TRENDS IN SUSPENDED SEDIMENT INPUT TO THE SAN FRANCISCO BAY FROM LOCAL TRIBUTARY WATERSHEDS

Prepared for
San Francisco Estuary Institute

Prepared by
Philip Williams & Associates, Ltd.

December 2005

PWA REF. #1765
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2. DATA SOURCES</td>
<td>2</td>
</tr>
<tr>
<td>3. CONCEPTUAL MODEL</td>
<td>4</td>
</tr>
<tr>
<td>3.1 Overview of Geomorphic Processes</td>
<td>4</td>
</tr>
<tr>
<td>3.2 Conceptual Model for Spatial Variability</td>
<td>7</td>
</tr>
<tr>
<td>3.3 Conceptual Model for temporal variability</td>
<td>10</td>
</tr>
<tr>
<td>4. DATA ANALYSIS</td>
<td>16</td>
</tr>
<tr>
<td>4.1 The Relation of Suspended Sediment load to Watershed Characteristics</td>
<td>16</td>
</tr>
<tr>
<td>4.1.1 Spatial Variables</td>
<td>16</td>
</tr>
<tr>
<td>4.1.2 Regression Analysis of Spatial Variables</td>
<td>22</td>
</tr>
<tr>
<td>4.2 Temporal Trends in Suspended Sediment Load</td>
<td>23</td>
</tr>
<tr>
<td>5. RESULTS AND DISCUSSION</td>
<td>25</td>
</tr>
<tr>
<td>5.1 Spatial Trends</td>
<td>25</td>
</tr>
<tr>
<td>5.2 Temporal Trends</td>
<td>36</td>
</tr>
<tr>
<td>6. SUMMARY AND CONCLUSIONS</td>
<td>59</td>
</tr>
<tr>
<td>7. REFERENCES</td>
<td>61</td>
</tr>
<tr>
<td>8. LIST OF PREPARERS AND ACKNOWLEDGEMENTS</td>
<td>64</td>
</tr>
</tbody>
</table>

## LIST OF FIGURES

- Figure 1 - Sediment Processes and Movement throughout the Watershed | 5
- Figure 2 - Watershed Map of the San Francisco Bay Local Tributaries | 9
- Figure 3 - Timeline of land use changes in San Francisco Bay Area | 11
- Figure 4 - Aerial Photograph of the San Francisco Bay Area | 15
- Figure 5 - Percent Sand Content in the Corte Madera Creek Watershed | 17
- Figure 6 - Land Use Characteristics in the Corte Madera Creek Watershed | 18
- Figure 7 - Landslide Susceptibility in the Corte Madera Creek Watershed | 19
- Figure 8 - Correlation of sediment load and drainage area | 27
- Figure 9 - Correlation of specific sediment load and drainage area | 28
Figure 10 - Correlation of sediment load and annual runoff  
Figure 11 - Correlation of sediment load and relief  
Figure 12 - Dominant Processes for Different Climatic, Topographic, and Vegetative Characteristics  
*Figure 13 to 30 – Results Section, Section 5-2

**Figure 31 - Significant Trends in Suspended Sediment Loads for Four Long Term Stations**
1. INTRODUCTION

Traditional perspectives on the San Francisco Bay sediment budget have emphasized the importance of sediment inflow from the Sacramento and San Joaquin watersheds. However, several studies in the last three decades have suggested a decreasing trend in sediment inputs to the San Francisco Bay from the Sacramento and San Joaquin Rivers (Krone, 1979; Porterfield, 1980; Ogden Beeman & Associates, 1992; Wright and Schoellhamer, 2004; McKee et al, 2002). In response, sediment loads from local tributaries represent an increasingly larger percentage of the overall sediment budget of the Bay. McKee et al (2003) suggested that about forty percent of the total sediment inputs to the Bay are supplied by the urbanized and agricultural watersheds around the Bay, even though these comprise less than five percent of the Bay’s total watershed area.

Sediment input to San Francisco Bay from fluvial sources is an important component of ecosystem function. It provides substrate for marsh development, which is particularly important given ongoing (and likely accelerated) sea level rise. Sediment is also an important component in the transport of nutrients, as well as pollutants in the ecosystem. San Francisco Bay is listed as impaired for contaminants including PCBs, mercury, and organochlorine pesticides. These contaminants are derived from anthropomorphic change in the watersheds, including legacy mining activities and the urban areas of watersheds around the Bay. Most of the mercury was produced during the California gold rush in the late 1800’s. However, the transport and delivery of these contaminants to the Bay continues, primarily through suspended sediment transport. Due to the increasing relative importance of local tributary sediment inputs and the importance of sediment as the main vector in transporting these persistent and bioaccumulative contaminants, it is important to understand the history of suspended sediment load from local tributaries, to understand the effects of basin and land use characteristics on the suspended sediment yields from the Bay watersheds, and to improve our quantitative tools for predicting sediment yields.

The Sources Pathways and Loading Workgroup (SPLWG) of the Regional Monitoring Program for Trace Substances (RMP) recommended that several watersheds be studied to estimate sediment and contaminant loads and develop methods to extrapolate data from well-monitored areas to watersheds where data is not collected. SPLWG seeks guidance on the use of sediment data to predict pollutant transport, and on the predictability of sediment supply to the Bay, based on easily measurable parameters. The current study is designed to provide this information.

Philip Williams & Associates, Ltd. (PWA) is working together with the San Francisco Estuary Institute (SFEI) to develop a statistically based model that links sediment transport to stream flow regime. In addition, the study will identify if temporal trends are detectable in the available record of suspended sediment loads from local tributaries to the San Francisco Bay. Finally, we will determine if easily measured watershed characteristics provide a method of refining our ability to predict suspended sediment concentrations and loads. The goals of the study are to determine the feasibility of extrapolating the available measured suspended sediment data set in space and time to a broader range of local tributaries.
2. DATA SOURCES

PWA compiled a sediment database, containing data from thirty six suspended sediment gauges (Table 1) in the San Francisco Bay Area. Sediment gauge data was provided by the United States Geological Survey (USGS), Los Medanos College, the Joint Powers Authority, the San Pablo Watershed Neighbors Education and Restoration Society, the Sonoma Ecology Center, and the San Francisco Estuary Institute. We attempted to use all available data; however, certain gauges contained incomplete records, and thus were not included in the statistical analysis. The primary source for suspended sediment data used in this report is the United States Geological Survey. Typical suspended sediment measurement parameters collected at the gauges include water discharge, suspended sediment concentration, and suspended sediment load. Other parameters may include turbidity and transparency. The sediment database is a comprehensive accounting of readily available data by various organizations and agencies and of the suspended sediment monitoring efforts around the San Francisco Bay by the USGS. It was used to investigate the temporal trends in suspended sediment yield from local tributaries to the Bay.

Spatial trends of suspended sediment yield were studied using numerous GIS. Digital Elevation Models (DEMs) were downloaded from the USGS National Elevation Dataset (http://ned.usgs.gov/), and stream channels were derived from the USGS National Hydrography Dataset (http://nhd.usgs.gov/index.html). GIS coverages of rainfall threshold values and landslides were taken from …… and USGS Open File Report 97-745, respectively. Information on soil characteristics for the GIS database were taken from the SSURGO soil survey from the Natural Resource Conservation Service (NRCS) (http://soils.usda.gov). The Association of Bay Area Governments (ABAG) provided land use data from 2003. Mean annual rainfall values were obtained from the NRCS PRISM data collection (USDA, 2003). Spatial information for all watersheds was derived from these resources except Pinole Creek watershed. Spatial watershed variables for Pinole Creek is based on field data collection by Sarah Pearce.
<table>
<thead>
<tr>
<th>PWA Gage ID</th>
<th>Watershed Name</th>
<th>Watershed Area Above Gage (km²)*</th>
<th>Current Period of Record</th>
<th>Years</th>
<th>Qs</th>
<th>SSC</th>
<th>Daily</th>
<th>15 Minute</th>
<th>Annual Sampled</th>
<th>Latitude</th>
<th>Longitude</th>
<th>County</th>
<th>Agency</th>
<th>Agency ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Alameda Creek at Niles, CA</td>
<td>592</td>
<td>1960-1973, 2000-2004</td>
<td>18</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>37.6572</td>
<td>121.6997</td>
<td>Alameda</td>
<td>USGS</td>
<td>11179000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Arroyo de la Laguna near Pleasanton, CA</td>
<td>683</td>
<td>2000-2003</td>
<td>4</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>37.6150</td>
<td>121.8806</td>
<td>Alameda</td>
<td>USGS</td>
<td>11179000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Arroyo Valley near Livermore, CA</td>
<td>381</td>
<td>1963-1987</td>
<td>5</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>37.6233</td>
<td>121.7578</td>
<td>Alameda</td>
<td>USGS</td>
<td>11179000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Colma Creek at South San Francisco, CA</td>
<td>28</td>
<td>1966-1976</td>
<td>11</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>37.6539</td>
<td>122.4253</td>
<td>San Mateo</td>
<td>USGS</td>
<td>11162720</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Corte Madera Creek at Ross, CA</td>
<td>47</td>
<td>1978-1989</td>
<td>3</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>37.9625</td>
<td>122.5556</td>
<td>Marin</td>
<td>USGS</td>
<td>11160600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Coyote Creek near Gilroy, CA</td>
<td>282</td>
<td>1962-1970</td>
<td>9</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>37.0278</td>
<td>121.4933</td>
<td>Santa Clara</td>
<td>USGS</td>
<td>11168000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Crow Creek near Hayward, CA</td>
<td>27</td>
<td>2000-2003</td>
<td>4</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>37.705</td>
<td>122.0428</td>
<td>Alameda</td>
<td>USGS</td>
<td>11160900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Cull Creek below Cull Creek Dam near Castro Valley, CA</td>
<td>1</td>
<td>1979</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>37.6722</td>
<td>122.0542</td>
<td>Alameda</td>
<td>USGS</td>
<td>11160900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Cull Creek above Cull Creek Reservoir</td>
<td>15</td>
<td>1979-2003</td>
<td>23</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>37.7178</td>
<td>122.0033</td>
<td>Alameda</td>
<td>USGS</td>
<td>11160900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Guadalupe River above 101 at San Jose, CA</td>
<td>414</td>
<td>2003-2005</td>
<td>3</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>37.3739</td>
<td>121.9319</td>
<td>Santa Clara</td>
<td>USGS</td>
<td>11160925</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Kirk Creek</td>
<td>46</td>
<td>2002-2004</td>
<td>2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>38.9652</td>
<td>122.0022</td>
<td>Napa</td>
<td>USGS</td>
<td>11458000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Napa River near Napa, CA</td>
<td>569</td>
<td>1977-1978</td>
<td>9</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>37.3333</td>
<td>122.0542</td>
<td>Napa</td>
<td>USGS</td>
<td>11458000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Pinole Creek</td>
<td>10</td>
<td>1985-1987</td>
<td>3</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>37.3084</td>
<td>122.2678</td>
<td>Contra Costa</td>
<td>USGS</td>
<td>11165675</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>San Francisco Creek at Stanford University, CA</td>
<td>51</td>
<td>1962-1969</td>
<td>8</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>37.4423</td>
<td>122.1983</td>
<td>Santa Clara</td>
<td>Joint Powers Authority</td>
<td>USGS</td>
<td>11181390</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>San Lorenzo Creek at San Lorenzo, CA</td>
<td>70</td>
<td>1992</td>
<td>1</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>37.6842</td>
<td>122.1389</td>
<td>Alameda</td>
<td>USGS</td>
<td>11187000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>San Lorenzo Creek above Don Castro Reservoir</td>
<td>47</td>
<td>1981-2003</td>
<td>23</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>37.6953</td>
<td>122.0438</td>
<td>Alameda</td>
<td>USGS</td>
<td>11180825</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>San Pablo Creek at Appian Way</td>
<td>112</td>
<td>2002-2004</td>
<td>3</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>38.3029</td>
<td>122.6044</td>
<td>Napa</td>
<td>Sonoma Ecology Center</td>
<td>323</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Sonoma Creek</td>
<td>46</td>
<td>2002-2004</td>
<td>3</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>38.3119</td>
<td>122.5475</td>
<td>Napa</td>
<td>Sonoma Ecology Center</td>
<td>379</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Walnut Creek at Concord, CA</td>
<td>221</td>
<td>1976</td>
<td>1</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>37.9453</td>
<td>122.0448</td>
<td>Contra Costa</td>
<td>USGS</td>
<td>11183600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>West Fork Permanente Creek near Monte Vista, CA</td>
<td>8</td>
<td>1985-1986</td>
<td>2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>37.3331</td>
<td>122.0542</td>
<td>Contra Costa</td>
<td>USGS</td>
<td>11183600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Wildcat Creek at Vale Road at Richmond, CA</td>
<td>20</td>
<td>1978-1980</td>
<td>3</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>37.9533</td>
<td>122.5722</td>
<td>Contra Costa</td>
<td>USGS</td>
<td>11183600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Garnet Creek (RCD site- tributary to Napa River)</td>
<td>NA</td>
<td>2001-2002</td>
<td>NA</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>38.5929</td>
<td>122.9008</td>
<td>Napa</td>
<td>Sonoma Ecology Center</td>
<td>289</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Miliken Creek (RCD site- tributary to Napa River)</td>
<td>NA</td>
<td>2003-2004</td>
<td>NA</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>38.3420</td>
<td>122.2647</td>
<td>Napa</td>
<td>Sonoma Ecology Center</td>
<td>302</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Napa River</td>
<td>NA</td>
<td>2000-2003</td>
<td>NA</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>38.5115</td>
<td>122.5475</td>
<td>Napa</td>
<td>USGS</td>
<td>11456000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Zone II Line B</td>
<td>2</td>
<td>2000-2002</td>
<td>3</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>38.4897</td>
<td>121.6166</td>
<td>Alameda</td>
<td>USGS</td>
<td>11172385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Camerson Creek (RCD site- tributary to Napa River)</td>
<td>NA</td>
<td>2003-2004</td>
<td>NA</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>38.2779</td>
<td>122.3618</td>
<td>Napa</td>
<td>Sonoma Ecology Center</td>
<td>190</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Camerson Creek (RCD site- tributary to Napa River)</td>
<td>NA</td>
<td>2002-2004</td>
<td>NA</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>38.2592</td>
<td>122.3628</td>
<td>Napa</td>
<td>Sonoma Ecology Center</td>
<td>190</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Camerson Creek (RCD site- tributary to Napa River)</td>
<td>NA</td>
<td>2004</td>
<td>NA</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>38.2965</td>
<td>122.3628</td>
<td>Napa</td>
<td>Sonoma Ecology Center</td>
<td>190</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Hopper Creek (RCD site- tributary to Napa River)</td>
<td>NA</td>
<td>2001</td>
<td>NA</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>38.4053</td>
<td>122.3618</td>
<td>Napa</td>
<td>Sonoma Ecology Center</td>
<td>190</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Hopkins Creek (RCD site- tributary to Napa River)</td>
<td>NA</td>
<td>2007</td>
<td>NA</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>38.3941</td>
<td>122.3645</td>
<td>Napa</td>
<td>Sonoma Ecology Center</td>
<td>190</td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>Hulchica Creek (RCD site- tributary to Napa River)</td>
<td>NA</td>
<td>2001-2004</td>
<td>NA</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>38.2204</td>
<td>122.3541</td>
<td>Napa</td>
<td>Sonoma Ecology Center</td>
<td>190</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>Miliken Creek (RCD site- tributary to Napa River)</td>
<td>NA</td>
<td>2002-2003</td>
<td>NA</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>38.3834</td>
<td>122.2988</td>
<td>Napa</td>
<td>Sonoma Ecology Center</td>
<td>190</td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>Murphy Creek (RCD site- tributary to Napa River)</td>
<td>NA</td>
<td>2003-2004</td>
<td>NA</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>38.3223</td>
<td>122.2899</td>
<td>Napa</td>
<td>Sonoma Ecology Center</td>
<td>190</td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>Salvadore Creek (RCD site- tributary to Napa River)</td>
<td>NA</td>
<td>2004</td>
<td>NA</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>38.3223</td>
<td>122.2899</td>
<td>Napa</td>
<td>Sonoma Ecology Center</td>
<td>190</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Watershed area does not include area above the reservoir.
3. CONCEPTUAL MODEL

The Conceptual Model briefly describes the mechanisms by which sediment is transported from the watersheds to the San Francisco Bay. It depicts the natural sources of variability in sediment production and delivery processes and describes how these processes have been altered by human-induced change following the European settlement of the San Francisco Bay Area. This serves as the background for the current study and provides a physical basis for possible temporal and spatial trends in the suspended sediment yield. The Model incorporates a brief overview of geomorphic processes in Bay watersheds with the affect on sediment yield of physical watershed characteristics and the history of change throughout the local tributaries to the Bay. We cataloged spatial characteristics of Bay watersheds, identifying those parameters most likely to be effective in the prediction of sediment yield. To identify possible causes for temporal trends, we reviewed the history of land use changes in Bay watersheds. This provides a qualitative understanding of the effects of particular land use on sediment yield. At present, the effect that different land uses had on sediment yield around the Bay cannot be quantified due to lack of data.

3.1 OVERVIEW OF GEOMORPHIC PROCESSES

The local tributaries to the San Francisco Bay store and transport sediment received from various hillslope and channel processes. The dominant sediment sources in the Bay area watersheds are landslides, gullies, bed and bank erosion, rills and sheetwash. Once the sediment reaches the channel, it is either temporarily or permanently stored in sediment sinks including alluvial fans, channel bars, floodplain deposits, and wetlands. Sediment sources across the watershed contribute sediment variably depending upon geology, vegetation, slope, soil, and hydrologic conditions. In addition to these natural physical variables, land use is a key determinant in sediment generation. Sediment sources and erosion types in coastal streams and San Francisco Bay tributaries have been characterized in several studies over the past 30 years (Cooke and Reeves, 1977; Madej et al, 1986; Dietrich and Montgomery, 1994; Inman and Jenkins, 1999; Heimsath, 1997; Willis and Griggs, 2003; McKee et al., 2003). This study does not provide a comprehensive discussion of the geomorphic processes in the San Francisco Bay watersheds. Please refer to McKee et al study (2003) that includes detailed literature review of dominant geomorphic processes around the Bay and that presents available quantitative information on sediment processes.

The erosional processes in the local watersheds of the Bay can be summarized by four categories extending downstream from the watershed divide: headland and hillslope processes; tributary and sub basin channels; main stem channels and floodplain; and ‘other general watershed sources’. This watershed based sediment source classification is illustrated in Figure 1.
Watershed Processes

Sediment Production

- Hillslope mass movement of sediment (landslides, debris flows, etc.)
- Gradual downslope movement of sediment (sheetwash, soil creep, dry ravel, etc.)
- Gullies

Sediment Transport & Storage

- Bed incision
- Bank erosion
- Channel bars

Fluvial Sediment Delivery

- Delta & alluvial fans
- Floodplain deposits

Channel Processes

- A source zone
- B transport zone and temporary deposition zone
- C deposition zone

Note:
Schematic illustrates the geomorphic processes & zones in a typical local watershed. The watershed and the depicted geomorphic features are hypothetical.

Figure 1

Trends in Suspended Sediment Input to the San Francisco Bay from Local Watersheds

Geomorphic Processes in San Francisco Bay Local Watersheds
The headwater zone of the tributary channels to the Bay is primarily a source for sediment through headland and hillslope processes. Hillslope mass movements including landslides, debris flows, and gullies and gradual downslope movements of sediment including sheetwash soil creep and dry ravel contribute sediment to the channels in this zone. The efficiency by which the sediment is delivered and transported downstream depends on the hillslope-channel connectivity. Once sediment is delivered to the channels, it moves rapidly downstream with minimal channel and valley bottom storage because the channels in this zone tend to be steep and narrow, and thus efficient sediment conveyiers.

Tributary and sub-basin channels provide the sediment transport link between headwater zone and the lower main stem channel. They constitute the transport zone where channels have moderate gradients, moderate confinement and well-developed floodplains. Large amounts of sediment are stored along primarily valley bottoms and to a lesser degree in channels. Sediment in storage throughout this transport zone has a longer residence time than sediment in the source zone. Many of the channels in the Bay Area have the characteristics of channels in the transport zone. In many cases tributary channels are incised. Concentrated runoff in incised tributary channels can scour channel beds and undermine banks further mobilizing sediment. The transport zone of many tributary channels in the local watersheds of the Bay is typified by deep head cuts and steep unvegetated banks. Sub-basin tributary channels also convey finer materials directly downstream without storage depending upon the flow event magnitude.

The main stem channels and floodplains of the Bay Area creeks represent both the transport and deposition zones. They are more limited sediment sources than the headlands and sub-basin areas unless subjected to significant channelization or other flood management activities. Due to the history of significant channel management in the Bay Area watersheds, some of the main stem channels are incised and widened or are currently undergoing erosion. These streams may presently be contributing sediment through channel bed and bank erosion or through the upstream movement of knickpoints remnant from earlier incision history. However, main stem channels and floodplains often characterize transport and depositional zones. Indeed, similar to the sub-basin creeks, these channels are the direct transport conduit to the Bay. Degree of sediment transport, or net removal, along the main stem channels is a function of flow event magnitude, duration and channel hydraulic parameters (e.g., geometry, roughness, bed material, sheer stress, etc.). The channels in this zone also act as sediment sinks, where the sediment transported from the uplands is stored for different periods of time along the floodplains, channel bars, alluvial fans and deltas, and wetlands. Sediment stored in the channels may be removed from the system before being transported to the Bay due to ongoing dredging activities.

There are other sediment sources around the local tributary watersheds in the San Francisco Bay. These sources include farms and ranches (especially vineyards in the North Bay), urban construction activities, roads, culverts, mines, and other impacted surfaces. These anthropogenic sources are found throughout the watersheds and contribute sediment to the San Francisco Bay local tributaries.
These processes represent the shorter term impacts that affect the sediment budgets and the morphologies of the local tributaries to the San Francisco Bay. The Bay watersheds are subject to numerous external natural forces that affect their evolution in the long term. The sea level rise, a function of climate change, alters the base level condition for the main stem channels, decreasing their overall slope and associated conveyance characteristics. Sea level rise creates significant increases in the volume acting as a sediment sink as sea level rises further above the current base level. At the opposite ends of the watersheds, tectonic uplift raises the upper watersheds, increasing slopes and probably sediment supplies. In the lower reaches of the watersheds, subsidence – both tectonic and anthropomorphic in origin – can alter slopes and increase accommodation space as land levels drop relative to sea level. Hydrologic change, a function of both climate change and anthropomorphic influence, will also be reflected in the morphology and sediment budgets of the tributary watersheds. As climate change shifts precipitation towards greater rainfall, runoff from the watersheds will tend to occur more often as shorter-duration flood flows with distinct peaks and the seasonality of runoff may shift earlier in the year. To the extent that all of these external forcing functions occur trigger adjustments in the landscape, they will produce gradual but important changes in the local tributary watersheds to the San Francisco Bay.

3.2 CONCEPTUAL MODEL FOR SPATIAL VARIABILITY

A number of spatial watershed variables are thought to affect sediment load either directly or indirectly. In the following paragraphs, we summarize the anticipated effects that various watershed characteristics, determined from empirical geomorphic knowledge of San Francisco Bay tributaries and previous studies (Bent, 2001; Madej, 1986; Anderson, 1970), have on sediment load. The primary watershed characteristics expected to control sediment yield and that we explored in this study are drainage area, topography, climate, hydrology, geology/soils, and land use.

Watershed specific sediment yield (amount per area) is expected to be inversely related to drainage area. Previous researchers observed decreases in sediment yield with increasing drainage area (e.g. Brune, 1948: Langbein and Schumm, 1958: Dendy and Bolton, 1976: Milliman and Syvitski, 1992). This occurs because smaller catchments are often in the headwaters of larger ones, and have a higher average slope gradient and a less systematic decrease in gradient downstream along the stream course. In addition, there may be changes in other variables in the downstream order -including precipitation, vegetation, or lithology, which would have an effect on sediment yield.

Topography is has a direct effect on sediment processes. Watersheds with a larger percentage of steeper slopes produce more sediment in transport-limited situations (Dietrich and Montgomery, 1994; Wohl et al., 1998). Steeper slopes initiate more frequent mass wasting events and contribute to the transport of loose particles on the hillslope and in the channel.

Sediment processes also depend on precipitation, which acts as a driver for natural erosion processes. Under otherwise equivalent conditions, higher rates of precipitation and higher precipitation variability should result in higher rates of erosion from slopes, incision by streams into valley sides, and the transport of supplied sediment to the basin outlet (Hooke, 2000). Wilson (2001) and McKee et al. (2003)

P:\Projects\1765_SFBay_Local_Sediment_Budget\Report\1765_TOC_v15-OutDec9.doc
emphasized the importance of rainfall in generating runoff and increasing sediment production in watersheds in the San Francisco Bay Area. Higher rainfall increases the likelihood of sediment-producing events, and therefore a higher sediment load. As a first approximation, mean annual precipitation is a measure of the differing amounts of rainfall throughout the Bay Area, or specifically between different gauged watersheds. Similarly, mean annual precipitation gradient may be a proxy for the effect that the topography of a given watershed has on increasing precipitation in that basin. Basins with high topographic relief typically display a wider range in precipitation, owing to orographic effects on precipitation (Roe et al., 2002) and changes in barometric pressure and temperature with elevation.

Sediment production and delivery from a watershed also depends in part on the availability of loose material to be transported (Wohl et al., 1998). Bent (2001) determined that sediment load in Massachusetts watersheds was well correlated with the presence of surficial material left behind from glaciers. In California, such surficial material is generally lacking, owing to the fact that glaciation was not widespread in this region. However, the sand content in soils is considered a proxy for loose, available material, and soil erodibility also provides an indication of the erosive nature of surface materials.

McKee et al (2003) emphasized the importance of hillslope failure in the San Francisco Bay Area, either by debris flow or landslides, in producing loose sediment directly supplied to channels, or in indirectly generating loose sediment eventually supplied to the channel through future runoff. To quantify the likelihood of future debris flow generation, Wilson and Jayko (1997) generated maps of “Rainfall Thresholds”. The Rainfall Threshold links the capacity of rainstorms to initiate debris flows with the antecedent moisture conditions present in the watershed. Gradually, as more rainstorms occur throughout the winter, more moisture is stored in the soil increasing the likelihood of hillslope failure and debris flow initiation. To generate the Rainfall Threshold maps, Wilson and Jayko (1997) combined annual and seasonal rainfall data with data on slope steepness, another positive contributing factor to debris flows. The resultant Rainfall Threshold data was separated into 6 hour and 24 hour maps to address the likelihood of debris flow initiation for differing storm magnitudes.

Ground cover is the resisting force to erosional forcings. Poor cover or lack of vegetation contributes to rill, gully, and arroyo formation, which historically is one of the greatest contributors to sediment production and delivery in California watersheds (Cooke and Reeves, 1976; Haltiner and Thor, 1991). Urban, or impervious areas, contribute less sediment to a watershed or channel; however the increase in runoff associated with impervious land uses can increase the peak discharge and volume of water delivered to the channel. This effect (referred to as “hydromodification”) can cause channel instability and increased erosion and sediment load downstream, and/or transport sediment supplied from upstream reaches of the watershed (McKee et al., 2003, Dunne and Leopold, 1978).

We explored the possible relationship between several watershed characteristics that might capture the above effects and sediment yield through multiple regression analysis. The null hypothesis for spatial variability in suspended sediment is that watershed characteristics, or other easily measured parameters, do not improve our ability to predict sediment yield from local tributaries to the San Francisco Bay.
Trends in Suspended Sediment Input to the San Francisco Bay Watershed and Gage Location Map

Figure 2

Ref. 1765
3.3 CONCEPTUAL MODEL FOR TEMPORAL VARIABILITY

The temporal variability of sediment yield to the Bay from local tributaries can be explored within two very different contexts: before and after the European settlement of the area. Prior to the European settlement, sediment yield from local watersheds was likely in a state of dynamic equilibrium: variations year to year were driven by the natural processes of rainfall and stream flow and the production of sediment in the watershed. Gradual progressive changes in sediment supply would have resulted from tectonic processes. Since the European settlement of the Bay Area, there has been a series of land use changes in the local watersheds that have had significant impacts on sediment yield at an unprecedented rate (see Figure 3 as an example of the timeline of changes in the Los Gatos Watershed).
Figure 3

Trends in Suspended Sediment Input to the San Francisco Bay from Local Watersheds

Timeline of Landuse Changes in San Francisco Bay Area
The nature of equilibrium conditions in a given watershed and watershed processes during the pre-settlement era will be discussed briefly in the following paragraphs. History of land use in the Bay watersheds and the qualitative effects of land use changes on sediment yield will also be presented. Specific land uses that will be included in this discussion are the introduction of grazing, urbanization, and flood control projects. How a particular change may have affected sediment conveyance to the Bay over time can not be specified due to insufficient historic data and the impacts that legacy land use features have on past, present, and future sediment dynamics.

San Francisco Bay and its watershed are part of an integrated physical system in which cascading arrangements of mass (i.e. sediment) pass through the morphological components of the system (i.e. landforms) over varied time scales. The components mutually adjust to changes in inputs of mass, frequently with negative feedback arrangements, which allow the system to be self-regulating. Self-regulation is usually directed toward an equilibrium state where the inputs of energy and mass are equal to the outputs from the system. There are several forms of equilibrium state including static, stable, unstable, metastable, steady-state and dynamic (Chorley and Kennedy, 1971). The time scale of interest strongly influences the view of system stability and the cause of any induced change.

In the short term (e.g., one to one hundred years), there may be unceasing adjustment between the system components. Variable conditions produce fluctuations about an average value (i.e., stable equilibrium). The long term (e.g., one to several hundred years) can involve the establishment and maintenance of a characteristic set of landforms within a system that persist through time, although individual components will be evolving and the pattern and interrelationships of these features will be continuously changing (i.e., steady-state equilibrium). In the very long term (e.g., a thousand to several hundred thousand years), progressive or major episodic changes become more apparent (i.e., dynamic or metastable equilibrium, respectively).

San Francisco Bay started to form approximately 10,000 years ago with the onset of a climatic warming trend known as the “Holocene Transgression” during which rapid sea level rise (approximately 20 mm/year after Atwater et al., 1979) intruded inland to form the estuary and the delta. By 6,000 years bp, the general form and large-scale features of the Bay watershed we know today had emerged. Over the last six millennia until the arrival of the Europeans, sediment yield to the Bay from local watersheds was in a state of dynamic equilibrium with very long-term progressive environmental change and short-term stochastic perturbations. Short-term variations in sediment yield were due to watersheds responding to constantly changing environmental conditions driven by the natural processes of rainfall and stream flow, and the production of sediment in the watershed.

Large-scale colonization and settlement of the San Francisco Bay watersheds have come with substantial changes to riverine and coastal floodplains (Figure 4). These land-use changes are documented in detail elsewhere (e.g. Gilbert, 1917; The Bay Institute, 1998) and each have had the effect of inducing a disturbance to the geomorphic integrity of the individual components of the system (upland domain, river reaches, etc.). As a result of significant and both episodic and persistent human interventions, it is
apparent that the steady-state condition of small, steady long-term change in storage no longer applies to the local watersheds of the San Francisco Bay. Instead, the rate of change of storage has been and likely is progressively changing in each river reach.

The introduction of grazing in the early 1800s initiated much of the subsequent, dramatic change in the Bay watersheds and the morphology of the creeks. Grazing reduces vegetative cover, compacts the soils, and physically dislodges soil articles. These physical impacts increase runoff volumes and erosion rates from uplands and decrease the lag time between the beginning of the storm and peak runoff flows. Over time, the denudation of grasses from the hillsides and destruction of trees along the channel banks result in increased sediment production in the watershed. Grazing also initiates the development of gullies and distinct channels where previously only ephemeral vegetated swales existed, resulting in higher sediment yields. In addition, the direct impacts of grazing on the riparian zone include the removal of forage and trampling of the banks which destroy riparian vegetation, compact the soil and break down down stream banks. Increased flow volumes and velocities and decreased bank stability due to grazing initiate a process of arroyo cutting or incision into the surrounding landscape. As the channels deepens, larger flows are confined to the channels and can no longer access the overbank floodplain area, causing further erosion and bank instability.

The process of channel incision is common in California. Once downcutting is initiated, the process can persist over centuries. Essentially, the channel is tending toward a new equilibrium slope and greater width which together will reduce flow velocities. Thus, downcutting will continue until this new configuration is achieved or until the channel encounters erosion-resistant subsurface materials. Another important characteristic of an incising channel is the tendency for channel erosion to proceed upstream through the watershed (often as “knickpoints” or abrupt drops in the channel bottom elevation). Thus, different portions of the watershed may be experiencing different erosion rates.

Subsequent urban development in the Bay watersheds most probably had heterogeneous impacts on the sediment production and delivery processes. The generally accepted model of the impact of urbanization on sediment production is that of a brief increase in erosion while urban construction is under way, followed by lack of erosion once the system is stabilized and matured (Wolman, 1967). At the same time that upland areas are being stabilized and are becoming increasingly impervious, magnitude and flashiness of runoff increase during small to moderate precipitation events. This increase in runoff accompanied by a decrease in erosion results in channel erosion, siltation of downstream channels, and increased sediment yields to the Bay. Following completion of urban development, sediment yield decreases and full impact of runoff increases are felt, usually excavating the previously deposited sediment and enlarging the channel cross section to accommodate the flows. Increased runoff may have resulted in more efficient hydraulic connections between tributaries and main channels, also effectively conveying more sediment to the Bay.

Urbanization is often accompanied by channel management activities; in conjunction with urban development, creeks are channelized for flood control purposes. Channelization results in higher conveyance of runoff and decreased sediment storage. Flood flows contained within the banks transport
more sediment than a natural channel that has overbank flows. Typically, during construction, channelization releases a considerable amount of sediment from the channel bank and bed. Further sediment release and subsequent increases in sediment yield should be expected where steepened and unvegetated banks are unstable. However, sediment yield to the Bay would decrease if channelization is accompanied by bed and bank protection. Further factors complicating the sediment budget of urban streams draining to the Bay are the artificial removal of sediment from lower flood control channels and the existence of reservoirs in the watersheds acting as sediment traps.

Table 2 below lists the disturbances in the Bay’s local watersheds and the expected responses of sediment yield. Several factors have the potential to increase sediment yield, while several others have the potential to decrease it. The overall effect on sediment yield to the Bay will be determined by the dominant disturbances during a given time period and by the balance of competing factors affecting the yield.

This section sets the context for the null hypothesis for the temporal trends analysis: that temporal changes in sediment yield and delivery have not occurred, or are not significant because of the lack of data covering sufficiently long time periods to be statistically detected.

Table 2 - Anthropogenic disturbances affecting sediment yield

<table>
<thead>
<tr>
<th>Disturbance</th>
<th>Expected effect on sediment yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grazing</td>
<td>Increase</td>
</tr>
<tr>
<td>Urban/suburban development</td>
<td>Initial increase, then decrease</td>
</tr>
<tr>
<td>Channelization</td>
<td>Increase</td>
</tr>
<tr>
<td>Bed and bank protection</td>
<td>Decrease</td>
</tr>
<tr>
<td>Dams and reservoirs</td>
<td>Decrease</td>
</tr>
<tr>
<td>Channel dredging</td>
<td>Decrease</td>
</tr>
<tr>
<td>Other factors including agricultural development and logging</td>
<td>Increase</td>
</tr>
</tbody>
</table>

Modified from Wright and Schoellhamer (2004).
Figure 4

Trends in Suspended Sediment Input to the San Francisco Bay from Local Watersheds

Aerial Photograph of the San Francisco Bay Area
4. DATA ANALYSIS

The methods with which we carried out our analysis is detailed in the following sections. The spatial analysis described in Section 4.1 is divided into two parts: the calculation of spatial parameters and the statistical analysis regressing these parameters on suspended sediment load. The temporal analysis is described in Section 4.2.

4.1 THE RELATION OF SUSPENDED SEDIMENT LOAD TO WATERSHED CHARACTERISTICS

PWA compiled a GIS database of spatial watershed characteristics for all the gauged watersheds around nine counties in the San Francisco Bay Area. We performed both single and multiple regression analyses between these spatial parameters and suspended sediment load.

4.1.1 Spatial Variables

The watershed characteristics that we explored in this study are drainage area; topography (represented here by slope gradients, relief, and area of steep slopes); climate (represented by mean annual precipitation and mean annual precipitation gradient); hydrology (represented by mean annual runoff); geology/soils (represented by area of sandy soils, soil erodibility factor, and area of repeated landslide activity); land use (represented by area of rangeland and urban land; and several rainfall threshold statistics (based on the work of Wilson and Jayko, 1997) (See Figure 5 through Figure 7 as an example of GIS coverage of soils, land use, and landslides characteristics).
Figure 5
Sand Content in Corte Madera Creek Watershed
Prediction and Trends in Sediment Input to the San Francisco Bay
Data Source: NRCS Soils
Ref 1765
Figure 6: Trends in Sediment Input to the San Francisco Bay
Land Use in the Corte Madera Creek Watershed
Landslide in Corte Madera Creek Watershed

Prediction and Trends in Sediment Input to the San Francisco Bay

Data Source: ABAG

Ref. 1765
Watershed basin boundaries were created using the ArcToolbox Hydrology Tool, which calculates flow direction, accumulation and networks above a specified point, in this case the gauge location, using the existing topography defined by the DEM. The basin boundary above the gauge was generated from these inputs.

Watershed areas from digitized basins were checked against the watershed area specified in the gauge metadata. For watersheds with reservoirs, such as the Alameda Creek watershed, the area above the reservoir was clipped out of the overall watershed boundary above the gauge. The watershed boundary above each gauge was used to clip GIS data layers with spatial watershed characteristics thought to contribute to sediment production and/or delivery.

DEMIs for the whole San Francisco Bay were clipped to each gauged watershed, and summary statistics were derived from the watershed specific DEM, such as minimum and maximum elevations, and relief (Table 3). Slopes were calculated from the clipped DEMs, and the resulting slope grids were re-classified into three groups, areas with 0-3 per cent slopes, 3-20 per cent slopes, and greater than 20 per cent slopes. The area within each of these groups was divided by the total area of the gauged watershed to obtain the percentage of the total area with similar slopes (i.e. slopes greater than 20 per cent).
<table>
<thead>
<tr>
<th>PWA Gage ID</th>
<th>Annual Suspended Sediment Load</th>
<th>Max USGS Rainfall Threshold</th>
<th>Median USGS Rainfall Threshold</th>
<th>Average % Sand in Soils</th>
<th>Average Soil Erodibility Factor (Kw)</th>
<th>Landslide (%)</th>
<th>Range in Mean Annual Precip in Basin (in)</th>
<th>Average Mean Annual Precip in Basin (in)</th>
<th>Range in Elevation (feet)</th>
<th>Percent Poor Cover Land Use*</th>
<th>Percent Impervious Land Use**</th>
<th>Percent Slopes Greater Than 20%</th>
<th>Watershed Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 59106</td>
<td>3.6</td>
<td>2.6</td>
<td>39</td>
<td>4.4</td>
<td>0.52</td>
<td>16</td>
<td>8</td>
<td>17</td>
<td>1307</td>
<td>0.45</td>
<td>0.04</td>
<td>0.77</td>
<td>Alameda Creek at Niles, CA</td>
</tr>
<tr>
<td>2 63802</td>
<td>2.7</td>
<td>1.7</td>
<td>33</td>
<td>3.8</td>
<td>0.31</td>
<td>8</td>
<td>17</td>
<td>1152</td>
<td>0.23</td>
<td>0.21</td>
<td>0.45</td>
<td>Arroyo de la Laguna near Pleasanton, CA</td>
<td></td>
</tr>
<tr>
<td>3 45883</td>
<td>3.4</td>
<td>2.3</td>
<td>42</td>
<td>4.0</td>
<td>0.56</td>
<td>12</td>
<td>20</td>
<td>1090</td>
<td>0.55</td>
<td>0.00</td>
<td>0.81</td>
<td>Arroyo Valley near Livermore, CA</td>
<td></td>
</tr>
<tr>
<td>4 16084</td>
<td>4.8</td>
<td>4.3</td>
<td>39</td>
<td>3.3</td>
<td>0.46</td>
<td>8</td>
<td>42</td>
<td>764</td>
<td>0.16</td>
<td>0.40</td>
<td>0.74</td>
<td>Corti Madera Creek at Ross, CA</td>
<td></td>
</tr>
<tr>
<td>5 44575</td>
<td>2.7</td>
<td>2.4</td>
<td>43</td>
<td>4.0</td>
<td>0.46</td>
<td>10</td>
<td>23</td>
<td>872</td>
<td>0.43</td>
<td>0.00</td>
<td>0.88</td>
<td>Coyote Creek near Gilroy, CA</td>
<td></td>
</tr>
<tr>
<td>6 16662</td>
<td>2.8</td>
<td>2.7</td>
<td>25</td>
<td>3.1</td>
<td>0.68</td>
<td>4</td>
<td>22</td>
<td>495</td>
<td>0.08</td>
<td>0.15</td>
<td>0.80</td>
<td>Crow Creek near Hayward, CA</td>
<td></td>
</tr>
<tr>
<td>7 938</td>
<td>2.9</td>
<td>2.7</td>
<td>26</td>
<td>3.5</td>
<td>0.63</td>
<td>4</td>
<td>23</td>
<td>161</td>
<td>0.13</td>
<td>0.16</td>
<td>0.84</td>
<td>Cull Creek below Cull Creek Dam near Castro Valley, CA</td>
<td></td>
</tr>
<tr>
<td>8 7595</td>
<td>5.7</td>
<td>2.8</td>
<td>NA</td>
<td>0.14</td>
<td>42</td>
<td>30</td>
<td>1150</td>
<td>0.24</td>
<td>0.48</td>
<td>0.48</td>
<td>0.48</td>
<td>Guadalupe River above 101 at San Jose, CA</td>
<td></td>
</tr>
<tr>
<td>9 92384</td>
<td>5.0</td>
<td>3.2</td>
<td>40</td>
<td>5.2</td>
<td>0.14</td>
<td>34</td>
<td>38</td>
<td>1226</td>
<td>0.24</td>
<td>0.07</td>
<td>0.59</td>
<td>Napa River near Napa, CA</td>
<td></td>
</tr>
<tr>
<td>10 764</td>
<td>3.6</td>
<td>2.9</td>
<td>NA</td>
<td>0.17</td>
<td>12</td>
<td>31</td>
<td>756</td>
<td>0.48</td>
<td>0.13</td>
<td>0.13</td>
<td>0.82</td>
<td>Permanante Creek near Monte Vista, CA</td>
<td></td>
</tr>
<tr>
<td>11 9964</td>
<td>2.4</td>
<td>2.4</td>
<td>35</td>
<td>5.9</td>
<td>0.37</td>
<td>2</td>
<td>23</td>
<td>350</td>
<td>0.18</td>
<td>0.04</td>
<td>0.66</td>
<td>Pinole Creek</td>
<td></td>
</tr>
<tr>
<td>12 10693</td>
<td>4.0</td>
<td>3.0</td>
<td>38</td>
<td>5.0</td>
<td>0.26</td>
<td>20</td>
<td>31</td>
<td>551</td>
<td>0.37</td>
<td>0.39</td>
<td>0.55</td>
<td>San Francisco Creek at Stanford University, CA</td>
<td></td>
</tr>
<tr>
<td>13 10621</td>
<td>2.8</td>
<td>2.5</td>
<td>28</td>
<td>4.3</td>
<td>0.28</td>
<td>4</td>
<td>22</td>
<td>572</td>
<td>0.06</td>
<td>0.61</td>
<td>0.46</td>
<td>San Lorenzo Creek at San Lorenzo, CA</td>
<td></td>
</tr>
<tr>
<td>14 720</td>
<td>2.9</td>
<td>2.6</td>
<td>NA</td>
<td>0.19</td>
<td>10</td>
<td>31</td>
<td>577</td>
<td>0.31</td>
<td>0.12</td>
<td>0.88</td>
<td>West Fork Permanent Creek near Monte Vista, CA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 21470</td>
<td>2.5</td>
<td>2.4</td>
<td>35</td>
<td>5.3</td>
<td>0.64</td>
<td>2</td>
<td>25</td>
<td>561</td>
<td>0.09</td>
<td>0.39</td>
<td>0.79</td>
<td>Wildcat Creek at Vale Road at Richmond, CA</td>
<td></td>
</tr>
<tr>
<td>16 9670</td>
<td>1.9</td>
<td>1.8</td>
<td>22</td>
<td>3.6</td>
<td>0.42</td>
<td>10</td>
<td>19</td>
<td>487</td>
<td>0.64</td>
<td>0.27</td>
<td>0.51</td>
<td>Zone 6 Line B</td>
<td></td>
</tr>
<tr>
<td>17 29567</td>
<td>2.8</td>
<td>2.6</td>
<td>25</td>
<td>4.7</td>
<td>0.38</td>
<td>2</td>
<td>20</td>
<td>495</td>
<td>0.19</td>
<td>0.50</td>
<td>0.81</td>
<td>San Lorenzo Creek above Don Castro Reservoir</td>
<td></td>
</tr>
<tr>
<td>18 21251</td>
<td>2.9</td>
<td>1.8</td>
<td>23</td>
<td>3.2</td>
<td>0.67</td>
<td>4</td>
<td>23</td>
<td>513</td>
<td>0.14</td>
<td>0.11</td>
<td>0.86</td>
<td>Cull Creek Above Reservoir</td>
<td></td>
</tr>
</tbody>
</table>

* Includes 'Rangeland' and 'Sparsely Vegetated' Land Uses
** Includes 'Urban,' 'Employment,' and 'Residential' Land Uses

Data from this table was obtained from:
P:\Projects\1765_SFBay_Local_Sediment_Budget\SpatialAnalysis\1765_Parameters_3.xls
Average Mean Annual Precipitation for each gauged watershed was calculated by performing zonal statistics on the USDA PRISM (2005) rainfall coverage for the entire SF Bay area. Range in Mean Annual Precipitation is a byproduct of the zonal statistics function. The 24 hour and 6 hour Rainfall Threshold grids for the SF Bay area were clipped based on the gauged watershed boundaries, and we calculated the zonal statistics for each gauged watershed. The median Rainfall Threshold in each basin also was calculated by deriving the second quartile from the histogram of each Rainfall Threshold grid from the ArcGIS symbology window.

Using the SSURGO 2.1 data model, we extracted Total Representative Percent Sand and Soil Erodibility Factor (Kw) of all mapped soil units in the SF Bay area. The SSURGO spatial soils data does not include significant portions of Santa Clara County, including areas encompassing the Permanente and West Fork Permanente Creek watersheds, and Guadalupe River watershed. We used the Zonal Statistics function within ArcGIS Spatial Analyst and the gauged watershed boundaries to calculate the Average Percent Sand and Soil Erodibility Factor within each gauged watershed.

The Bay Area land use coverage provided by ABAG was clipped to each gauged watershed. These land use files were summarized based on the “Mapping” attribute, which specified several land use categories (Military, Rangeland, Sparsely Vegetated Land, Urban Open, Agriculture, Employment Areas, Infrastructure, Forest Land, Residential, Wetlands, Water, No Data). Land use categories which were thought to have similar effects on imperviousness, runoff, or sediment production in the watershed were combined. For example, rangeland and sparsely vegetated land were combined to quantify “poor cover” in a watershed. Urban, employment area, and residential land uses were combined to quantify impervious areas within a watershed.

Because landslides and debris flows present a significant geologic hazard, the USGS produced hazard maps for landslides in the Bay area, which characterize the frequency of landslides in different regions (Pike, 1999). The USGS landslide map is broken into eight categories, including Unmapped, Water, Surficial Deposits, Very Few Landslides, Few Landslides, Many Landslides, and Mostly Landslides. For each gauged watershed, PWA calculated the ratio of the area in the latter two categories (Many Landslides and Mostly Landslides) to the entire gauged watershed area. This percentage was used as an indicator for watersheds with a higher density of landslides.

4.1.2 Regression Analysis of Spatial Variables

PWA performed single regression analysis between the individual spatial parameters and suspended sediment load. Single regression tests the ability of individual parameters to explain the variation in a dependent variable (Helsel and Hirsch, 2002): in this case suspended sediment load. Single regression also provides a measure of the strength of the relationship between various spatial parameters and suspended sediment load, and therefore, can determine which spatial parameters are suitable for multiple regression analysis.
Multiple regression analysis tests the ability of using a combination of independent variables to explain the variation in a dependent variable (Helsel and Hirsch, 2002). In this case, we performed multiple regression to determine if any combination of spatial parameters could explain the variability found in the suspended sediment load of SF Bay tributaries. Some spatial parameters are expected to affect suspended sediment load through similar processes or mechanisms. For example, steeper basin relief may result in an increase in suspended sediment load, in the same fashion that steep slopes may increase suspended load. This effect is known as auto-correlation, and to reduce or eliminate this bias in the multiple regression analysis, we first performed an analysis of covariance using the “mregress” code in Matlab.

We used Matlab’s built-in stepwise fit routine, developed as part of the Matlab Statistics Toolbox, to perform the multiple regression analysis. The stepwise procedure provides the capability to test the ability of individual independent variables to predict the variability in the dependent variable. Each variable is added in stepwise manner until the optimal predictive model is achieved. The optimal predictive model includes the least number of independent variables required to explain the most variability in the dependent variable. In this case, we tested combinations of spatial parameters, such as the percentage of steep slopes within a basin and percentage of poor cover, to explain the variability in suspended sediment load.

### 4.2 TEMPORAL TRENDS IN SUSPENDED SEDIMENT LOAD

Logarithmic plots of daily mean stream discharge versus daily mean sediment load were drawn for seventeen gauging stations for their respective periods of record (see Table 1 for period of record). Daily mean sediment concentration was related to daily mean stream discharge by the equation:

\[
Q_s = a Q^b
\]

where \(Q_s\) is mean sediment load in tons per day, \(Q\) is daily mean discharge in cubic feet per second, and \(a\) and \(b\) are coefficients. Logarithmic transformation gives

\[
\log Q_s = b \log Q + \log a
\]

which transforms the sediment data for a least-squares linear regression.

We investigated temporal trends in suspended sediment concentrations for those streams with suspended sediment sampling records over at least 10-year period, namely Alameda Creek at Niles, Colma Creek, Cull Creek above Cull Creek Reservoir, and San Lorenzo Creek above Don Castro Reservoir. The periods of record for these gauges are 18, 11, 23, and 25 years, respectively. Suspended sediment records were analyzed to detect consistent changes in concentration over time for equivalent discharge events. We modeled our investigation after that of Dinehart (1997), who studied the decline in sediment loads in streams draining Mount St. Helens following the volcano’s eruption in 1980. For each gauging station, the time series of suspended sediment concentrations and water discharge were sorted into discharge
ranges based on flow frequency. We focused our analysis on the temporal trends evident in highest discharge ranges, which were defined as 2 percent to 10 percent range and 10 percent to 20 percent range (highest flows that occur between 2 percent and 10 percent and between 10 percent and 20 percent of the time). This is because these low-frequency, high-magnitude events transport bulk of the sediment to the San Francisco Bay. To detect any statistically significant, monotonic correlation with time in years, the non-parametric Kendall tau analysis was applied to concentrations for the high discharge events. The underlying assumption of the suspended sediment trends analysis is that exogenous variables do not have significant influence on sediment load. Since sediment load is derived by streamflow, we first screened for trends in streamflow to investigate that trends in sediment load over time are independent of streamflow.
5. RESULTS AND DISCUSSION

Hydrologic, physical, and land-use characteristics of the watersheds of interest and suspended sediment records were evaluated to explore the differences in suspended sediment yield over time and space. The results of the temporal and spatial analyses are presented in the following sections.

5.1 SPATIAL TRENDS

Qualitative and quantitative relation between watershed sediment yield and geomorphic processes, as well as watershed parameters have been studied for over seventy years (Dunne and Leopold, 1978). Many examples of multiple regression equations are available in the literature. Earlier studies have mostly concentrated on the agricultural lands and many useful predictive equations were developed by the Soil Conservation Service and the Agricultural Research Service, including the work of Brune (1948), Universal Soil Loss Equation, USLE (Wischmeier and Smith, 1978), reservoir sedimentation studies by Dendy and Bolton (1976), Modified Universal Soil Loss Equation, MUSLE (Williams, 1975) etc. Later, such studies focused on the impacts of different land uses on sediment yield; such as rangeland (Williams and Berndt, 1972; Flaxman, 1972; PSIAC, 1968) and urban areas (Wolman and Schick, 1967). In addition, there have been numerous studies of broader interest correlating sediment yield with watershed variables all of which can not be listed here (a couple of examples would include Hansen, 1966; Anderson, 1981; Ohmuri, 1983; Bent, 2001). These studies investigated the effect on sediment yield of climatic, topographic, vegetative, land use, and physical variables that logically should control sediment yield from watersheds. Such variables include but are not limited to amounts and variability of precipitation and runoff, relief, area of certain land use categories, area of soils with high erodibility, vegetation cover, watershed area, hillslope process parameters, and channel disturbance parameters.

Our results indicate that drainage area, mean annual runoff, and relief are the best variables for predicting sediment yield from the San Francisco Bay watersheds. These variables explain 79, 78, and 68 percent of the total sediment yield, respectively (Figure 8 through 11). The other variables that are loosely correlated to sediment yield are percent area of sandy soils, percent area of mapped landslides, and percent impervious area. The correlation coefficients for these variables are 0.15, 0.12, and 0.10, respectively. The remaining variables that were tested for their relation with sediment yield did not result in statistically significant correlation (Table 4).
Figure 8

Trends in Suspended Sediment Input to San Francisco Bay

Correlation of Sediment Yield and Drainage Area

\[ y = 93.49x + 13664.21 \]

\[ R^2 = 0.79 \]
figure 9

Trends in Suspended Sediment Input to San Francisco Bay
Correlation of Specific Sediment Yield and Drainage

$y = 2474.17x^{-0.51}$

$R^2 = 0.39$

PWA Ref 1765
Figure 10

Trends in Suspended Sediment input to San Francisco Bay
Correlation of Sediment Yield and Mean Annual Runoff

\[ y = 0.63x + 15128.53 \]
\[ R^2 = 0.78 \]
Correlation of Sediment Yield and Relief

\[ y = 65.09x - 16492.47 \]

\[ R^2 = 0.68 \]
<table>
<thead>
<tr>
<th>Avg Ann Load</th>
<th>Drainage Area</th>
<th>Median USGS Rainfall Threshold</th>
<th>Average % Sandy Soils</th>
<th>% Area with Landslides</th>
<th>Average Mean Annual Precipitation</th>
<th>Relief</th>
<th>% Area of Rangeland &amp; Barren Land</th>
<th>% Impervious Area</th>
<th>% Area With Steep Slopes</th>
<th>% Area of Rangeland With Steep Slopes</th>
<th>Mean Annual Runoff</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.79</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avg Ann Load</td>
<td>0.00</td>
<td>0.01</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average % Sandy Soils</td>
<td>0.15</td>
<td>0.28</td>
<td>0.12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Area with Landslides</td>
<td>0.12</td>
<td>0.05</td>
<td>0.01</td>
<td>0.03</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Mean Annual Precipitation</td>
<td>0.02</td>
<td>0.00</td>
<td>0.77</td>
<td>0.13</td>
<td>0.06</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relief</td>
<td>0.68</td>
<td>0.88</td>
<td>0.02</td>
<td>0.45</td>
<td>0.01</td>
<td>0.03</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Area of Rangeland &amp; Barren Land</td>
<td>0.09</td>
<td>0.15</td>
<td>0.08</td>
<td>0.08</td>
<td>0.00</td>
<td>0.07</td>
<td>0.19</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Impervious Area</td>
<td>0.10</td>
<td>0.21</td>
<td>0.02</td>
<td>0.37</td>
<td>0.25</td>
<td>0.00</td>
<td>0.22</td>
<td>0.21</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Area With Steep Slopes</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.11</td>
<td>0.61</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.34</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>% Area of Rangeland With Steep Slopes</td>
<td>0.08</td>
<td>0.08</td>
<td>0.07</td>
<td>0.01</td>
<td>0.06</td>
<td>0.03</td>
<td>0.09</td>
<td>0.83</td>
<td>0.05</td>
<td>0.03</td>
<td>1</td>
</tr>
<tr>
<td>Mean Annual Runoff</td>
<td>0.78</td>
<td>0.78</td>
<td>0.03</td>
<td>0.27</td>
<td>0.07</td>
<td>0.08</td>
<td>0.74</td>
<td>0.08</td>
<td>0.20</td>
<td>0.00</td>
<td>0.06</td>
</tr>
</tbody>
</table>

ALLTABLES_v2.xls
Watershed specific sediment yield is perceived to be inversely related to drainage area. McKee et al. (2003) plotted suspended sediment yield from California and San Francisco Bay watersheds using data extracted from previous research and USGS suspended sediment records of the gauged tributaries to the Bay. Their analysis showed that suspended sediment yield normalized to the area (i.e. specific sediment yield) is inversely related to watershed area with a high correlation coefficient ($R^2=0.80$). Their study period was up to 2000. We used the same data set as provided to us by SFEI with a couple of modifications. We updated the sediment record to cover the period between 2000 and the end of the Water Year 2003 or 2004, if available. We excluded two watersheds from the data set, namely Pescadero and Pine Creek watersheds, because they drain into the Pacific Ocean. We also delineated the watershed area that drain into each USGS gauge after removing the drainage area of upstream reservoirs. Our data set has 16 watersheds for which we have more than one year of suspended sediment data (see Table 1). Our results indicate that the correlation between specific sediment yield and drainage area is not as strong using the modified and updated data set ($R^2=0.39$). However, given that our objective was to develop a predictive relationship between suspended sediment yield and watershed variables, we correlated the total sediment yield with drainage area. The correlation is significantly positive ($R^2=0.79$) and is illustrated in Figures 8 and 9.

Runoff is directly correlated with sediment yield: higher runoff increases probable erosion and transport. The effect of climatic factors, including runoff and/or precipitation, on sediment yield have been extensively studied previously (such as Langbein and Schumm, 1958; Dendy and Bolton, 1976; Dunne, 1979; Walling and Webb, 1983; Milliman and Syvitski, 1992). Our results indicate that mean annual runoff explain 78 percent of the sediment yield from the San Francisco Bay watersheds (Figure 10).

Relief is another factor that is strongly correlated with watershed sediment yield within the San Francisco Bay. It explains 68 percent of the variability in watershed sediment yield (Figure 11). It is intuitive that high relief, which implies high slope gradient, should result in high sediment yields. The importance of relief in explaining sediment yield was demonstrated in previous studies (Hooke, 2000). This essential correlation is corroborated by PWA’s previous work within the San Francisco Bay Area watersheds. It should be noted that relief is measured in different ways. In this study, we defined relief as the difference in elevation between the divide and the outlet.

Despite the significance of individual correlations, a multiple regression model can not be developed based on the current suspended sediment data set. This is because introducing additional variables to any single correlation does not statistically significantly improve the overall correlation model (that it does not significantly increase the $R^2$ value of the multiple regression equation). It is common practice to stratify data sets according to variables such as drainage area, land use type, or other topographic factors. We did not stratify the data for further multiple regression analysis because the data set is limited.

Percent area of sandy soils, percent area of landslides, and percent impervious area are variables that are weakly correlated to sediment yield. These variables accounted for 15, 12, and 10 percent of the model variance, respectively (Table 4). The remaining variables are not correlated to sediment yield for the
gauged watersheds of interest (Table 4). In actuality, most of these variables do control sediment yield directly or indirectly. The poor correlations do not suggest the lack of relationship between these variables and suspended sediment yield from the San Francisco Bay watersheds. Rather they indicate that available sediment record is spatially and temporally limited and therefore it is difficult to detect statistically significant correlations. In addition, the dependence of sediment processes on these variables (such as slopes, precipitation etc) is strongly non-linear. Therefore applying average values will not provide valid results unless the area is uniform in character. However, the watersheds that are currently studied have different topographic, climatic, land use, and vegetation characteristics. Therefore, the relation of sediment yield to watershed variable can be expected to be strongly non-linear in the Bay Area local tributaries. In addition, in such varied environments, there is a wide range of erosional processes that are active (Figure 12 – Dunne and Leopold p. 507) and sediment yields may not be dominated by episodic events.
Arid to subhumid climate: sparse vegetation; or disturbed by man. Overland flow occurs over large areas of hillslope.

Humid climate; dense vegetation; most runoff occurs by subsurface percolation; overland flow restricted to small vegetated areas of low slope.

Climate, vegetation or land use

Mudflows, landslides, and debris flows

Landslides, debris flows, mudflows, soil creep

Mass movements

Earth flows, soil creep

Rainsplash, sheetwash, and gullying

Soil creep

Gentle slopes

Steep slopes

Topography

Trends in Suspended Sediment Input to the San Francisco Bay from Local Watersheds

Dominant Processes for Different Climatic, Topographic, and Vegetative Characteristics

Source: Dunne & Leopold, 1978
It was hoped that landslides would correlate with sediment yields from the Bay Area watersheds since landslides contribute 38 to 64 percent of the sediment delivered to the Bay (McKee et al, 2003). There are several reasons for this discrepancy. The most obvious reason for the poor correlation between landslides and sediment yield is the size of the data set. The spatial limitations of the current data set make it unfeasible to detect any statistically significant relationship between sediment loads and watershed parameters. Moreover, the landslide data have inherent issues stemming from the way landslides in the Bay Area were defined, depicted, classified, and generalized (Wentworth et al, 1997). The data set is based on Nilsen and Wright map (1979), which used varied mapping sources (e.g., detailed engineering geologic maps versus general geologic maps). The distribution of varied sources was generalized by proximity to each other or by similar topographic settings. Other sources of maps were also used where Nilsen and Wright map did not cover. The different source maps and the interpretation of different landslide categories (e.g., “Mostly Landslide” or “Many Landslide”) inevitably introduce inconsistencies and inaccuracies. Even if accurate information on the magnitude, frequency, and location of landslides were available, their signal may not be detected in sediment loads at the gauges due to lack of coupling of hillslopes and channels. Significant correlation of sediment yield with landslides would be dependent on the physical connectivity between hillslopes and channels. Finally, the landslide susceptibility map is a two dimensional representation of a three dimensional process. The map provides the surface area of previous and/or frequent landslides. However, neither quantitative (e.g. landslide volumes) nor qualitative (deep versus shallow) information is available for the landslide data. Further information on landslide volumes and locations relative to channels would improve the correlation of sediment yield with landslides.

We also investigated the affect of landslides on sediment yield indirectly using precipitation as an indicator for landslides and debris flows. Precipitation character strongly controls the distribution of landslides. Nilsen et al (1976) identified rainfall characteristics capable of triggering landsliding in the San Francisco area. Wilson and Jayko (1997) mapped the Rainfall Thresholds that are capable of triggering significant debris flow activity. However, the Rainfall Thresholds did not correlated well with sediment yield. This most probably stems from the effects of local factors, which control whether a landslide will actually occur when the threshold is surpassed. Caine (1980) used published records of landslide-triggering storms to define a threshold rainfall for shallow landslides. He noted that the relation cannot be used as a general predictor for landsliding and that a local analysis of the magnitude of triggering events is particularly important where an abnormally large storm has recently caused widespread landsliding.

Our observations on the geomorphic processes in local tributaries are that gullies and channel bed and bank erosion are dominant processes that contribute significant amounts of sediment to the Bay. McKee et al (2003) corroborates this based on a compilation of information on channel erosion around the Bay. Trimble (1997) found a similar result in the San Diego Creek watershed. He studied the sediment budget of the watershed between 1983 and 1993 and found that channel erosion supplied two thirds of the total sediment yield from basin. The causes and the spatial variability of sediment contributed by channel and gully erosion affect the amounts and variability of suspended sediment from local tributaries. Our analysis
did not take into account these processes due to lack of region-wide coverage on channel and gully erosion. Further study investigating the distribution of gullies and channel failures, either by mapping these features or by using indicators as proxy, would improve our ability to predict sediment yield based on spatial characteristics.

5.2 Temporal Trends

Logarithmic plots of daily mean stream discharge versus daily mean concentration were drawn for seventeen gauges for their respective periods of record (Figs 13 through 30). The plots illustrate a large scatter, which is inherent to natural sediment transport processes and measurement errors. The relation between stream discharge and sediment concentration is nonlinear, therefore a range of concentrations can be associated with a single discharge. There are random changes in any system at any given time such as changes in the tributary systems, mass wasting, changes in sediment size and reentrainment of sediment deposits by subsequent floods. Additional factors that would result in scatter in sediment rating curves are the hysteresis and sediment lag of floods.

As detailed in Section 4.2, daily sediment loads were related to daily mean stream discharge by a power relation. Table 5 includes the summary of regression equations including the intercept (a) and slope (b) values of the power trend lines, as well as the coefficients of determination, $r^2$, for all gauging stations. The results illustrate that sediment loads correlate very well with discharges for all stations as indicated by high coefficients of determination. The $r^2$ values are higher than 0.7 for all the stations of interest. The rating curves were plotted using all of the data. Predictive capability of rating curves could be improved by excluding low discharges (see Figure 15). This would result in a better fit for the high sediment producing events at higher discharges, which contribute the majority of the suspended sediment to the Bay.

The high correlation of sediment loads to discharges suggests that we can use the regression equations to temporally extend the data for appropriate stations. Such stations would include stations with a couple of years of up to date record of suspended sediment loads, including Arroyo de la Laguna, Crow Creek, Guadalupe River, Napa River, Sonoma Creek, and Zone 6 Line B gauging stations. For these stations, the sediment rating curve regression equations can be coupled with discharge records of longer durations or flow duration curves to extrapolate the sediment record over time or to estimate average annual sediment yield from their respective watersheds. The sediment rating curves for stations with a long term or outdated record should be used with more caution since sediment dynamics change with changing climate and land use characteristics. Errors in estimating suspended sediment loads should also be taken into account while extrapolating data sets over time. These errors arise from measurement errors of suspended sediment in the field and statistical errors in rating curve calculations. USGS sampling techniques are designed to ensure measurement errors are no more than $\pm 15\%$ (Edwards and Glysson, 1999). Therefore, the overall uncertainty for daily suspended sediment load will be $\pm 15\%$ and the average difference between measured suspended sediment loads and calculated suspended sediment loads. Therefore, the overall uncertainties that are implicit in rating curve analyses may be large. However, sediment dynamics in a watershed are stochastic and the measurement of sediment in any part of this system comprises
errors. Any attempt to model or estimate the amounts of sediment in different parts of the system entails significant assumptions, uncertainties, and inaccuracies. Estimates that are within an order of magnitude of actual amounts can be considered appropriate for most sediment production or transport studies.
**Figure 13**

**Trends In Suspended Sediment Input to San Francisco Bay**

**Alameda Creek Sediment Rating Curve**

Source: USGS gauge #11179000 Alameda Creek at Niles

- Equation: \[ y = 0.012x^{1.566} \]
- \( R^2 = 0.79 \)

**Discharge (cfs)**

**Sediment Yield (tons/day)**
Source: USGS gauge# 11177000 Arroyo de la Laguna

Figure 14

Trends In Suspended Sediment Input to San Francisco Bay
Arroyo de la Laguna Sediment Rating Curve

PWA REF 1765

y = 0.003x^{1.854}

R^2 = 0.81
Trends In Suspended Sediment Input to San Francisco Bay

Arroyo Valle Sediment Rating Curve

Source: USGS gauge # 11176500 Arroyo Valle

Figure 15

\[ y = 0.044x^{1.148} \]

\[ R^2 = 0.70 \]
Source: USGS gauge # 11162720 Colma Creek

Trends In Suspended Sediment Input to San Francisco Bay
Colma Creek Sediment Rating Curve

Figure 16
Corte Madera Creek Sediment Rating Curve

Figure 17

\[ y = 0.004x^{1.703} \]

\[ R^2 = 0.90 \]

Source: USGS gauge # 11460000 Corte Madera Creek

Trends In Suspended Sediment Input to San Francisco Bay
Corte Madera Creek Sediment Rating Curve

PWA Ref 1765

12/9/2005
Figure 18

Source: USGS gauge # 11180900 Crow Creek

Trends In Suspended Sediment Input to San Francisco Bay
Crow Creek Sediment Rating Curve

\[ y = 0.091x^{1.635} \]
\[ R^2 = 0.80 \]
Source: USGS gauge # 11180965 Cull Creek below the Cull Creek Dam

**Figure 19**

Trends In Suspended Sediment Input to San Francisco Bay

Cull Creek below Cull Creek Dam Sediment Rating Curve

$y = 0.079x^{1.152}$

$R^2 = 0.80$
Trends In Suspended Sediment Input to San Francisco Bay

Cull Creek above Reservoir Sediment Rating Curve

Source: USGS gauge # 11180960 Cull Creek above Cull Creek Reservoir near Castro Valley

$y = 0.055x^{1.858}$

$R^2 = 0.72$
**Guadalupe River Sediment Rating Curve**

**Figure 21**

\[ y = 4 \times 10^{-5} x^{1.673} \]

\[ R^2 = 0.94 \]

**Source:** USGS gauge # 11169025 Guadalupe River

**Trends In Suspended Sediment Input to San Francisco Bay**

Guadalupe River Sediment Rating Curve
Source: USGS gauge # 11458000 Napa River near Napa
Trends In Suspended Sediment Input to San Francisco Bay
Permanente Creek Sediment Rating Curve

Source: USGS gauge # 11166575 Permanente Creek

Figure 23

\[ y = 0.066x^{2.004} \]
\[ R^2 = 0.75 \]
Trends In Suspended Sediment Input to San Francisco Bay

Pinole Creek Sediment Rating Curve

Source: SFEI gauge Pinole Creek

$y = 5.0 \times 10^{-4} x^{1.527}$

$R^2 = 0.87$
$y = 0.011x^{1.693}$

$R^2 = 0.90$

Source: USGS gauge # 11181040 San Lorenzo Creek at San Lorenzo

**Trends In Suspended Sediment Input to San Francisco Bay**

San Lorenzo Creek at San Lorenzo Sediment Rating
Source: USGS gauge # 11180825 San Lorenzo Creek above Don Castro Reservoir

\[ y = 0.055x^{1.528} \]

\[ R^2 = 0.729 \]

Trends In Suspended Sediment Input to San Francisco Bay
San Lorenzo Creek above Reservoir Sediment Rating

PWA REF 1765
Source: USGS gauge # 11180825 West Fork Permanente Creek

Trends In Suspended Sediment Input to San Francisco Bay

West Fork Permanente Creek Sediment Rating Curve

Figure 27

\[ y = 0.035x^{1.583} \]

\[ R^2 = 0.86 \]
Figure 28

Wildcat Creek Sediment Rating Curve

\[ y = 0.037x^{1.850} \]

\[ R^2 = 0.86 \]

Source: USGS gauge # 11181390 Wildcat Creek

Trends In Suspended Sediment Input to San Francisco Bay

PWA Ref 1765
y = 4.625x^{1.750}

R^2 = 0.88

Source: USGS gauge # 11172365 Zone 6 LineB
Source: USGS gage #11456000 Napa River near St. Helena

Trends In Suspended Sediment Input to San Francisco Bay
Napa River near St. Helena Sediment Rating Curve
### Table 5

**1765 Daily Linear Regression between Qw and Qs**

Data from this table was obtained from:
P:\Projects\1765_SFBay_Local_Sediment_Budget\Temporal_Analysis\1765_DailyRatingCurve.xls

<table>
<thead>
<tr>
<th>Watershed Name</th>
<th>Slope, b</th>
<th>Intercept, a</th>
<th>Coefficients of Determination (r^2) for Daily Qs and Daily Qw</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Alameda Creek at Niles, CA</td>
<td>1.566</td>
<td>0.012</td>
<td>0.79</td>
</tr>
<tr>
<td>2 Arroyo de la Laguna near Pleasanton, CA</td>
<td>1.854</td>
<td>0.003</td>
<td>0.81</td>
</tr>
<tr>
<td>3 Arroyo Valle near Livermore, CA</td>
<td>1.148</td>
<td>0.044</td>
<td>0.70</td>
</tr>
<tr>
<td>4 Colma Creek at South San Francisco, CA</td>
<td>2.076</td>
<td>0.075</td>
<td>0.85</td>
</tr>
<tr>
<td>5 Corte Madera Creek at Ross, CA</td>
<td>1.703</td>
<td>0.005</td>
<td>0.90</td>
</tr>
<tr>
<td>6 Coyote Creek near Gilroy, CA*</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7 Crow Creek near Hayward, CA</td>
<td>1.635</td>
<td>0.091</td>
<td>0.80</td>
</tr>
<tr>
<td>8 Cull Creek below Cull Creek Dam near Castro Valley, CA</td>
<td>1.152</td>
<td>0.079</td>
<td>0.80</td>
</tr>
<tr>
<td>37 Cull Creek above Reservoir near Castro Valley, CA</td>
<td>1.858</td>
<td>0.055</td>
<td>0.72</td>
</tr>
<tr>
<td>9 Guadalupe River above 101 at San Jose, CA</td>
<td>1.673</td>
<td>4.0E-05</td>
<td>0.94</td>
</tr>
<tr>
<td>11 Napa River near Napa, CA</td>
<td>1.553</td>
<td>0.004</td>
<td>0.84</td>
</tr>
<tr>
<td>12 Permanente Creek near Monte Vista, CA</td>
<td>2.004</td>
<td>0.066</td>
<td>0.75</td>
</tr>
<tr>
<td>15 Pinole Creek</td>
<td>1.527</td>
<td>0.001</td>
<td>0.87</td>
</tr>
<tr>
<td>16 San Francisquito Creek at Stanford University, CA*</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>17 San Lorenzo Creek at San Lorenzo, CA</td>
<td>1.693</td>
<td>0.011</td>
<td>0.90</td>
</tr>
<tr>
<td>36 San Lorenzo Creek above Don Castro Reservoir</td>
<td>1.528</td>
<td>0.055</td>
<td>0.73</td>
</tr>
<tr>
<td>21 West Fork Permanente Creek near Monte Vista, CA</td>
<td>1.583</td>
<td>0.035</td>
<td>0.86</td>
</tr>
<tr>
<td>22 Wildcat Creek at Vale Road at Richmond, CA</td>
<td>1.850</td>
<td>0.037</td>
<td>0.86</td>
</tr>
<tr>
<td>35 Zone 6 Line B</td>
<td>1.750</td>
<td>4.625</td>
<td>0.87</td>
</tr>
</tbody>
</table>

*Annual Only*
To detect temporal trends in suspended sediment yields from the San Francisco Bay local watersheds, we statistically examined the instantaneous sample concentrations and associated stream discharges for those stations with a period of record of greater than ten years. Different methods are available to investigate the change over time in suspended sediment yield. These methods would include regressing daily mean concentrations over daily mean discharges for each year to detect a shift in sediment rating curves or studying annual sediment discharges over longer periods. The available sediment data for the gauging stations of interest is sporadic and mostly spans a short term, and thus, is not appropriate for these methods. The use of instantaneous values is advantageous because the resulting analysis is independent of estimation procedures and associated errors for calculating daily mean values.

We used Kendall’s tau analysis to detect the temporal trends in sediment yield. Tau is more resistant to the effects of extreme values and to deviations from a linear relation, and may be more appropriate than simple linear regression for sample sizes less than 20 (Helsel and Hirsch, 1992). A positive Kendall’s tau correlation on the time versus sediment concentration graph, where time is the horizontal axis and concentration is the vertical axis, indicates that concentration values increase more often than decrease over time. A negative Kendall’s tau correlation indicates the opposite; concentration values decrease more often than increase over time.

Figure 31 – Significant Trends in Suspended Sediment Loads for Four Long Term Stations
Among the USGS stations within the San Francisco Bay local watersheds, four stations have a period of record over ten or more years: Alameda Creek at Niles, Colma Creek at South San Francisco, Cull Creek above Cull Creek Reservoir, and San Lorenzo Creek above Don Castro Reservoir (Table 1). Only Cull Creek and San Lorenzo Creek station records are continuous and up to date. For these long term stations, the change in sediment concentration with time was evaluated for two higher discharge ranges: 2 to 10 percent and 10 to 20 percent. The null hypothesis of no significant slope with time was tested for concentration with the non-parametric Kendall tau analysis. Statistically significant decreases in suspended sediment concentrations were present in three of the four stations, as shown in Figure 31. No trend was present at San Lorenzo Creek station. San Francisquito and Coyote Creeks have annual sediment load records for a period of eight and nine years during 1960s, respectively. We did not examine annual trends at these stations since the data is not up to date.

In the San Francisco Bay watersheds, suspended sediment concentrations over time are affected by dams, channel modifications, urbanization, and agricultural and other land use practices. At present, it is not possible to attribute temporal changes in sediment concentrations to specific land-use changes in individual watersheds. However, decreasing sediment yields that this study revealed corroborate previous studies that pointed to decreasing sediment loads in California Rivers (Willis and Griggs, 2003; Wright and Schoellhamer, 2004). The implications of decreasing sediment supply from the Bay watersheds are significant, especially when recent large scale restoration projects are considered (SBSP reference). Decreasing sediment supply to the South Bay could delay the time it takes for marsh to evolve within the tidally-restored ponds of the South Bay Salt Pond Restoration Project. The goal of the project is to rely on estuarine sedimentation, including direct tributary capture of sediments, to gradually build the tidally-restored ponds high enough in the tidal frame to allow natural vegetative colonization to occur. This process is highly dependant on suspended sediment concentrations, and as concentrations decrease, the time it takes for a site to evolve increases. Significant delays in marsh evolution could compromise achievement of ecologic goals such as endangered species recovery efforts, and could also compromise flood management efforts, as salt-marsh vegetation can provide considerable wave protection for flood-control levees, thereby reducing long-term operations and maintenance costs.
6. SUMMARY AND CONCLUSIONS

We explored spatial and temporal trends in suspended sediment input to the San Francisco Bay from local tributaries. Suspended sediment records primarily consisted of USGS gauging station records. We found that the sediment data recorded at the USGS gauging stations around the San Francisco Bay local watersheds is temporally and spatially limited. The majority of available sediment record either covers short periods or relatively longer periods from prior decades, preceding the land use changes within the last two decades. There are only four stations with a period of record over ten years, and ten stations with a current period of record of three years or more.

We developed suspended sediment rating curves for eighteen stations with daily record. The suspended sediment rating curves indicate a statistically significant functional relationship between concentration and discharge for all stations, as evidenced by high coefficients of determination, \( r^2 \). The suspended sediment rating curves for those stations with a current record can be used to estimate sediment yields from watersheds they drain and to extrapolate the data set for prediction purposes.

We analyzed trends in suspended sediment input by statistically examining the instantaneous sample concentrations and associated stream discharges. Non-parametric Kendall’s tau analysis was used to test for temporal trends. Statistically significant decreases in suspended sediment concentrations were present in three of the four stations. The suspended sediment record at the Alameda Creek at Niles, Cull Creek above the Cull Creek Reservoir, and Colma Creek at South San Francisco stations indicated small to moderate decreasing trends.

We investigated the relationship between sediment yield and the hydrologic, physical, and land use characteristics of the watersheds using regression analysis. We found that drainage area, mean annual runoff, and relief are the variables for predicting sediment yield from San Francisco Bay local watersheds. These variables explain 79, 78, and 68 percent of the total sediment yield, respectively. Despite the significance of individual correlations, a multiple regression model could not be developed based on the current suspended sediment data set, because introducing additional variables to a regression equation did not explain more of the variance in suspended sediment yield. The size of the data set is a limiting factor to develop a statistically significant spatial extrapolation model. Other things being equal, statistical significance of a regression increases as the sample size increases. More measurements of suspended sediment and more data on the dominant geomorphic processes in the watersheds, such as rates of gully and channel erosion, would improve the relationship between watershed characteristics and suspended sediment yields.

Previous studies revealed decreasing trends in suspended sediment from Central Valley Rivers. This study points to probable decreasing trends in suspended sediment from local tributaries based on a limited number of gauges. The implications of decreased sediment yield within the context of the restoration efforts around the San Francisco Bay are significant. Decreasing trends in sediment from the local tributaries of the San Francisco Bay raise the question of sediment availability that is crucial for the
viability of larger scale restoration projects around the Bay and have implications on the sustainability of estuarine habitats.
7. REFERENCES


USDA. 2003.


8. LIST OF PREPARERS AND ACKNOWLEDGEMENTS

This report was prepared by the following PWA staff:

Setenay Bozkurt, M.S., Geomorphologist, Project Manager
Jeffrey Haltiner, P.E., Ph.D., Project Director
Wei Luo, Ph.D., GIS Specialist
Adam Parris, M.S., Geomorphologist

We wish to thank the following individuals for their invaluable and generous assistance in providing information:

Lester McKee, SFEI
Sarah Pearce, SFEI