APPENDIX C – ESTIMATING EROSION VOLUMES IN SEARSVILLE LAKE, LOS TRANCOS AND BEAR SUBWATERSHEDS

C.1. Searsville Lake

OVERVIEW

Sources in the Searsville Lake watershed that contribute sediment to streams can be divided into two broad categories; discrete sources, such as landslides and gully erosion, and chronic sources, such as bank erosion, sheetwash or surface erosion, and other hillslope erosion processes. As described earlier, landslides are thought to be the dominant erosion process and the greatest effort has applied to documenting this source, with less effort applied to those sources that are thought to be less important overall. The nature of each source, how we identified them in the watershed, and the estimated rates of erosion for the 1995 to 2000 period are described below and summarized in Table C-1. Tables in the main text summarizes erosion volumes contributed to streams from 1995 to 2000 and indicate the range of uncertainty in these estimates and the likely grain sizes of the erosion products.

LANDSLIDES

The inventory of landslides in the Searsville watershed was prepared from two different sources. Frey (2001) mapped landslides along stream channels and classified them as either small or large; the surface area of small landslides was measured whereas large landslides were simply noted. Her surveys followed the large flood of 1998 and her measurements are thought to be fairly representative of the total number of landslides that occurred along valley bottoms near streams from 1995 to 2000, although a few that occurred after her survey may not be included. We estimated the volumes eroded from her small landslides by multiplying the surface area by an average depth of 4 feet, typical for the soil slips or small landslides measured in the Santa Cruz Mountains by Ellen and Weiczorek (1988). Field inspection confirmed that average depths were about 4 feet, but they varied considerably from one slide to another. The eroded material is typically sand with small quantities of gravel and up to 25% silt and clay (see Wentworth et al 1985; Ellen and Weiczorek 1988). We assumed that all the sediment from these landslides entered streams.

Frey identified considerably fewer large landslides than small ones. We do not have a good indication of the size of these landslides so we assumed that their area averaged about twice that of the small landsides, or about 0.08 acres. We assumed the same depth, so the large landslides produced an average sediment volume of 600 yd^3, about double that of the average small landslide. There is considerable uncertainty in the estimated volumes for each landslide and for the total volume from this source. We assumed that all the sediment from these landslides entered streams.

Large landslides on slopes away from stream channels were measured from 2000 stereo air photos (Historic Conditions Memorandum). The inventory focused on landslides with disturbed areas that exceeded 500 yd^2 (0.10 acres) as this appeared to be about the minimum size that would be clearly visible through the forest cover, given the air photo scale. This minimum size is much larger than the average size of the small landslides identified by Frey (2001). We deleted any landslides from the air photo inventory that appeared to match or correspond to sites where Frey had identified landslides, however, for the most part, the landslides she identified could not be identified on the 2000 air photos. We assumed that the landslides that were bare of vegetation on the 2000 air photos occurred during the 1998 storm or at least after 1995 and were part of the yield from 1995 to 2000. We have assumed that these landslides primarily contributed sand and coarser material, with up to 25% silt and clay.

The surface area of each landslide was estimated from the air photos and an eroded volume calculated based on an estimated average landslide depth of 5 ft, typical for the medium and large landslides observed in the Santa Cruz Mountains by Ellen and Weiczorek (1988). The portion of the landslide volume entering a stream was estimated from the general appearance of the landslide and its deposit, if visible. These landslides were divided into natural and man-made types, the latter including those landslides that initiated adjacent to road prisms, where they may have been caused by slope loading or drainage diversion, or those that initiated in areas disturbed by development or other land uses.

Two large landslides were examined during field inspections. The Alpine Road landslide on upper Corte Madera Creek is a large failure that was also described by Frey (2001) and Kittleson *et al* (1996). It appears to be a deep-seated rotational failure that has a displaced volume of over 10,000 yd^3 and that has confined Corte Madera Creek along its toe. The slide initiated well before 1995 although it has continued to be active since then. We included a contribution to Corte Madera Creek of 10,000 yd^3 from this landslide for 1995 to 2000. As noted, this may over-estimate the actual contribution to the creek since 1995. Bank erosion and small landslides along the toe of the failure and their volumes are also incorporated in the budget.

A large debris flow fan has been deposited in Corte Madera Creek at the mouth of Damiani Creek. Frey (2001) notes that much of this deposit formed during the storms of 1998. However, field inspection of vegetation on and near the deposit indicates that it may have been in place for much longer. It appears that much of the coarse sediment carried down Damiani Creek remains in the fan; however, fine sediment was likely carried downstream. We did not include the debris flow volume in the 1995-2000 sediment budget but erosion of the landslide deposit by Corte Madera Creek is included under stream erosion.

STREAM EROSION

Stream erosion is subdivided into bank and bed erosion. Frey (2001) reported bank erosion for all major streams, identifying the percentage of stream reaches that exhibited either moderate or severe bank erosion. We have assumed that all of the observed erosion occurred after 1995 and most occurred during the 1998 flood. Based on field inspections of Corte Madera Creek and its tributaries, we estimated that banks were about 3 feet high;

severe erosion was assumed to consist of 2 feet of retreat on each bank; moderate erosion to consist of 0.67 feet of erosion on each bank. These values likely overestimate the erosion that actually occurred. We have assumed that all the material eroded from banks entered the stream and that the sediment was dominantly sand and gravel, typical of the observed alluvial deposits. The main body of the report describes how natural and human-related erosion were distinguished.

Frey (2001) also noted areas of channel incision in her description of each stream. For the tributaries to Corte Madera Creek and other streams in the Searsville Watershed, we assumed that incision averaged about 1 foot, or 0.3 yd^3/yd, assuming that channel bottoms average about eight feet wide. It was assumed that all material entered the stream and that it was nearly entirely coarse sediment – gravels and cobbles. The record of incision on the tributaries may not be complete, and it is likely that only the more significant incised sections were identified. Incision along Corte Madera Creek was estimated from field inspections in the summer of 2003. The main body of the report describes how natural and human-related incision were distinguished.

STREAM DEPOSITION

Frey (2001) also mapped areas of deposition or aggradation along streams. In steep tributaries, deposition primarily occurred upstream of logjams or in sheltered locations along the channel. Along Corte Madera Creek and other large streams, deposition consisted of sand and gravel in pools and on bar tops, often up to 1 foot or so thick. Based on field inspections, we have assumed that deposition averages about 0.5 feet over the lengths of stream identified as aggrading by Frey (2001), or about 0.15 yd^3/yd, assuming an eight-foot bottom width. The above estimate is likely too high for the tributaries and may be too low for some sections of Corte Madera Creek. Gravel accumulation along Corte Madera Creek is not well documented and is not included in the above estimates.

Deposition is subtracted from total erosion to provide net transport from the subwatershed or sub-subwatershed. Net transport can be negative in some lower reaches of some subwatersheds, indicating net storage of sediment within the sub-subwatershed (see Table C-1).

ROAD EROSION

Erosion along roads is from chronic sheetwash on natural or gravel road surfaces, on cut and fill slopes, and from ditch erosion. Sediment is eroded from paved roads, natural or gravel surfaced roads and trails; often, trails are old roads. The length of existing roads in the individual sub-subwatersheds, both paved and unpaved, is from Appendix E of the Historic Conditions Memorandum. Trails in the Searsville Watershed are included in this inventory as unpaved roads.

Erosion rates for unpaved roads are higher than for paved roads; however, the erosion rates for unpaved roads vary widely depending on climate and the frequency and type of traffic (see Reid and Dunne 1996). Road surfacing, maintenance practices, spacing of drainage structures, road slope and other factors also affect erosion from individual roads

(McCashion and Rice 1983, Reid and Dunne 1984, Rice 1999). Reid and Dunne (1984) provide annual erosion rates for gravel-surfaced logging roads in mountainous watersheds, for different types and frequency of traffic, based on sediment transport measurements. Very high erosion rates occur on road segments with frequent traffic by logging trucks; much lower rates were observed for abandoned roads and those with only light vehicle traffic (McCashion and Rice 1983; Reid and Dunne 1984).

There are no studies of erosion from roads in the San Francisquito Creek watershed. Pacific Watershed Associates (2003) examined erosion along paved and unpaved (assumed mostly natural surface) roads and trails in San Mateo County Parks in Pescadero Watershed in the Santa Cruz Mountains. Predicted future surface erosion from the unpaved roads to streams averaged about 40 yd^3/mi per year over the road network, with most of the erosion expected from that part of the network where long-term lowering of ditches, cut slopes, and road surfaces is assumed to average 0.2 feet/year. Pacific Watershed Associates also estimated surface erosion from trails in the County Parks in the Pescadero Watershed. For the total length of 34.4 miles of trail, erosion averaged about 1.7 yd^3/mile per year, assuming a 6-foot wide trail prism and averaging lowering of 0.2 feet/year at those sites that appeared to have chronic erosion. The blended average erosion rate for all their unpaved roads and trails is 23 yd^3/mile per year.

The estimated average erosion from Reid and Dunne (1984) for light traffic on gravel-surfaced roads is much less than that estimated by Pacific Watershed Associates – only 3.8 tonnes/km per year (5 yd^3/mi per year, assuming 1.5 tonnes/m^3). The volume entering streams would be even less than their quoted erosion value because of deposition between roads and streams. It is our view that the average road erosion quoted by Pacific Watershed Associates would over-estimate contributions to streams if applied in the Searsville Lake watershed. Rainfall is less in Searsville Watershed, roads and trails are often distant from streams, there are relatively few stream crossings on mid and upper slopes (see Figure 8), and many roads and trails have no ditches or drainage structures to convey sediment to streams.

We have adopted an average value that is half of their blended erosion rate (11 yd^3/mile per year) and applied it to all unpaved roads in the Searsville Watershed, including both roads and trails. The sediment eroded from roads that reaches steams is assumed to be mostly silt and clay but may include some sand and is all assumed to be human-related.

Our estimate for surface and ditch erosion from unpaved roads and trails in the Searsville Watershed is likely conservative, particularly when applied to trails. However, a conservative value seems appropriate because some erosion processes along roads are not included in the above total, such as erosion from cut or fill failures, or failure of stream crossings. Some erosion from small failures on cut and fill slopes, which are less than the minimum area included in the air photo inventory, was observed. Field inspections indicate that cut slope failures are unlikely to enter streams as they are intercepted by road surfaces, however, some of these sediments may be later eroded by sheetwash or removed by maintenance activities. Erosion of road crossings is also not included in the above estimate. As noted earlier, there are relatively few crossings by unpaved roads in

Searsville Watershed and past failures of these crossing may not have provided a large contribution to erosion.

Large fill and road surface failures seem to be uncommon. Landslide maps prepared for Portola Valley and Woodside (Rodine 1975; Cummings and Spangle & Associates 1975; Dickinson et al 1992) show few active landslide scarps originating in road prisms, other than in subdivisions along Bull Run and Sausal Creeks, suggesting roads and trails are reasonably stable. Note that these maps do not include all of unpaved roads and trails in the Searsville Lake Watershed.

Erosion along paved roads results from sheetwash on cut and fill slopes, failures on cut and fill slopes, and ditch erosion. Reid and Dunne (1984) estimated that paved road erosion averages 2 tonnes/km per year (2.8 yd^3/mi per year, assuming 1.5 tonnes/m^3) and we have adopted their value for paved roads in the Searsville Lake watershed. Sediment that reaches streams is assumed to be mostly silt and clay with some sand and to all be human-related.

Road erosion in the individual sub-subwatersheds is estimated from the above average annual rates applied to the measured lengths of paved and unpaved roads. Some road segments produce much more sediment than some others; consequently, the average values may result in over- or under-estimating actual road erosion. For instance, significant erosion has been observed on Alpine Road (cut and fill slopes), Highway 84 (debris flows observed during 1982 storm on cut and fill slopes) and on Kings Mountain Road (ditch erosion) and these paved roads are expected to contribute substantially more sediment than other paved road segments. Little is known about which unpaved roads and trails are significant contributors.

SURFACE EROSION

In the Searsville Watershed, surface erosion (sheetwash) is relatively rare on undisturbed, forested slopes and is usually confined to those sites where vegetation and soils are removed or disturbed, or soils are compacted, and overland flow occurs. Such sites include landslide scars, construction sites, range and agricultural lands, fire-damaged areas, and roads and urban developments. Roads are addressed separately in preceding sections. Erosion rates from these processes have not been measured in the Searsville Lake Watershed.

Erosion from landslide scars occurs by surface wash of areas of bare earth exposed by sliding, where vegetative re-growth is still in the early stages, and retreat of slide scarps along the headwall and margins of the slide. We have based our estimates of surface erosion rates on Lehre (1982) who conducted a 3-year study of erosion rates on Lone Tree Creek, a small, mountainous, forested watershed in Marin County. He observed surface erosion of between 2 and 5 mm/year on fresh landslides. We have assumed that surface erosion would average 3 mm/year, equivalent to 16 yd^3/acre per year for fresh or recent landslide scars. This rate was applied to the area of the small and large landslides of Frey and the landslides identified from the air photo inventory. We assumed surface erosion mobilized mostly fine sediment, with some sand, and that all sediment was carried to a stream. Surface erosion from human-related landslides was assigned to the human-related surface erosion category.

Lehre also observed average head scarp retreat of 0.017 yd^3/yd. In Searsville watershed, head scarp widths were estimated from landslide areas by assuming that the ratio of landslide length to width was 5. This rate was applied to the width of the small and large landslides of Frey and the landslides identified from the air photo inventory. We assumed surface erosion mobilized mostly fine sediment, with some sand, and that all sediment was carried to a stream. Scarp retreat from human-related landslides was assigned to the human-related surface erosion category. We assumed scar erosion mobilized mostly fine sediment, with some sand, and all sediment was carried to a stream.

Lehre (1982) also estimated the average rate of surface erosion from grasslands and denuded hillslopes in Lone Tree Creek to be 4 tonnes/km^2 per year (9 yd^3/mi^2 per year, assuming 1.5 tonnes/m^3). We have applied this average rate to all the area in each sub-subwatershed around Searsville Lake, rather than just grasslands, to account for past human disturbance of hillslopes, some contributions from construction sites, or other activities not explicitly incorporated above. We assume that all this eroded material enters streams and that it consists almost entirely of silt and clay.

While there are considerable uncertainties regarding the applicability of Lehre's estimates to the Santa Cruz Mountains, the total yields from these surface processes are relatively insignificant and it was not judged necessary to refine them further.

CONSTRUCTION SITES

Erosion from construction sites can be substantial, if no sediment and water management controls are in place (see Knott 1973). However, we have assumed that all winter construction and re-construction completed between 1995 and 2000 was well managed and contributed little sediment to creeks in the Searsville Watershed.

GULLIES AND ZERO ORDER STREAMS

Frey (2001) mapped gully intersections with stream channels in the Searsville Lake watershed. However, it is unclear if she identified all gullies or only included eroding gullies. A brief inspection of large-scale maps shows that the stream network included in the GIS database of San Francisquito Creek includes very few small gullies or zero-order channels and swales. Measurements from large-scale maps suggest that the drainage density including these channels may typically be from 4 /mi to 5/mi, whereas drainage densities calculated from the stream lengths in the GIS database are typically around 2/mi (Historic Conditions Memorandum). Consequently, we estimating the length of gullies and zero-order channels in each sub-subwatershed by calculating the total length of the channel network for each sub-subwatershed areas from its area and an estimated density of 4/mi and then subtracting the stream length measured in the GIS database.

Lehre (1982) estimated a gully sidewall erosion rate of 0.013 m^3/m per year (0.016 yd^3/yd per year), combining retreat rates observed on vegetated and bare walls. We have adopted his erosion rate for gullies in the Searsville Lake watershed even though it is uncertain if his rate is applicable there.

Field and air photo inspection suggests that a number of the small gullies and zero-order channels have been disturbed by drainage diversion, road construction or other human activities. We have assumed that about one-third of the gully erosion in each sub-subwatershed results from human disturbance. This is a very rough estimate and is likely to over-estimate disturbance in some watershed and underestimate it in others. The sediment derived from gully erosion was assumed to be about half sand and half silt and clay and to all enter a stream.

SOIL CREEP

Soil creep includes all processes that cause soil to move downslope under gravity, such as animal burrows, frost heave, soil expansion and contraction from wetting and drying or other processes, and plastic flow. Creep occurs at slow rates on most slopes and it is most significant in moving sediment to colluvial banks along steep streams. This sediment is then eroded during floods, and the streambank erosion at the slope toe helps maintain creep. Creep rates are usually not well known and are thought to vary widely. Lehre (1982) estimated creep rates of 11 to 27 yd^3/mi^2 (5 to 12 $tonnes/km^2$ per year) directly to stream banks in Lone Tree Creek; Reid and Dunne (1996) quote typical rates of 10^{-3} m^3/m of stream bank per year, or up to 17 yd^3/ mi^2 for colluvial stream banks. Much higher rates occur at deep-seated landslides or other unstable sites. Brown and Jackson (1973) quote an estimated annual contribution to streams of 1 ton/50 feet in the Moraga Valley in the Oakland Hills.

We have not included soil creep as a sediment source in our short-term budget because its contributions are later mobilized by bank erosion and we wish to avoid counting the same sediment contribution twice. However, in the long-term, creep and other slope processes carry the sediment downslope that is moved to streams by landslides and erosion of colluvial bank deposits.

C.2. Los Trancos

OVERVIEW

Sediment sources in the Los Trancos watershed that contribute to streams can be divided into two broad categories; discrete sources, such as landslides and gully erosion, and diffuse sources, such as bank erosion, sheetwash or surface erosion, and other hillslope erosion processes. The nature of each source, how we identified them in the watershed, and the estimated rates of erosion for the 1995 to 2000 period followed the procedures adopted for Searsville Lake Watershed, with the exceptions described below. Erosion estimates are summarized in Table C-2. Tables in the main text summarize erosion volumes contributed to streams between 1995 and 2000 and indicate the range of uncertainty in these estimates and the likely grain sizes of the erosion products.

LANDSLIDES

The area or volume of sediment contributed by streamside landslides in Los Trancos Watershed has not been measured. We attempted to correlate the small landslide volumes for in Searsville Lake Watershed to the erosivity index described below and to other physical characteristics of the sub-subwatersheds. However, we were unable to construct a satisfactory predictive relationship in the Searsville Watershed that could be applied to the Los Trancos sub-subwatersheds. Instead, we estimated the volume of streamside landslides by balancing erosion and sediment transport, calculating the small landslide contribution as the remainder. Estimated erosion was about equal to transport in Los Trancos and the volume from small and large streamside landslides was arbitrarily set to zero. This was consistent with field observations of the main channel of Los Trancos Creek. We saw no evidence of small landslides entering the creek from steep lower valley slopes, which are mostly distant from the creek. However, streamside landslides may be more important in the upper watershed, which was not inspected.

STREAM EROSION

We also did not have any information on where bank erosion occurred in Los Trancos watershed or the severity of the erosion that occurred. To correct this deficiency, we correlated the percentage stream length with severe or moderate bank erosion observed in Searsville Lake Watershed to an erosivity index constructed by adding the percentages of erosive geology, stream length with erosive slope, and stream length near a landslide zone listed in the sub-subwatershed characteristics included in the Historic Conditions Memorandum. The relationships showed reasonably high correlations and they were applied to estimate the percent severe and moderate in the sub-subwatersheds in the sub-subwatersheds. Once the eroding bank lengths were predicted, erosion volumes were calculated as described previously (Table C-2).

The extent of channel incision was based on existing reports and field inspections (see main text). We observed no recent incision along Los Trancos Creek, other than its lowest 500 feet or so. One small tributary to Los Trancos Creek in Los Trancos Woods (LT-06) showed one or two feet of recent incision that is included in the gully erosion estimates.

STREAM DEPOSITION

The volumes of coarse sediment deposited along Los Trancos Creek and its tributaries were estimated from existing reports and field observations. We observed accumulation of cobble, gravel and sand along much of Los Trancos Creek in LT-03, LT-04 and LT-06. Deposition volumes were estimated by assuming that deposition averaged 0.25 feet over the stream bottom over about half of the stream length in each of these sub-subwatersheds. Deposition is also reported in a marsh or wetland in Buckeye Creek (LT-05); however, we did not inspect this creek to confirm if this occurs and have not included this area is our total.

C.3. Bear Subwatershed

OVERVIEW

Sediment sources in the Bear Creek watershed that contribute to streams can be divided into two broad categories; discrete sources, such as landslides and gully erosion, and diffuse sources, such as bank erosion, sheetwash or surface erosion, and other hillslope erosion processes. The nature of each source, how we identified them in the watershed, and the estimated rates of erosion for 1995 to 2000 followed the procedures adopted for Searsville Lake Watershed, with the exceptions described below. Erosion volumes are summarized in Table C-2. Tables in the main text summarize erosion volumes contributed to streams between 1995 and 2000 and indicate the range of uncertainty in these estimates and the likely grain sizes of the erosion products.

LANDSLIDES

The area or volume of sediment contributed by streamside landslides in Bear Watershed has not been measured. We attempted to correlate the small landslide volumes in Searsville Lake Watershed to the erosivity index described below and to other physical characteristics of the sub-subwatersheds. However, we were unable to construct a satisfactory predictive relationship in the Searsville Watershed that could be applied to the Bear sub-subwatersheds. Instead, we estimated the volume of small landslides by roughly balancing erosion and transport volumes, calculating the small landslide contribution as the remainder. On this basis about 10,000 yd^3 was assigned to this process, distributed roughly evenly over the eight steeper sub-subwatersheds – Bear (BG-02 and 03), Appletree, Tripp, Squealer, and McGarvey Gulches and upper West Union Creek (WUC-9 and WUC-11) (see Table C-2).

STREAM EROSION

We also did not have any information on where bank erosion occurred in Bear sub-subwatersheds or the severity of the erosion that occurred. To correct this deficiency, we correlated the percentage stream length with severe or moderate bank erosion observed in Searsville Lake Watershed to an erosivity index constructed by adding the percentages of erosive geology, stream length with erosive slope, and stream length near a landslide zone listed in the sub-subwatershed characteristics included in the Historic Conditions Memorandum. The relationships showed reasonably high correlations and they were applied to estimate the percent severe and moderate bank erosion in the Bear sub-subwatersheds. Once the eroding bank lengths were predicted, erosion volumes were calculated as described previously.

Observations by Smith and Harden (2001) indicated long-term incision on Bear Creek and West Union Creek but they identified no evidence of recent incision (see main text). However, they identified incision along Bear Gulch downstream of the CalWater diversion (BG-01 and much of BG-02) as a result of interception and removal of coarse material load. We have assumed that incision of about one foot occurred along half of the stream channel in these two sub-watersheds from 1995 to 2000 (Table C-2).

STREAM DEPOSITION

Volumes of coarse sediment deposited along Bear Creek and its tributaries were estimated from existing reports and field observations. Smith and Harden (2001) reported sporadic accumulation of sand and fine sediment along Bear Creek and West Union Creek. We have assumed that deposition covers about one-quarter of the length of stream in BC-01, BG-01, BC-02, WUC-03, WUC-05 and WUC-07 to a depth of about 0.25 feet. Some deposition likely also has occurred in the steep upper tributaries but it is not included in our sediment sources.