has more than 25 miles to travel from Barrett Dam to the beginning of the concrete channel in the Tijuana River. Therefore, the sediment load discharged by Barrett Dam may represent an underestimation of the sediment load entering the estuary. This is because the channel and bank erosion potentially taking place downstream of Barrett Dam has not been considered. Based on the peak flow values of Table 2-1, it has been estimated that the effect of Barrett Dam is to reduce the average peak discharge from 0.829 m^3/s to 0.291 m^3/s; that is, to 35.1%. In order to determine the potential equilibrium reduction in the sediment load, a power law equation relating water discharge Q to sediment discharge Q_s is assumed [7]:

$$Q_s = KQ^n \qquad (5)$$

Theoretically, the exponent n varies between 1.2 and 2.8. The Engelund and Hansen equation [8] suggests an exponent n=1.7 based on the critical shear stress approach. In the Colby method, the exponent n varies from about 2.8 to 1.2 as the flow increases [1, 9, 11]. Julien and Simons [12] suggest an exponent between 2.4 and 1.4. Ponce's Modified Lane Relation [9] suggests an exponent n=1.2 in equation (5) to reach a dimensionless constant k_1 that satisfies the following relation $q_s = Q_s \cdot B = \rho \cdot k_1 \cdot v^m$.

Equation (5) is applicable to daily discharges of Barrett Dam; therefore, applying this equation to the average daily discharge is an approximation. The application of equation (5) helps to estimate the reduction in sediment load associated with the 65% reduction in water discharge. Since the reduction in water is not linearly related with the reduction in sediment load, the expected sediment load would be reduced by 79% assuming that the coefficient K remains constant. The later will be the case under the three assumptions identified below.

1) The slope of the river has remained unchanged (for example, under the occurrence of mostly bank erosion).
2) Cottonwood Creek behaves as a hydraulically wide channel, and the hydraulic radius is equal to the water depth (which is almost always the case for natural rivers).
3) The mean diameter of the sediment has not changed. Since the estimated 97.5% sediment reduction from the Dam is larger than the needed reduction to maintain equilibrium, discharges of Barrett will have a tendency to erode downstream (hungry water) to reestablish equilibrium, as discharges downstream of dams typically do. The assumptions related to slope and sediment size remain to be confirmed by additional studies.

The average annual sediment load entering Barrett Dam is approximately 300,000 ton/yr (see Table 2-3). According to the Brune graph [1,3], the dam reduces this load downstream to 7,800 ton/yr. The equilibrium load downstream, considering the water reduction, is about 70,000 ton/yr. Therefore, Cottonwood Creek has the potential to erode about 62,000 ton/yr.

Table 2-4 shows a sensitivity analysis of the equilibrium load as a function of n. The increase in sediment load shown in Table 2-4 is associated with the flow discharges of Barrett Dam only, since the sediment load from areas draining to Cottonwood Creek downstream of the dam has already being considered as part of the SPA.

Table 2-4. Equilibrium Load for Barrett Dam Discharges (Sensitivity Analysis)

N exponent:	**1.2 (needed value for dimensionless k_1 in $Q_s = k_1 \cdot v^m \cdot p/B$)**	**1.5 (average value)**	**1.7 (Engelud-Hansen)**	**Assumed load**
Sediment load (ton/yr):	54,000	65,000	89,000	70,000 (average)

2.5 SEDIMENT LOAD ENTERING THE VALLEY UNDER RESTORED CONDITIONS

The sediment load carried by the water at the entrance to the Valley is estimated to be about 500,000 tons/yr (see Table 2-3), not taking into consideration the sediment load from the four canyons entering the Valley downstream of the U.S.-Mexico border. A large portion of this load reaches the Pacific Ocean, but the portion depositing in the Valley represents a significant amount of sediment.

A preliminary approach, based on geological considerations, was used to establish the percentage of the sediment load that is deposited in the Valley. A more precise determination would require the use of a two-dimensional water and sediment routing model of the Valley (2-D Model). This 2-D Model is outside the scope of the present study, and is recommended for future studies.

This page intentionally left blank

SECTION 3 GEOLOGIC APPROACH TO DETERMINE SEDIMENT DEPOSITION

A study by Mudie and Byrne [14, 17] has estimated that the expected accretion in the Valley marsh has been about 0.1 centimeter per year (cm/yr) in the last 1,100 years, using geologic measurements. It is important to consider the following observations with respect to these findings.

- The accumulation of sediments in the marsh should be significantly smaller than that in the main channels as the marsh is not subject to the same flooding process. Marshes are only flooded during extreme events at a low velocities and low depths, while channels carry the majority of the flow and sediment during extreme events, and the entire flow during those events does not cause overbank flooding. Hysteresis in the sediment rating curve may add an additional complication to the process [1,7].
- Accumulation of sediments in the floodplain is not constant in time or space, since preferred paths of water movement exist and, consequently, sediment is transported during the occurrence of extreme events.

Notwithstanding these observations, the accretion in the marsh can be used as an estimate for natural sediment deposition in the Valley and the Estuary, taking into account the following assumptions:

1) Deposition in the marsh is assumed to be 0.1 cm/yr and it is applied over the 1850s marsh area (about 2.5 square miles).
2) Deposition in the floodplain portion of the Valley that is not considered marsh is unknown. For preliminary purposes, it is assumed to be equal to that occurring in the marsh in naturally restored conditions. The depositional rate is applied to the 1850s estuary area (between 8 to 10 square miles, as the few maps from that era are not very accurate).
3) Deposition in the channels is deemed to be significantly larger than that occurring in the floodplain and the marsh. It is assumed to be an order of magnitude larger (1 cm/yr) than the value measured in the estuary and within the range measured by Weis et al [19]. Channel deposition is applied to the approximate 1850s channels area (about 1.5 square miles).
4) Since deposition in the channels is larger than in the surrounding area, eventually the channels will be filled. As the location of the main channel changes within the delta in geological time, the larger deposition in the channels will come into agreement with established geomorphological principles.

The approximate average volume of sediments V (in m^3) that had been deposited annually can be obtained as follows:

$$V = V_{marsh} + V_{floodplain} + V_{channel} \qquad (6)$$

$$V = 25{,}900\ m^3/(cm\text{-}mi^2) \cdot (0.1\ cm/yr \cdot 2.5\ mi^2 + 0.1\ cm/yr \cdot (8\ to\ 10)\ mi^2 + 1\ cm/yr \cdot 1.5\ mi^2)$$

$$V = 6{,}450 + (20720\ to\ 25{,}900) + 38{,}850 = 66{,}000\ to\ 71{,}200\ m^3/yr = 86{,}000\ to\ 93{,}000\ cu\text{-}yd/yr$$

Assuming a specific weight of the dry-deposited sediments of 1,590 kg/m^3 (2,680 lb/yd^3) the weight of sediments in tons/yr (1 ton = 2000 lb = 907.2 kg) is:

$S_{geology}$ = 116,000 to 125,000 ton/yr.

The previous deposited value was compared with the geological sediment production of the watershed before dams and human intervention occurred.

The application of the Dendy and Bolton equation to the entire area of the watershed results in the following sediment load (see Table 2-3):

S_{total} = 1,300,000 tons/yr

The sediment deposition percentage in the last 1,100 years has been: (116,000 to 125,000)/1,300,000 = 9 to 10%. As the depositional area has been reduced from 12 to 14 square miles to 3.5 square miles, the "natural" sediment load that can be deposited in the estuary to preserve its biological function may have to be reduced 25%-30% to satisfy the same level of geological deposition. Such amount would be about 31,000-35,000 ton/yr, which is only 6 -7 % of 492,000 ton/yr, the sediment load of the watershed *under restored conditions*. Therefore, it is clear that an improved mechanism of sediment transport is needed in the Valley so that sediment transport can become more efficient. It is also clear that, in the long term, the river under restored watershed conditions may have a natural tendency to carry more sediment than the estuary can accept as the depositional area of the river has been reduced to levels incompatible with the transport capacity of the river.

Note that under restored conditions (assumed here through the use of the Dendy-Bolton equation and accounting for the significant sediment load reduction of Rodriguez and Barrett Dams), there is still too much sediment to be deposited in a reduced estuary area. Consequently, anthropogenic intervention may be needed in the estuary to prevent sediment deposition even after a hypothetical restoration takes place upstream.

It must be emphasized that Rodriguez Dam has not released water in the last 26 years, and the accelerated increase of construction and population in the city of Tijuana has made the estuary even more prone to sizable deposition of sediment and trash. It should be noted that contributing canyons in the city of Tijuana proper can cause significant increases in anthropogenic sediment load. Ponce and Castro [13] reported that in 1993, "El Aguaje de la Tuna Canyon", with only 5.98 square miles of drainage area, discharged about 400,000 cubic meters (520,000 cubic yards) of sediment in a single extreme event. However, most of that load did not reach the estuary, as the sediment was deposited upstream of the main concrete channel because the culverts discharging into the channel were clogged. This example shows how extreme events and mudslides at a local scale can change the sediment load balance. In a single storm event, an area equal to 0.35% of the total watershed area was able to generate a sediment load similar to that of the average annual load of the entire watershed.

To complicate things further, the annual sediment distribution is highly dependent on extreme events that do not occur every year. As the exponent in equation (5) is larger than 1, the sediment distribution in the Tijuana River is more influenced by extreme events than the runoff distribution. From a statistical standpoint, this means that the sediment distribution is more skewed than the runoff distribution. Sediment distribution is discussed further in Section 4.

SECTION 4 CHARACTERISTICS OF THE SEDIMENT DISTRIBUTION

The skewed nature of the runoff distribution implies that the average annual deposition does not occur frequently. Assume that: (a) the 73 years of runoff data are statistically similar to future discharges under restored/optimal conditions, and (b) the average sediment load entering the Valley would be 492,000 ton/yr. Under these assumptions, an analysis can be performed to find the hypothetical distribution of sediments in the past 73 water years (from October 1, 1936 to September 30, 1937 and from October 1, 2008 to September 30, 2009). The application of a power-law distribution $Q_s = KQ^n$ with n=1.5 results in a value of K=80 to satisfy the daily average flow data.

The sediment distribution has been calculated in such a way that the average sediment load entering the Valley is 492,000 ton/yr. Figure 4-1 and Figure 4-2 show the sediment distribution per year as estimated (normal and logarithmic scale), and Figure 4-3 and Figure 4-4 show the sorted sediment annual load from largest to smallest (normal and log scale). The following paragraphs describe the theoretical sediment distribution during the last 73 water-years (i.e., October-September) of measurements, assuming that the discharge flows occurred under watershed conditions similar to those studied by Dendy and Bolton. The results also are shown in Table 4-1.

> Top 7 water years (from highest to lowest sediment load) – approximately top 10% (79-80, 92-93, 82-83, 40-41, 94-95, 43-44, 36-37): 4,700,000 ton/yr on average, with a maximum of 10,500,000 ton/yr and a minimum of 540,000 ton/yr. This includes all seasons producing a larger than average load, and, at the same time, generating 91.63% of the total sediment load. Notice that a larger-than-average season has not occurred since 94/95.
>
> Next highest 18 water years – approximately 25% of the time: 150,000 ton/yr on average (maximum of 420,000 ton/yr and minimum of 25,000 ton/yr), generating 7.53% of the sediment load.
>
> Next 24 water years – central third (approximately 33% of the time): 12,000 ton/yr on average (maximum of 23,000 ton/yr and minimum of 2,300 ton/yr). The median value of the sediment production (12,400 ton/yr) is included in this group. The central group generates 0.80% of the sediment load.
>
> Lowest 24 water years – bottom third (approximately 33% of the time): 610 ton/yr on average (maximum of 2,100 ton/yr and minimum of 0 ton/yr). The bottom third generates only 0.04% of the total sediment load. Those seasons have a tendency to occur in blocks: only one season after 1978 belongs to this group (01-02) and 16 of the 18 seasons in the period 59-60 to 76-77 belong to this group.

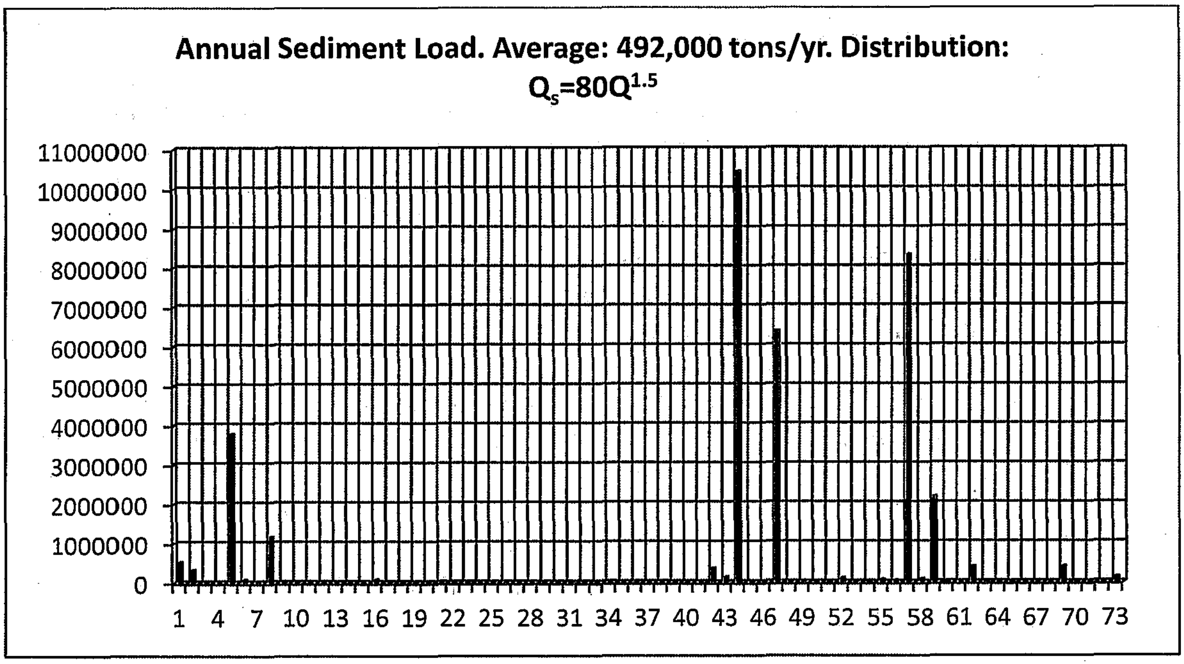

Figure 4-1. Annual Sediment Load in Normal Scale
Values 1 and 73 correspond to 10/36-9/37 and 10/08-9/09 respectively.

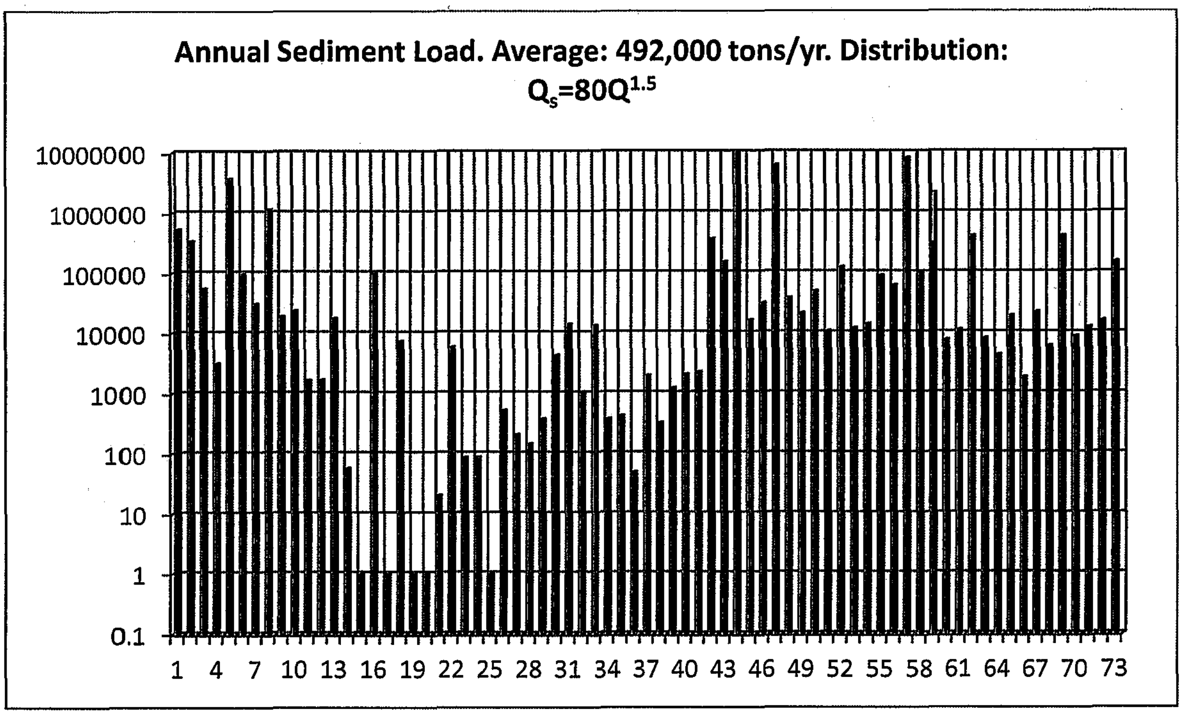

Figure 4-2. Annual Sediment Load in Logarithmic Scale
Values 1 & 73 correspond to 10/36-9/37 & 10/08-9/09 respectively. Minimum "y" value = 1 ton/yr.

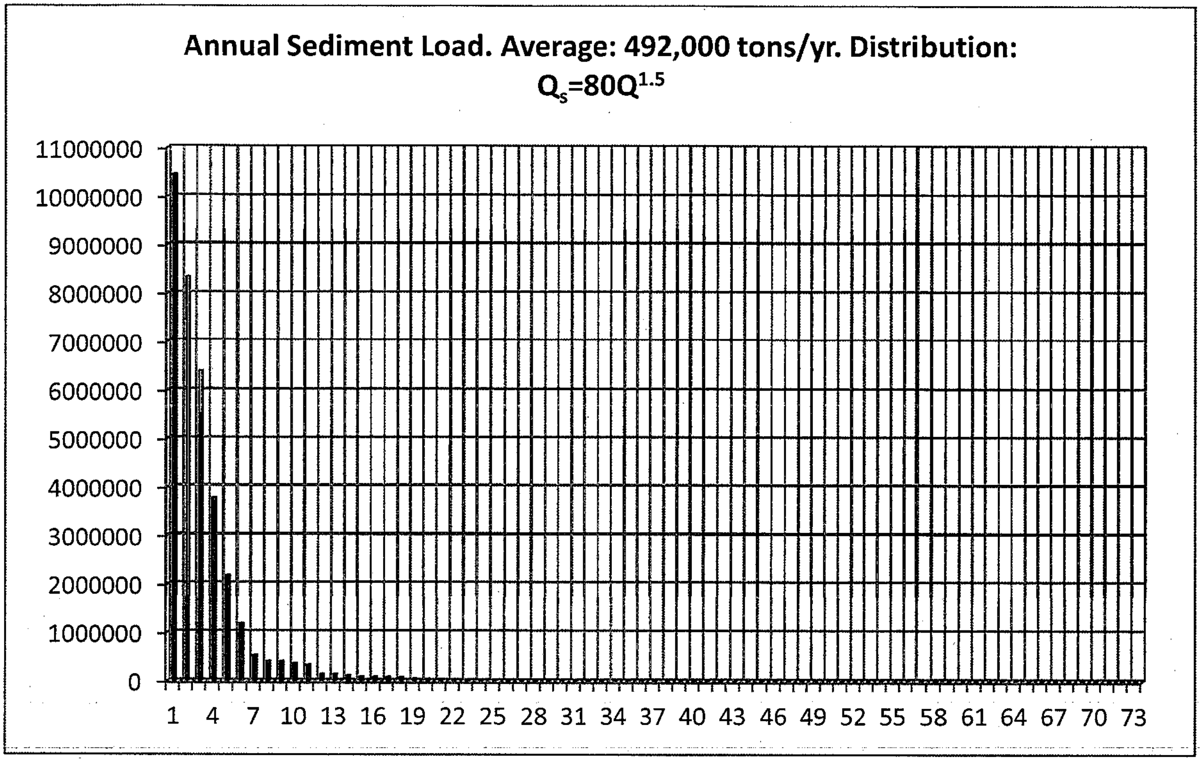

Figure 4-3. Sorted and Decreasing Sediment Load (ton/yr; natural scale)

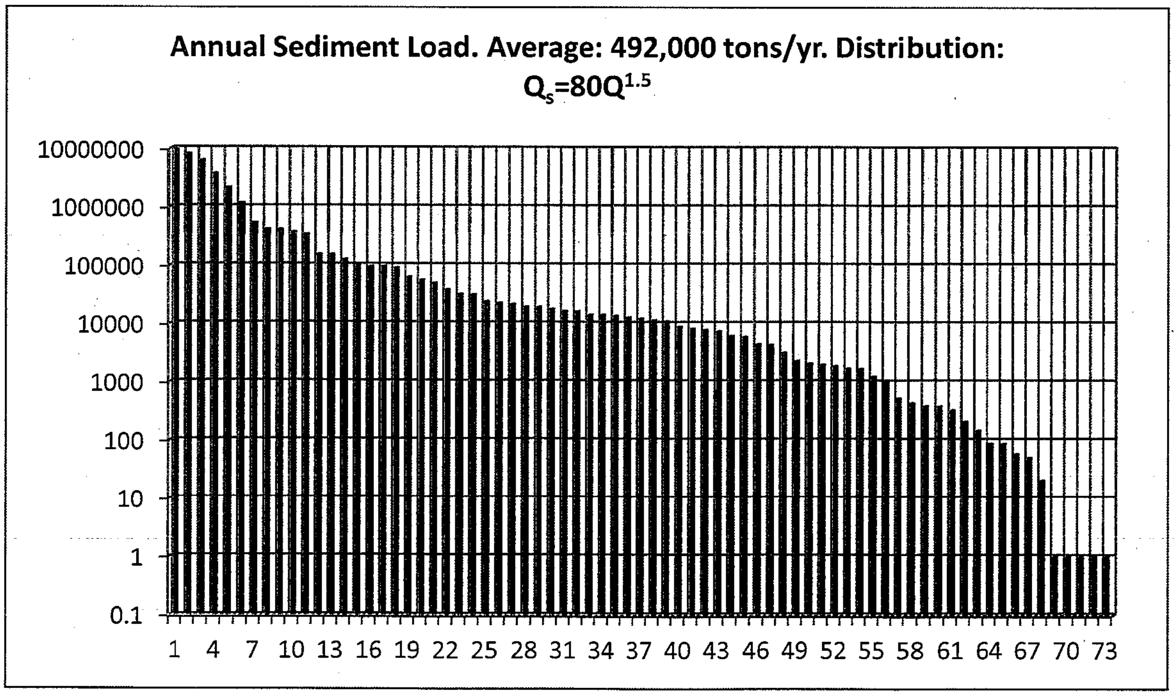

Figure 4-4. Sorted and Decreasing Sediment Load (ton/yr; logarithmic scale)

Table 4-1. Distribution of Sediment Load per Water Year

Number of Water-Years	Approximate Percentage of the Time	Percentage of the 73-Year Sediment Load
Top 7 years	10 %	91.63 %
Next 18 years	25 %	7.53 %
Middle third (next 24 years)	33 %	0.80 %
Bottom third (lowest 24 years)	33 %	0.04 %

Note that the previous analysis was performed in terms of water years. For a daily analysis, the sediment distribution is even more skewed: a small percentage of the time actually carries a large percentage of the load. In this assessment, it is expected that the 0.15% of the days in the last 50 years (the 30 days with highest mean runoff since 1950) can carry 70% of the total sediment load. Also note that the sediment distribution is the hypothetical distribution of sediments under restored conditions and not a representation of the past sediment load. Land use changes may have caused sediment load changes not accounted by equation (5) . Other local aspects (failure of slopes in canyons or mudslides, excessive accumulation of sediments due to anthropogenic intervention in the channels, unprotected construction activities, etc.) may have increased sediment loads significantly, as occurred in the 1993 event at El Aguaje de La Tuna (Section 3).

4.1 SIGNIFICANCE OF EXTREME EVENTS IN SEDIMENT DISCHARGE

The purpose of the previous analysis was to describe how extreme events drive the sediment load. Controlling sediments during large events is physically infeasible. In Section 4.1.1, a preliminary estimation of the capacity of the sediment pond was made. This capacity, amounting to 37,000 acre-feet (acre-ft), is the size of a hypothetical BMP designed to the point of diminishing returns in terms of sediment removal.

4.1.1 The Point of Diminishing Returns for Sediment Treatment

The point of diminishing returns is the point where a dimensionless graph of $x = V/V_{max}$ versus the fraction of sediment removal "f" reaches $df/dx= f_{max}$ (f_{max} usually equal to 1). This point represents the point where an increase in the sediment removal comes at the expense of a larger proportional increase in the volume supplied. V_{max} represents the volume needed to reach 99 to 100 % of the maximum theoretical removal f_{max} (see USEPA [16]). The use of a value smaller than the 100% value used by the U.S. Environmental Protection Agency (usually 99% or 99.5%) is to avoid the mathematical difficulty of finding $df/dx = f_{max}$ when the curve $f(V/V_{max})$ is asymptotic to its maximum value f_{max}. Per the Brune trap efficiency graph (shown in Figure 4-5), the maximum removal efficiency of a reservoir/sediment pond for medium-sized sediments is 0.975, and V_{max} is defined as the volume of the sediment pond needed to remove 99.5% of f_{max} ($0.995 \cdot 0.975=0.97$). Figure 4-6 and Figure 4-7 show the point of diminishing returns assuming that the Brune graph can be represented by equation (7), which can be written as the following spline:

$$f_{Trapped} = 0.01935\log^4\left(\frac{C}{AI}\right) + 0.0888\log^3\left(\frac{C}{AI}\right) + 0.02726\log^2\left(\frac{C}{AI}\right) + 0.01082\log\left(\frac{C}{AI}\right) + 0.974 \qquad (7)$$

where $f_{Trapped}$ is the fraction of trapped sediments, C is the capacity of the reservoir, and AI is the annual inflow to the reservoir.

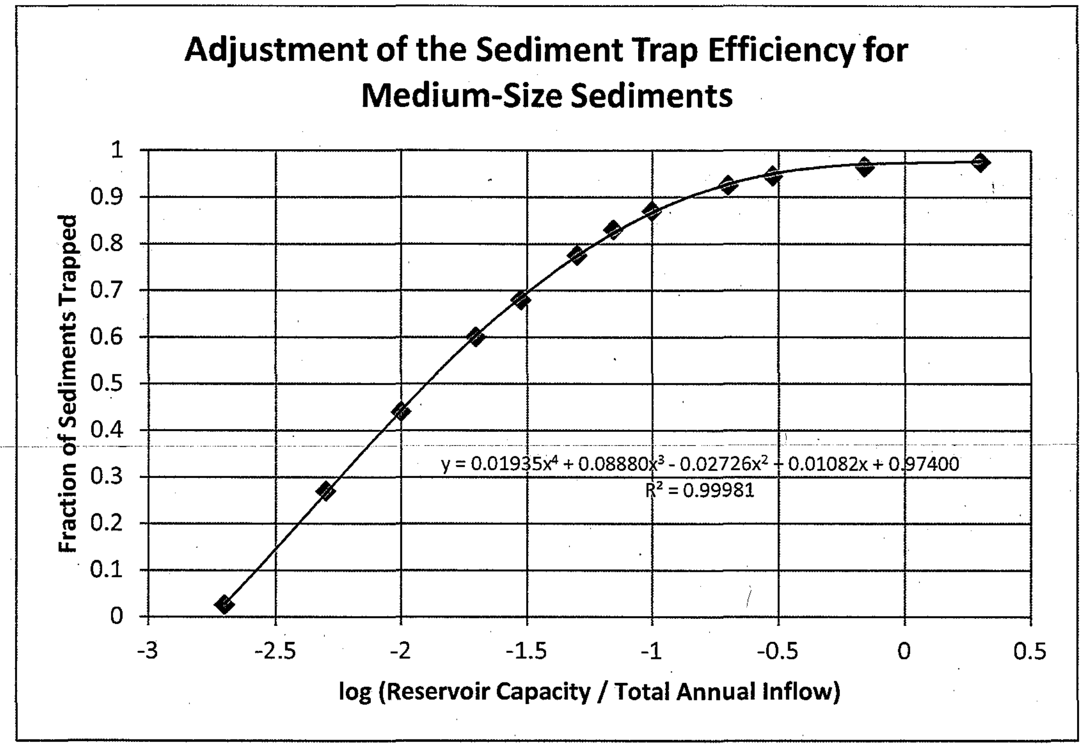

Figure 4-5. Sediment Trapped Efficiency for Modeling of the Point of Diminishing Returns.

For the diminishing return analysis, it was assumed that the sediment load carried by the river corresponded to the restored conditions load (i.e., an average of 492,000 ton/yr), with the daily concentration determined from the daily flows per equation (5). It is assumed that cleaning operations occurred at the end of each water-year in order to restore the pond to original conditions. The point of diminishing returns corresponds with a sediment removal of 85.3% with a V/V_{max} value of 0.118. Considering that V_{max} = 310,000 acre-ft, the volume of the sediment pond would have to be about 37,000 acre-ft (see Figure 4-6 and Figure 4-7).

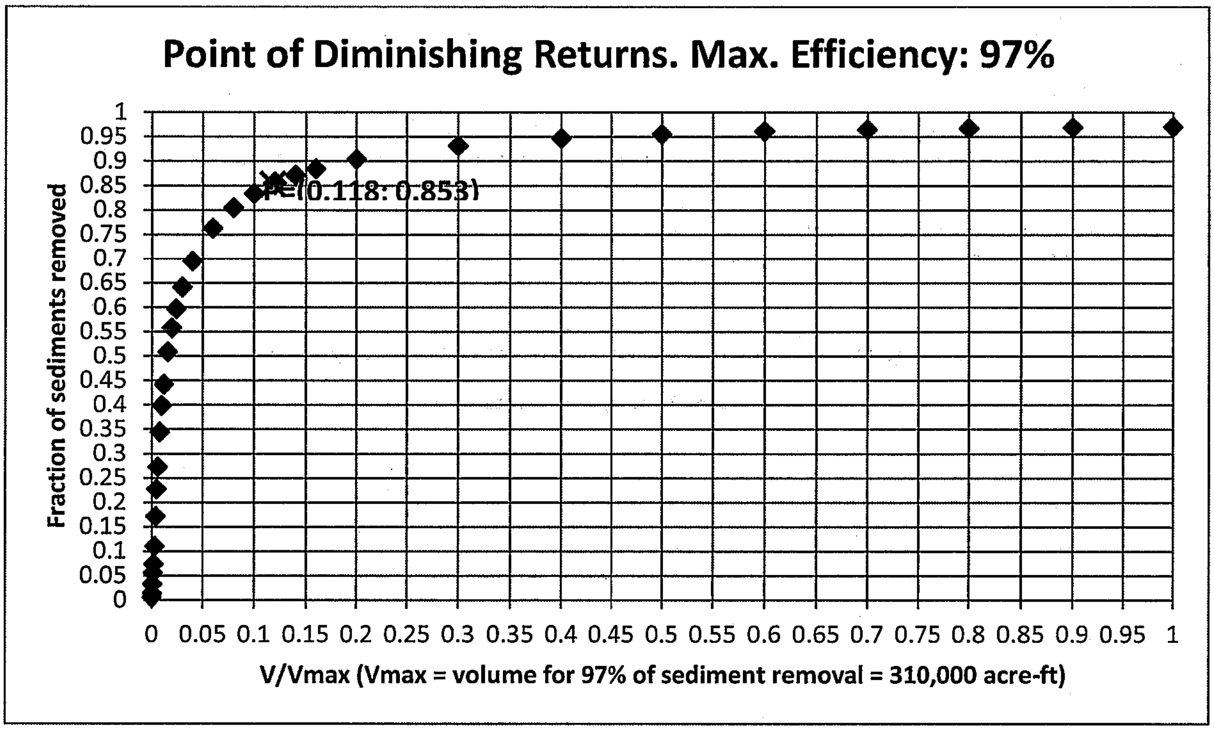

Figure 4-6. Point of Diminishing Returns (Normal and Logarithmic Scale in "x" Respectively)

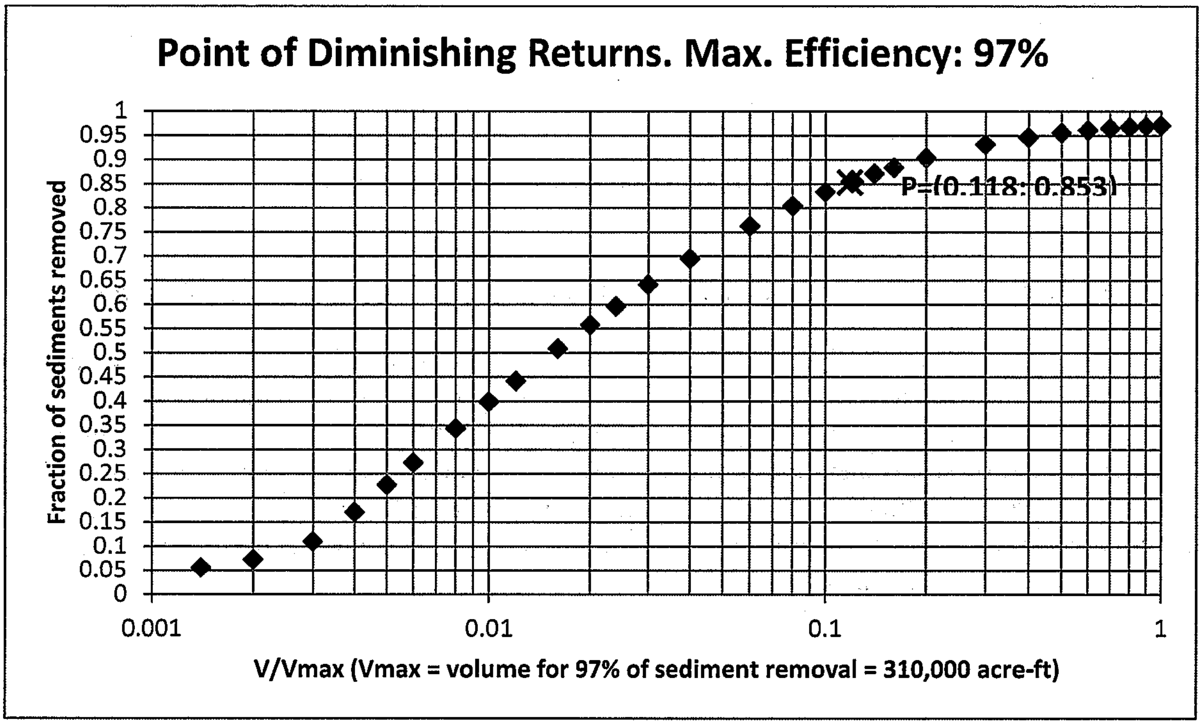

Figure 4-7. Point of Diminishing Returns (Normal and Logarithmic Scale in "x" Respectively)

The point of diminishing returns is independent of K as long as K remains constant with time. In fact, K (the proportionality constant between the flow and the sediment load) has increased along the years as the same flows are transporting a larger load of sediments due to watershed modifications mainly associated with the urbanization of the city of Tijuana. However, the point of diminishing returns is an indication of how large a sediment basin must be downstream of the concrete channel to have any significant impact on the sediment load.

Figure 4-6 displays the expected average sediment removal for various sediment basin sizes. In the hypothetical scenario that a 10- to 15-foot-deep sediment basin could be built at the entrance of the channel, downstream of the expansion of the Tijuana concrete channel into a natural channel, there would be a physical limitation based on the constrains of the land use in the area. Even under the most optimistic scenario (which may not be realistic), the largest sediment basin that could be physically built at the entrance to the Valley is about 200 to 300 acre-ft (or V/V_{max} about 0.0007 to 0.001). Therefore, the maximum long-term sediment removal that could be expected if such a basin were built is on the order of 5% annually, which makes this option inefficient from the point of view of sediment control. It must be emphasized that this scenario does not take into account possible tailwater effects upstream of the sediment basin, which could increase flooding risks for the city of Tijuana upstream. This scenario was analyzed here to show the low efficiency that a hypothetical maximum-size sediment basin at the entrance of the estuary would produce.

4.2 COMPARISON OF SEDIMENT LOADS IN SANTA CLARA AND TIJUANA RIVER

The second purpose of the above sediment distribution analysis was to compare the sediment distribution of the Tijuana River with the hyperpycnal sediment discharge of the Santa Clara River, studied by Warrik and Milliman [10]. Hyperpycnal discharges are those where the density of the water and sediment mixture is greater than the density of the ocean. Hyperpycnal events are particularly important in rivers draining the Transverse Range in California, and they account for 75% of the cumulative sediment load discharged by the Santa Clara River over the past 50 years. These events are highly pulsed, totaling only ~30 days (~ 0.15% of the total 50-year period). It can be seen that, in both rivers, Santa Clara and Tijuana, the total sediment load of the extreme events is extremely high. However, the use of a coefficient n=1.5 and K=80 in equation (5) does not allow the discharges to reach hyperpycnal conditions in the Tijuana River. More likely, hyperpycnal conditions (sediment concentration in excess of 40,000 parts per million) would not be reached in restored conditions due to the significant sediment reduction during extreme events caused mainly by Rodriguez Dam and, in smaller proportion, by Barrett Dam. Note that, without the dams, average annual sediment loads would be 1,300,000 ton/yr instead of about 500,000 ton/yr.

Since Barrett Dam discharges at a significant distance upstream of the concrete channel, the "hungry" water discharged may have the opportunity to reach its sediment load equilibrium, causing erosion of the downstream channel. Such sediment equilibrium would be smaller than without the dams, since Barrett Dam retains a significant percentage of the runoff draining to it. Meanwhile, Rodriguez Dam discharges are too close to the concrete channel to allow equilibrium in the sediment load, and water retention in Rodriguez Dam may represent a higher percentage of the runoff of the respective extreme event. Consequently, the net reduction in the sediment load due to the dams may prevent hyperpycnal conditions.

The percentage of sediments in the top 30 days is independent of the constant K and only a function of the constant n in equation (5). The constant n can be chosen so that identical conditions to the Santa Clara River are satisfied (that is, 75% of the sediments are transported by the maximum 30 days of discharge). In this case, the value of n would be n = 1.615, smaller than the n=1.7 predicted by the Engelund-Hansen equation. Both of these values are within the realm of possibility.

4.3 TRANSBOUNDARY FLOWS FROM THE COLORADO RIVER. EL CARRIZO DAM OPERATIONS AND TREATMENT PLANT DIVERSIONS

Assume that a power law represented by equation (5) is used to establish a relationship between sediment load and peak flows. In this case, large peak flows are responsible for the majority of the sediment transport in the Tijuana River. For a value of n = 1.5, only 5% of the sediments will be transported by daily flows smaller than 13.6 m^3/s, independently of the calibration coefficient K. Also, only 1% of the sediments will be transported by daily flows smaller than 2.63 m^3/s.

A sensitivity analysis of the results shows that the peak flow under which 5% of the sediment transport occurs increases to 28.9 m^3/s for n=1.7, and reduces to 2.61 m^3/s for n= 1.2, the lowest practical value [9]. The fact that most of the sediment transport occurs with relatively large flows is extremely important in order to disregard the contributions of changes at the base-flow level. The 2.61, 13.6 and 28.9 m^3/s flows have been equaled or exceeded 93.8, 98.2, and 99.1% of the time, respectively, which shows how a large percentage of time represents only a small percentage of sediment transport.

The withdrawal of water from the Colorado River for water usage in the city of Tijuana increases the base flow of the Tijuana River by an undetermined amount. The increase in baseflow is on the order of 0.1 - 1 m^3/s. Also, El Carrizo Dam stores water from the Colorado River and controls only a 2.6% of the Tijuana River watershed. This controlled area is not large enough to (a) generate extreme discharges in El Carrizo and (b) produce a significant change of the water balance. Additionally, it is known that since the pumping capacity at the PBCILA Treatment Plant has been increased to 1 m^3/s, all the potential modifications in the baseflow would occur for flows much smaller than 13.6 m^3/s. Therefore, exclusively from the point of view of sediment transport, and according to this analysis, Colorado River transboundary flows, El Carrizo Dam Operation and Treatment Plant Diversion will contribute less than 5% to the sediment problem in the estuary for n=1.2, and less than 1% for n values larger than 1.5.

SECTION 5 CONCLUSIONS

- A sediment yield of approximately 492,000 ton/yr under restored conditions, calculated with the Dendy-Bolton methodology, is expected in the Tijuana River at the entrance to the estuary, accounting for the reducing effect of Barrett and Rodriguez Dams.
- The geologic evidence of sediment deposition in the estuary and other adjacent areas amounts to 125,000 ton/yr in 14 square miles, for a deposition of 9,000 ton/yr/square mile. The pre-dam sediment yield estimate is 1,300,000 ton/yr; therefore, about 10% of the sediment load had been deposited in the Valley.
- ***The estuary and other adjacent depositional areas have been reduced to 25%-30% of their pre-1900 value. Therefore, to maintain the historic depositional rate of 9,000-10,000 ton/yr/sq-mile in the current 3.5 sq-mile estuary, a sediment deposition of 31,000-35,000 ton/yr is the maximum acceptable load, which amounts to 6%-7% of the estimated sediment yield. Consequently, the efficiency of the sediment transport must improve to reduce the natural depositional rate from 9%-10% to 6%-7%.***
- Annual sediment yield will remain highly variable in the future, assuming that peak flows will behave in a statistically similar way to the previous record. Annual sediment yield as low as 50 ton/yr, which is the lowest value estimated from IBWC flow measurements, and as high as 10,500,000 ton/yr, which is the highest estimated value, can be expected.
- The placement of a sediment pond at the entrance of the Valley to significantly reduce the long-term sediment load is infeasible due to space constrains. The point of diminishing returns in terms of size of a sediment pond would be 37,000 acre-ft, while the size for a 50% sediment reduction will be about 4,700 acre-ft. The available space would limit the size of the sediment pond to about 300 acre-ft. The sediment load reduction expected as a result of this sediment pond would be on the order of 5%.
- The variability in sediment discharges implies that 60-75% of the total sediment load can be carried, on average, in less than one day per year, and these days will be part of extreme events.
- A sediment pond in the Valley would be effective most of the actual time, but it would not be effective during extreme events; therefore, most of the sediments would bypass the basin.
- The values obtained in this study are based on generally accepted empirical formulas, and are not intended to precisely describe the complexity of the sediment dynamics in the Tijuana River Watershed. Detailed studies, complemented with sediment load measurements, will be recommended for increased accuracy.
- The findings of this report apply only to the mainstream Tijuana River at its entrance to the Valley. It specifically excludes Smuggler's Gulch, Goat Canyon, Yogurt Canyon and El Cañón del Sol, which discharge downstream of the U.S.-Mexico border.
- The findings of this study suggest a shift in emphasis to erosion control at the watershed level, mainly in Mexico, but also in SPAs located within the U.S.

This page intentionally left blank

SECTION 6 REFERENCES

[1] Ponce, Victor. "Engineering Hydrology. Principles and Practices". 1989, Prentice Hall.

[2] USDA Soil Conservation Service (1983). National Engineering Handbook, Section 3, Sedimentation, 2d. Edition.

[3] International Boundary and Water Commission web page: Data of Tijuana River. Available at: http://www.ibwc.gov/wad/ddqtjrib.htm

[4] USGS National Water Information System: USGS 11013500 Tijuana River. Available at: http://waterdata.usgs.gov/ca/nwis/dvstat/?format=sites_selection_links&search_site_no=11013500&agency_cd=USGS&referred_module=sw

[5] Hydrology and Hydroecology of the Binational Cottonwood Creek – Arrollo Alamar, California and Baja California. 2001. Available at: http://ponce.sdsu.edu/alamarmexicali2001.html

[6] Padilla-Corona, Antonio: "La Presa Abelardo Rodriguez, Modelo de Ingeniería Hidráulica". Article about the history of Abelardo Rodriguez Dam Construction (in Spanish). Available at: http://www.tijuana.gob.mx/ciudad/CiudadLaPresa4.asp

[7] Maidment, David. "Handbook of Hydrology". 1992, McGraw Hill.

[8] Engelund, F. and Hansen, E. (1967). "A Monograph on Sediment Transport in Alluvial Streams", Teknisk Forlag, Copenhagen, Denmark.

[9] Ponce, Victor "The Lane Relation Revisited". Available at: http://lane.sdsu.edu/

[10] Warrik and Milliman, (2003). "Hyperpycnal Sediment Discharge from Semi-arid Southern California Rivers: Implications for Coastal Sediment Budgets". *Geology.*2003; 31: 781-784

[11] Colby, B. R. (1964). "Discharge of Sands and Mean Velocity Relations in Sand-Bed Streams". U.S. Geological Survey Professional Paper 462-A, Washington DC.

[12] Julien, P. Y., and Simons, D. B. (1984). "Analysis of sediment transport equations for rainfall erosion". *Civil Eng. report: CER83-84PYJ-DBS52,* Colorado State University, Fort Collins, CO.

[13] Ponce, Victor from information of Castro, Alberto: "Sediment Retention Basins: To Be or not to Be". Available at: http://ponce.sdsu.edu/legacy_tales_sediment_retention_basins.html

[14] Tetra Tech, January 2010: "Tijuana River Watershed Technical Support Document for Solids, Turbidity and Trash TMDLs". Prepared for USEPA Region IX and San Diego Regional Water Quality Control Board.

[15] Tijuana River Watershed Map. Prepared by San Diego State University (SDSU) and El Colegio de La Frontera Norte (COLEF). Available at http://typhoon.sdsu.edu/tjwater/homepage/tjwnet.html

[16] Ben Urbonas, James C.Y. Guo, Ken MacKenzie: "Description of the WQ-COSM Computer Model to Generate a Water Quality Capture Volume for Stormwater BMPs". Available at: http://urbanwatersheds.org/links/pdf/Description%20of%20the%20WQ-COSM%20Computer%20Model.pdf

[17] Mudie, P.J. and Byrne, R., 1980; "Pollen evidence for historic sedimentation rates in California Coastal Marshes". Estuarine and Coastal Marine Science, 10:305-316.

[18] Brune, G.M., 1953; "Trap efficiency of reservoirs". Transactions, American Geophysical Union, 34, 407-418.

[19] Weis, D.A., Callaway, J.C., and Gersberg, R.M. 2001. "Vertical Accretion Rates and Heavy Metal Chronologies in Wetland Sediment of the Tijuana Estuary". Estuaries, 24(6A): 840-850.

Appendix A Average Peak Flows for the SPA, Upstream and Downstream of Rodriguez and Barrett Dam, and Total Contributing Area Upstream of the Entrance to the Valley for Different Conditions of Dam Release

The 73 years of Data has been divided in 5 Groups and 1 Sub-groups (6 blocks total) depending on the dam releases and nature of the runoff year:

1) Peak flows for 5 season-years when Rodriguez Dam and Barrett Dam release water (Group 1)
2) Peak flows for season-years when only Rodriguez Dam releases water (it has only occurred once, 1977-1978; Group 2)
3) Peak flows when only Barrett Dam releases water: 11 season-years total (Group 3), 5 of which (Sub-Group 3A) are on average almost four times wetter than the other 6
4) Peak flows for wet season-years when no Dam releases water, 5 season-years total (Group 4)
5) Peak flows for normal to dry season-years when no Dam releases water, 51 season-years total (Group 5).

Mathematical Determination of Average Peak Flows

The 36 variables are the following:

Q_{T_j} : Average total peak flow for the group "j" (j = 1, 2, 3, 3A, 4, 5)

$Qi_{R,j}$: Average incoming peak flow to Rodriguez Dam for the group "j" (j = 1, 2, 3, 3A, 4, 5)

$Qo_{R,j}$: Average discharge peak flow to Rodriguez Dam for the group "j" (j = 1, 2, 3, 3A, 4, 5)

$Qi_{B,j}$: Average incoming peak flow to Barrett Dam for the group "j" (j = 1, 2, 3, 3A, 4, 5)

$Qo_{B,j}$: Average discharge peak flow to Rodriguez Dam for the group "j" (j = 1, 2, 3, 3A, 4, 5)

$Q_{SPA,j}$: Average peak flow from Sediment Producing Areas (SPA or areas not controlled by dams) for the group "j" (j = 1, 2, 3, 3A, 4, 5). SPA does not include contributing area of canyons nor Tijuana Valley. Incoming and discharge peak flows are the same as no reservoir is reducing the average ($Q_{SPA,j} = Qi_{SPA,j} = Qo_{SPA,j}$) .

There are 13 variables that can be measured directly from the data:

Q_{T_j} : Six variables that can be calculated from the data (j=1, 2, 3, 3A, 4, 5)

$Qo_{R,j} = 0$. Four variables representing lack of discharge from Rodriguez Dam (j = 3, 3A, 4, 5)

$Qo_{B,j} = 0$. Three variables representing lack of discharge from Barrett Dam (j = 2, 4, 5)

There are 26 variables that must be estimated using equations and assumptions, so 23 independent equations are needed:

a) Continuity equation, applied 6 times

$QT_j = Qo_{R,j} + Qo_{B,j} + Q_{SPA,j}$ (j = 1, 2, 3, 3A, 4, 5) (equations (1) to (6))

b) Proportionality between volume of precipitation and runoff, applied 12 times.

$$\frac{V_R}{V_{SPA}} = \frac{A_R \cdot P_R}{A_{SPA} \cdot P_{SPA}} = \frac{Qi_{R,j}}{Q_{SPA,j}} \qquad (j = 1, 2, 3, 3A, 4, 5) \qquad \text{(equations (7) to (12))}$$

$$\frac{V_B}{V_{SPA}} = \frac{A_B \cdot P_B}{A_{SPA} \cdot P_{SPA}} = \frac{Qi_{B,j}}{Q_{SPA,j}} \qquad (j = 1, 2, 3, 3A, 4, 5) \qquad \text{(equations (13) to (18))}$$

In those equations V_R, V_B, V_{SPA} is the volume of precipitation of areas contributing to Rodriguez Dam, to Barrett Dam and to SPA respectively; A_R, A_B, A_{SPA} is the contributing area in square miles to Rodriguez Dam, to Barrett Dam and to SPA (equal to 980.2 mi^2, 234.9 mi^2 and 436.7 mi^2 respectively), and P_R, P_B, P_{SPA} is the average annual precipitation for the areas contributing to Rodriguez Dam, Barrett Dam and SPA (approximate values of 11", 19" and 10.5" respectively per the Map of reference [15]).

c) Water usage assumptions by Dams (5 equations)
It is assumed that the water usage of Rodriguez Dam is maximum for sub-group 3A, and it will be the same than the water usage for group 1 and 2 (the other groups when Rodriguez Dam is discharging):

$Qi_{R,3A} - Qo_{R,3A} = Qi_{R,j} - Qo_{R,j}$ (j = 1, 2) (equations (19) and (20))

The water usage of Barrett Dam is particularly high for Group 2 (the dam was at a very low elevation at the beginning of the water year) and larger than in any other scenario to satisfy the continuity equation (2), the proportionality equation (8) and the water usage equation (20). Consequently, it is assumed that the weighted average between the water usage of Barrett Dam for group 2 and for group 4 (wettest groups with no release of water by Barrett Dam) corresponds to the water usage of Barrett for groups 1, 3 and sub-group 3A:

$$\frac{365Qi_{B,2} + 1828Qi_{B,4}}{2193} = Qi_{B,j} - Qo_{B,j} \qquad (j = 1, 3, 3A) \qquad \text{(equations (21) to (23))}$$

The methodic and simultaneous solution of the 23 linear equations with 23 unknowns allows for the determination of the values displayed in Table 2-1.