3. Sediment Production

Excess sedimentation of waterbodies is a significant problem worldwide. Within California, sediment is considered the principal cause of water quality impairment along the northern coastal drainages (KRIS 2002). While sediment develops and occurs naturally, excess levels generally stem from the modification and intensification of land use practices and can create a multitude of associated problems. Intensified land use activities including silviculture, mining, and urban development significantly enhance sediment production elevating levels in drainages. The increased levels of sediment degrade the ecosystem by deteriorating water quality, changing a stream or river channel’s morphology, and decreasing propagation rates of anadromous fish species including the threatened resident steelhead trout (*Oncorhynchus mykiss*) population in SPCW.

Multiple geomorphic processes generate sediment, with water acting as the primary erosion, transport, and deposition agent. Mass wasting and surface erosion were found to be the predominant sediment-generation processes occurring in SPCW, primarily from hillslopes and tributaries. Mass wasting includes rapid shallow and slow deep-seated landslide events. San Mateo County is highly prone to landslide activity, which is enhanced by land use practices (Brabb and Pampeyan 1972). Surface erosion, the detachment of soil by processes associated with fluvial transport, is most effective on bare soil making it an important factor on dirt roads and adjoining drainages, gullies, and in areas with disturbed vegetation including new development and off-road recreational use.

Sediment generation in a landscape is a factor of multiple natural and anthropogenic influences. Selby (1993) identifies climate and geology as the predominant factors of erosion with a close interdependency of soil type and vegetation. In SPCW however, the relief is steep and urbanization is encroaching on toe slopes increasing the potential for landslide failures. This is just one example underscoring the significance of anthropogenic influences on levels of local sediment production.

3.1 Geomorphic and Fluvial Processes

Finco and Hepner (1998) identify the first step in sediment mitigation as the assessment of a study area as a collection of small, contiguous sources of nonpoint pollution. Understanding how these localized processes function and relate to contribute to the overall sediment generation in SPCW is fundamental to accurate source identification. The total erosion within a watershed is widely variable as it is assessed as sediment generated from surface erosion (Walling 1983) and mass wasting processes. These occurrences constitute the dominant hillslope and tributary mechanisms supplying sediment to San Pedro Creek and are significantly enhanced by land uses.

3.1.1 Mass Wasting

Mass wasting in SPCW occurs in the form of landslides, slumps, and soil creep. Landslides occur along a shear plane of bedrock (Ahnert 1996) and represent
the predominant form of mass wasting occurring within SPCW. Soil creep is also a factor but due to the high levels of rainfall, not as effective as landslides and fluvial erosion. For this paper, landslides include numerous mass movements including shallow debris flows and slumps, which are explained in more detail below.

Sediment production within steep-sloped watersheds is often dominated by episodic mass wasting events (Kasai et al. 2001). Shallow rapid landslides, or debris flows, are the dominant geomorphic process delivering sediment to SPCW. With connectivity to the drainage network, significant amounts of sediment can be entrained.

Most landslide activity seems to take place within or adjacent to areas that have a history of landsliding (Brabb and Pampeyan 1972). Debris flows generally originate in zero order basins that maintain a recurring pattern of filling and sliding (Montgomery and Dietrich 1989).

Urban development in SPCW is encroaching on the fringe of hillslopes increasing landslide hazard potential. Partially as a result of this growth, various aspects of geomorphic features related to slope instability have been mapped (Nilsen 1986). Few counties have as thorough a slope stability mapping history as San Mateo. However, only the slow deep-seated flows, or earthflows, which are not the most significant sources of sediment, had previously been examined in detail (Ellen et al. 1988).

A severe storm event delivering intense rainfall occurred from January 3-5, 1982 triggering 475 landslides in the town of Pacifica, California alone. The storm initiated predominantly shallow debris flows with a high concentration in SPCW (Howard et al. 1988). As a result, the relevance of shallow landslides was revealed and landslides were subsequently mapped throughout the Bay area. Nine slides in Pacifica, five that occurred in the North subwatershed of SPCW (Figure 21), were studied in extensive detail. The Oddstad slide dislodged 2,290 m³ of material demolishing two homes and killing three children (Figure 22) (Howard et al. 1988).

Debris Flows
Debris flows occur from slope instability (Davis 2002) and are common in SPCW due to the steep terrain, poorly consolidated bedrock, and heavy rainfalls associated with Mediterranean climates (Brabb and Pampeyan 1972). Ellen et al. (1988) define debris flows as shallow, rapid, and complex events generating internal turbulence and moving downslope a significant distance often delivering a substantial amount of sediment to streams. Subsurface water flow is the predominant cause of slope failure (Collins et al. 2001) while geology and topography are also significant controls (WFPB 1997a). In San Mateo County, the distribution of debris flows is directly correlated to the underlying geology (Figure 22) ( Wieczorek et al. 1988) and slides in Pacifica originate on slopes between 26-458 near the heads of first order drainages.
Figure 21: Select landslides triggered from January 1982 storm event that were studied in detail. Five of the nine occurred within the North subwatershed and fall within the generalized extents of SPCW outlined in red (modified from Howard et al. 1988).
(Figure 24). Within SPCW, the five landslides that received the greatest attention occurred between a narrow range of 26-308 (Howard et al. 1988). The ten subwatersheds are the focal zones of the study area. Hillslopes and tributaries are the predominant contributors of sediment to the main channel; however, the localized erosional processes occurring within each subwatershed vary significantly.

The amount of sediment generated is mainly controlled by precipitation but also by geomorphology, geology, soils, land use, and land cover. These factors vary significantly within and between the many subwatersheds. The North fork, which is the largest, is also the most heavily influenced by urbanization and most of the drainage is channeled underground. Conversely, the Middle and South forks are radically different, heavily vegetated open space with minimal current land use impacts. The remainder of the subwatersheds comprising the study area consists of a variety of different land uses and land cover ranging between minimal to high levels of use.
Slumps
Slumps are failures along a shear failure plane in which the upper portion of material retains its original structure (Ahnert 1996). Commonly occurring downslope of trails and channel terraces near the creek, evidence of slumps was found throughout SPCW. Slumps are also episodic in nature but generally don’t deliver as much initial sediment to the stream network as debris flows. Instead soils displaced from slump events are exposed to soil creep and surface erosion acting as long-term sediment sources. Areas prone to slumping are commonly recurring, ensuring future sediment supply.

Soil Creep
Creep is the process of unconsolidated material “creeping” downslope, either from continuous movement or expansion and contraction, up to a maximum rate of 1-2 cm per year (Ahnert 1996). Due to the mild climate, SPCW is not influenced by contraction and expansion generally associated with the freeze/thaw cycle reducing the rate of movement significantly. Other agents of creep include gravity and biogenic activity (Stillwater Sciences 1999).
Figure 24: Landslides triggered from January 1982 storm event with corresponding geological units, Pacifica, CA. Generalized extents of SPCW outlined in red. (modified from Howard et al. 1988).
3.1.2 Surface Erosion

Displaced soils from surface erosion acting on bare slopes has been calculated up to several tonnes per hectare per year (Ahnert 1996). Surface erosion occurs from fluvial processes acting on the landscape to detach and entrain sediments and its effectiveness is highly dependant upon the level of soil compaction and exposure (WFPB 1997b). It is therefore most effective on areas with bare and compacted soil or sparsely vegetated cover, which is limited mainly to trails and roads throughout SPCW. In headwater catchments channel degradation and gully erosion, both forms of surface erosion, are known to be significant sources of sediment (Kasai et al. 2001). Mass wasting events enhance surface erosion processes by disturbing or removing vegetative cover exposing bare soil. Recent landslide scars provide bare soil, which are then subjected to surface erosion (WFPB 1997a).

Sheetwash and Overland Flow
Sheetwash is the process of water flowing over the landscape surface in a “sheet” during a rainfall event and is known as the most common process of soil erosion (Ahnert 1996). Sheetwash moves through two types of overland flows: Hortonian, which is initiated when the soil infiltration rate is exceeded by rainfall intensity triggering surface runoff, and saturation, when the underlying soil is already inundated from throughflow and interflow sources of antecedent moisture. Hortonian overland flow is intensified in areas surrounding impermeable surfaces such as urbanization or bedrock whereas saturation overland flow most commonly occurs on lower gradient slopes near channel margins (Parsons and Abrahams 1993).

Rainsplash Erosion
Rainsplash, the process of soil displacement from raindrops, acts differently from sheetwash, but its denudational effects can be significant in rills and gullies. Rainsplash erosion is most effective in dislodging sediments on bare soils. The full impact of a raindrop in producing this erosion is minimized by the presence of vegetation, low gradient slopes, the inherent resistance of soil to displacement, and the intensity of the raindrop (Mount 1995).

Rills and Gullies
Rills and gullies are physical features formed in areas with sparse or no vegetative cover or with heavily compacted soil. Rills are shallower and occur when saturation overland flow becomes concentrated from an increased slope gradient or where the surface roughness increases, both creating more turbulent flow (Figure 25) (Ahnert 1996). Gullies, which are formed from the same initial processes, are much deeper than rills and have incised into deep channels (Figures 26 and 27) (Collins et al. 2001).

Rilled and gullied slopes are potentially major sources of sediment, although the contribution from each varies greatly (Meyer 1986). Areas with bare soil cover occur in SPCW only where land uses have significantly altered vegetative cover and revegetation has not yet occurred. Sediment generated from surface erosion of gullies and rills are currently effective sources of sediment where connectivity to the drainage has been established.
Figure 25: Rills on the nearly vertical face of an uphill trail cut in the South subwatershed.

Figure 26: Gullies along a trail on Cattle Hill in the upper North subwatershed.
Fluvial Erosion
Water flowing through a stream channel acts as the agent of fluvial erosion (Collins et al. 2001). Fluvial erosion, other surface erosion processes, and mass failure occur in conjunction to entrain sediment from channel banks (Prosser et al. 2000; Couper and Maddock 2001). These processes work together to cause weakening of the stream bank and are the dominant sediment-contributing processes in upper watersheds (Figure 28) (Couper and Maddock 2001). On the other hand, massive failures occurring along tributaries can stabilize the channel by reducing the bank gradient. Unless the critical shear stress to remove the material is exceeded, the bank will be reinforced (Thorne 1982). Erosion of channel banks is also influenced by water flow properties, bank material composition, climate, subsurface conditions, channel geometry, man-induced factors, and biology, including animal burrows and root systems (Knighton 1984).

Numerous researchers have determined that where fluvial erosion along channels, including adjacent valley sides, is the predominant source of sediment, the relationship between sediment yield and catchment area is positive (Kasai et al. 2001). This is important to SPCW as a whole because much of the main channel is straightened, which lead to major bank incision and headward erosion possibly causing bank erosion to be a major source of sediment.
3.2 Anthropogenic Influence

Sediment generated from natural processes in SPCW is often enhanced by land use practices (Figures 29 & 30). Agriculture, grazing, and a regular fire regime have historically influenced SPCW hillslopes and tributaries. Significant gullies have developed along some of the coastal hillslopes as a result of agriculture and subsequent grazing (Davis 2002). While a large portion of SPCW is currently urbanized, the main sediment influenced by anthropogenic activities is derived from concentrated and diverted flows from trails and roads on hillslopes and along the tributary.

Figure 28: Fluvial erosion causing incision through a former landslide deposit in an intermittent tributary draining into Sanchez Fork (Davis 2003).
Figure 29: Severe surface erosion from concentrated Horton overland flow downslope of Coastside Boulevard, draining to a culvert draining to the storm drain network near Sanchez Fork.

Figure 30: Concentrated flow creating surface erosion and increasing the effective drainage density along the Hazelnut Trail draining to South Fork.
Recreational use in the open space areas of the upper watershed has resulted in the establishment of maintained and unmaintained trails. Multiple user groups frequent the trails in designated areas including pedestrians, mountain bikers, equestrians, and even off-road vehicles. These trails increase the effective drainage density of SPCW diverting and concentrating flow creating high erosion areas and compact soil creating nearly impervious surfaces similar to those of urbanized areas. Mountain bikers have constructed courses on trails that may not have been previously established (Figure 31). Several ranch and stable facilities in the area frequently use the surrounding trails for horse riding. In at least one situation at Park Pacifica Stables, this has resulted in off-road vehicle use for trail maintenance. Previous use by off-road motorcyclists created a network of trails throughout Pedro Point II heavily compacting soils and removing substantial amounts of vegetative cover.

Biogenic activity accelerates the downslope movement of soil known as creep. Animals, such as the local deer, mountain lion, and bobcat populations, also contribute to this process. Biogenic activity from small burrowing animals often results in piping, which is the funneling of water through these holes causing erosion at the outlet (Figure 32). Piping, found along trails throughout most landscapes in the watershed, can significantly contribute to gully formation and trail erosion. Human activity on trails also expedites this process increasing the potential amount of sediment delivered to the stream network.

Figure 31: Mountain bike trails and constructed features along an otherwise unmaintained trail draining to Shamrock Fork.
Large construction projects within SPCW have significantly impacted the creek and modified the sediment levels and delivery from upstream. One such project is the Devil’s Slide Tunnel currently being constructed by Caltrans (Caltrans 2003). The tunnel is being bored within Shamrock subwatershed to divert Highway 1 from the current slide prone route along the coast. Rerouting of the highway will expose significant amounts of soil susceptible to erosion at least temporarily during construction. A long-term repercussion could include interbasin transfer or the routing of water from the natural drainage to another increasing the possibility for surface erosion where the diverted flow has been concentrated.

Many mitigation measures have been installed that reduce the sediment produced by some of the previously listed sources. Some of the trails frequented on horseback near the Park Pacifica stables were graded and regularly maintained to prevent soil compaction and channel formation. The restoration site at Pedro Point II formerly used by off-road motorcyclists has since been partially revegetated with netting and downed organic material promoting more growth on hillslopes prone to significant surface erosion. Water bars are commonly placed along trails diverting flow in efforts to reduce incision along the trail. Along Coastside Boulevard on which control measures such as tarps and sandbags have also been adopted, water bars were found to be ineffective or even significantly damaging areas downslope from the trails generating several landslides and gullies. Terraced hillslopes near residential areas stabilize hillslopes by diverting water and debris accumulation.

Figure 32: Burrow hole that may soon lead to piping along the upper edge of a gully complex in the Middle subwatershed.
preventing delivery of sediment from landslides. Sediment is instead delivered through the concrete channels and culverts routed directly to the storm drain system and ultimately to the stream network.

### 3.3 Influence of Vegetation

Vegetative buffers act as sinks preventing the delivery of most sediment transported by surface erosion and mass wasting processes to the channel (WFPB 1997b). While many studies have recognized the sediment filtering capabilities of riparian buffers (Budd et al. 1987; Lynch et al. 1985; Gilman and Skaggs 1988; Petersen et al. 1992), the minimum distance required to filter sediments from streams varies from 6.5 meters (Riley 1998) to 100 meters (Budd et al. 1987). This wide range of buffer distances is primarily a factor of variations in slope, land use, and vegetation cover. One study found the effectiveness of vegetation buffers in filtering sediment to be up to 90% (Gilliam and Skaggs 1988). On the other hand, channelized and culverted reaches facilitate delivery to a stream network by eliminating the riparian buffer and surface friction that might otherwise filter or reduce the amount of sediment delivered. The contributing variables work together in SPCW to produce a range of filtering capabilities. A section of one tributary with high sediment filtering capacity is shown in Figure 33.

In addition to acting as a sediment trap, root cohesion from vegetation stabilizes banks and hillslopes (Petersen et al. 1992). The overall benefits of vegetation in reducing sediment and stabilizing banks and hillslopes are significant. However, large trees can also expose soil to erosion when tree throw occurs (Figure 34). Tree throw is the upheaval of the root system that can be caused by bank incision from fluvial erosion undercutting the roots. When the underlying stability is removed, the roots cannot support the trunk causing it to fall also overturning and exposing the roots to sediment generating erosional processes. While tree throw increases short-term sediment supply it can mitigate long-term sediment supply by stabilizing hillslopes and providing barriers to sediments dislodged and transported by geomorphic processes (Budd et al. 1987).
Figure 33: Riparian corridor along Pedro Point I channel. Most of the vegetation is growing directly in the channel in this intermittent stream while in other parts of the watershed it is mainly concentrated adjacent to the channel.
3.4 Summary

Sources in SPCW were characterized by the obvious processes generating the sediment. All sources were distinguished into one of five categories: debris flows, slumps, surface erosion (including creep), gullies, or fluvial erosion. Slumps and debris flows tend to be large mass wasting processes easily identified relative to sources influenced by creep alone. Surface erosion was modified to include creep processes whereas gullies and fluvial erosion were distinguished from areas only influenced by rainsplash erosion, sheetwash, and overland flow. Efforts to estimate quantities of sediment derived from sources influenced by only sheetwash, overland flow, and creep processes would require a long-term monitoring study. As a result, quantities of sediment produced from these sources were not estimated and were only designated as possible sources.

Figure 34: Tree throw from an overturned blue gum eucalyptus creating mound ~3 ½ feet tall adjacent to the tributary channel Pedro Point II subwatershed.