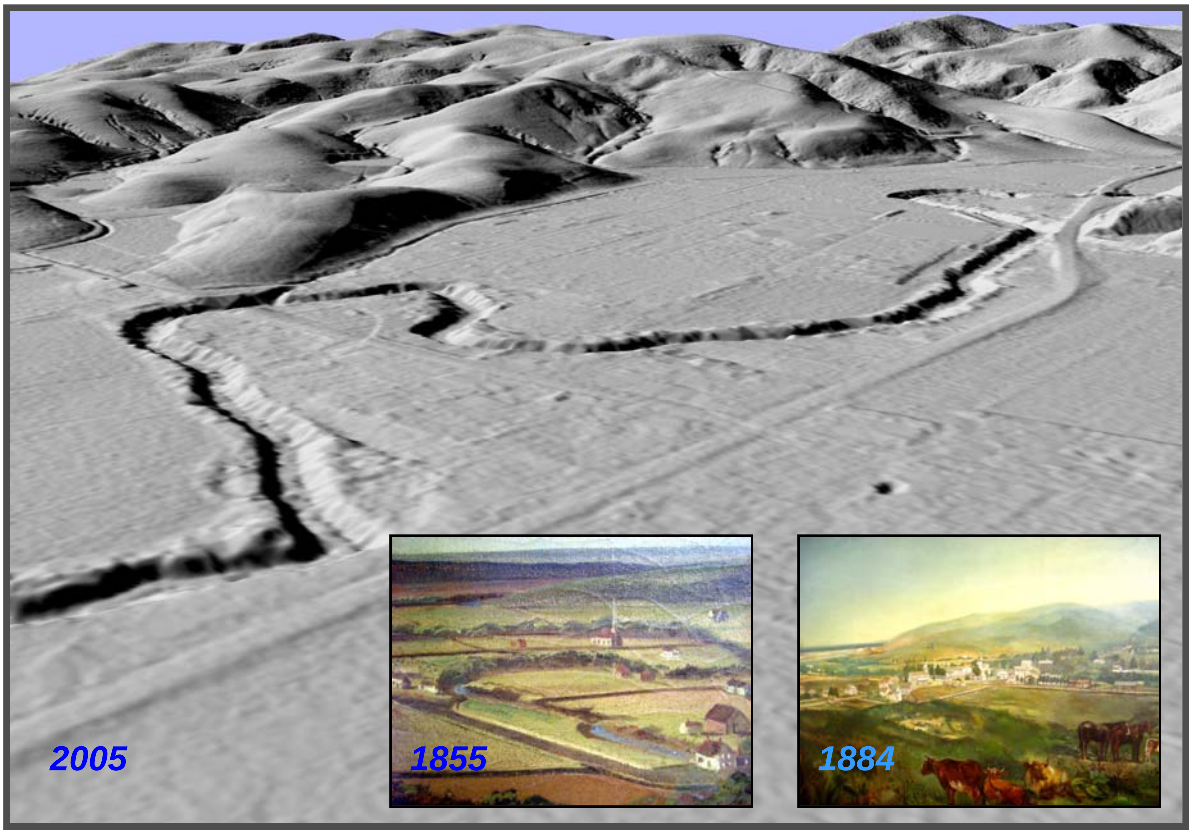
Pescadero-Butano Watershed, San Mateo County, California: Assessment of Historical Channel, Floodplain and Estuarine Changes, Sediment Delivery, and Sediment Yield

In support of Pescadero and Butano Creeks Watershed Sediment TMDL and Salmonid Population Dynamics Modeling Study

TECHNICAL MEMORANDUM

Summary of Results



Prepared For:

Department of
Earth and Planetary Science
University of California, Berkeley

and

California
San Francisco Bay Region
Protecting California's Water

Prepared By:

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January 2015

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Signed: ________________________________

Martin Trso, P.G., C.P.G., CPESC, QSD/QSP
California Professional Geologist License No. 7216 (Expiration 6/30/2015)
Certified Professional Geologist License No. 11475 (Expiration 12/31/2015)
Certified Professional in Erosion and Sediment Control License No. 5590 (Expiration 1/20/2016)
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January 2015

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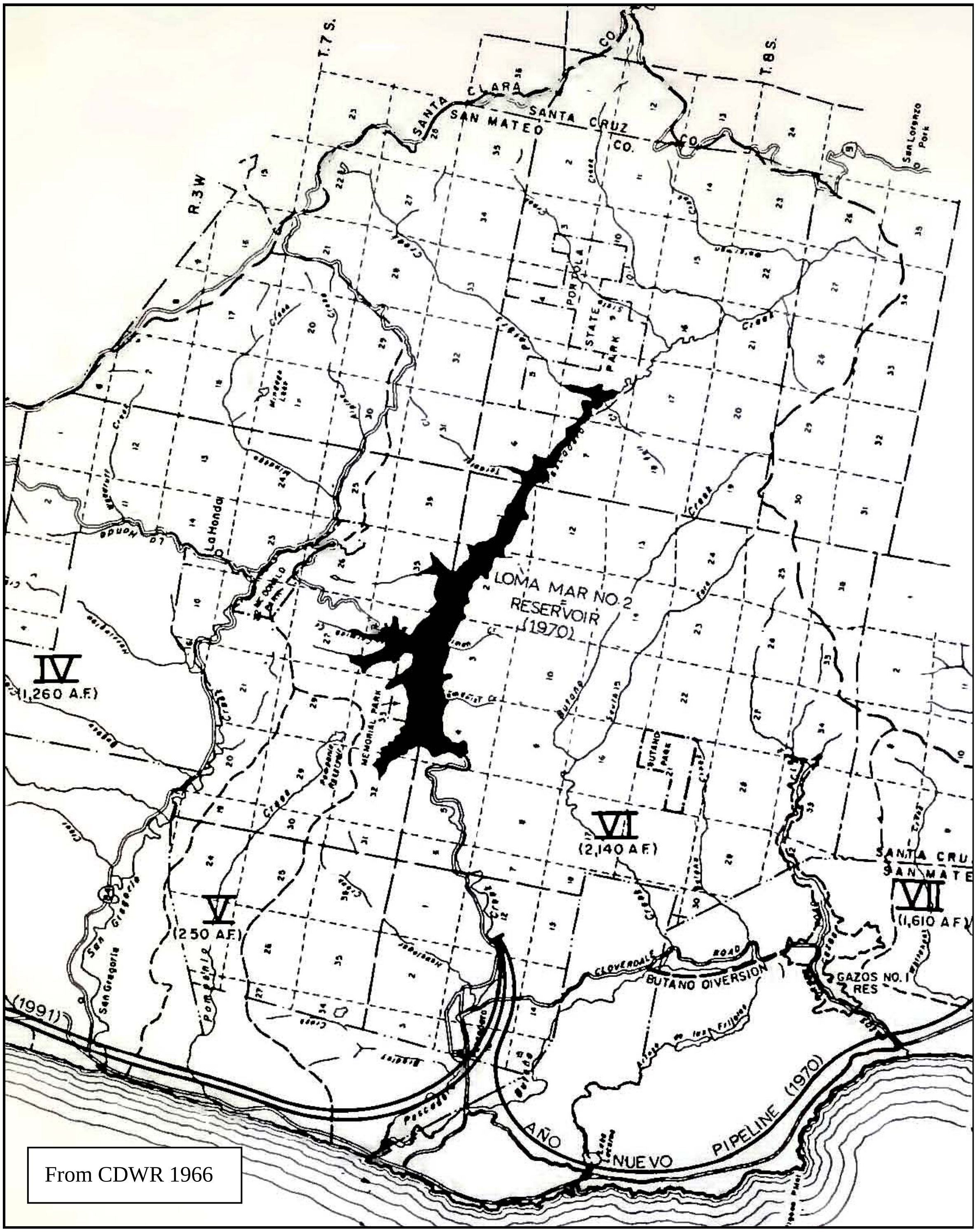

From CDWR 1966

Note: This image shows the dam and reservoir proposed within the Pescadero-Butano watershed by development interests in the 1960s and 1970s. The watershed was protected from the far reaching consequences of these plans by numerous residents, conservationist advocates, and naturalists.

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TECHNICAL MEMORANDUM

Date: January 26, 2015

To: Professor William E. Dietrich, Ph.D. (University of California, Berkeley), Setenay Bozkurt Frucht, P. E. (San Francisco Bay Regional Water Quality Control Board)

From: Martin Trso (Balance Geo)

Subject: Pescadero-Butano Watershed, San Mateo County, California: Assessment of Historical Channel, Floodplain and Estuarine Changes, Sediment Delivery, and Sediment Yield

Dear Professor Dietrich and Ms. Bozkurt Frucht:

At your request, I have prepared this technical memorandum, which provides an updated summary of the results of my geomorphic assessments for the Pescadero-Butano Watershed, located in San Mateo County, California. During period February 2010-June 2012, I have carried out the following geomorphic assessments: (1) geomorphic history and mapping; (2) disturbance history (natural and anthropogenic land-use); (3) geomorphic response to disturbance, including historical channel and floodplain changes, sediment delivery and sediment yield; and (4) sediment budgets for the Pescadero Creek Sub-Watershed, Butano Creek Sub-Watershed, and the Pescadero Marsh/Lagoon Complex. These assessments were developed in support of the Pescadero-Butano Watershed Sediment TMDL (Region 2 Water Board 2013a, 2013b, 2013c, 2015) and the Pescadero and Butano Creeks salmonid population dynamics modeling study (Stillwater Sciences, Inc. 2015).

The following technical memorandum presents the results of my geomorphic assessments, and expands the previously disseminated technical information, historic paintings, maps, ground photographs, science team presentations, and brief memoranda collected during the period February 2010-June 2012 (Martin Trso, P.G. 2011a, 2011b, 2012a, 2012b, 2012c, and other). The memorandum also includes a summary of about 200 technical e-mail communications with Professor William E. Dietrich, Ph.D. (Department of Earth and Planetary Science, University of California, Berkeley) and Michael N. Napolitano, P.G. (San Francisco Bay Regional Water Quality Control Board) during the period February 2010-June 2012; about 30 technical e-mail communications with Zooey Diggory, Frank Ligon and Rafael Real de Asua (Stillwater Sciences, Inc.) during the period February 2010-December 2013; and about 30 technical e-mail communications with Setenay Bozkurt Frucht, P.E. (San Francisco Bay Regional Water Quality Control Board) in the period February July 2012-November 2014. The above constitutes an estimated 10% of all visual documentation (historic paintings, lithographs, topographic and land grant maps, nautical charts, aerial photographs, and ground photographs), and a fraction of the technical information that was assembled, interpreted, and produced. The assessments seek to provide the context for understanding runoff and sediment dynamics on hillslopes and in stream channels across the Pescadero-Butano Watershed, as well as the effects of natural and historic and current anthropogenic (land-use) disturbances on the hillslope and channel runoff, sediment delivery and transport, sediment storage, and ecological processes that create and maintain freshwater salmon and steelhead trout habitat.

Specifically, the geomorphic assessments of the historical channel, floodplain and estuarine changes, sediment delivery, and sediment yield for the Pescadero-Butano Watershed and the Pescadero Marsh/Lagoon Complex involved the following: (1) the development of hypotheses concerning the natural state of sediment delivery and sediment transport, stream channels, floodplains, Pescadero Marsh/Lagoon Complex, and the pre-1820 locations of rearing and spawning reaches for steelhead trout (*Oncorhynchus mykiss*) and coho salmon (*Oncorhynchus kisutch*); (2) the assessment of the watershed's natural disturbance and land-use history post-1820; (3) the qualitative and quantitative assessment of the geomorphic response to post-1820 natural disturbance and land-use, including the transformation of the channel network, floodplains, and Pescadero Marsh/Lagoon Complex; (4) the collection of field data on stream channel dimensions (bankfull and summer-flow) and channel morphology; (5) sediment source analysis, involving a) the identification of natural and anthropogenic (land-use) related sediment sources and storage on hillside and along the watercourses, as based on surveys and GIS/DTM modeling from the 2/2010-6/2012 period, and b) the interpretation of available technical data developed by other consultants, researchers, and agencies; and (6) the construction of closed, process-, causality- and grainsize-specific sediment budgets (sediment delivery, transport, storage, and yield) for the Pescadero Creek Sub-Watershed, Butano Creek Sub-Watershed, and the Pescadero Marsh/Lagoon Complex for the pre-1820, 1820-1920, 1920-1970, 1970-1990, and 1990-2010 periods.

Since the end of the Mexican-American War and California's admission to the United States, as well as the arrival of Euro-American and European settlers (in about 1850 and 1860, respectively), the 208.4-km^2 (52,000 acres) Pescadero-Butano Watershed has experienced the widespread extraction of its natural resources, notably fish, terrestrial wildlife, timber, water, ore minerals, and oil and gas over about 70% of its landscape. The agricultural activities (ranching, dairy farming, dryland farming, and industrialized farming) have been taking place over an area of 11,200 acres since 1850 (of this, 3,300 acres were converted from scrublands and 3,900 acres from timberlands in 1850-1970), and the timbering activities took place over an area of 25,500 acres from 1850 to 1970. Since 1970, most of the timberlands were turned into public parks, and the remainder (about 1,000 acres) experienced sustainable forestry practices.

In response to the land-use post-1820, a profound geomorphic transformation took place over the subsequent 190 years across the entire Pescadero-Butano Watershed, its channel network, and its estuary. The majority of the land-use related impacts and the associated geomorphic transformation had already occurred by 1920, including the near elimination of native fish populations by the 1890s. Over the past 100 years, the watershed has been experiencing the cumulative effects of multiple environmental changes associated with particular land-use practices. Many of these cumulative hydrological effects, and the effects of watershed changes on sediment sources and sediment routing along channel networks, are severe and have nearly irreversible impacts. The effects included the following: (1) a 99% loss of flood-prone swampy meadow valley floors by the 1870s and the abandonment of 99% of the natural floodplains by the 1940s, with the associated reduction in riverine winter off-channel (floodplain and/or side channel) rearing habitat for salmonids in low-gradient stream channels; (2) an increase of 100-130% in the total sediment delivery to stream channels across the watershed by the 1890s, including the transformation of long-term geomorphic sediment sink landforms (storing an estimated 99 millions tons of fine-textured and unconsolidated sediment) to sediment sources and the formation of new fine- and coarse-textured unconsolidated land-use-related sediment deposits across the watershed (9 million tons), with the associated degradation of the channel streambed substrate and the quality of the spawning habitat for salmonids (the permanent coarsening of formerly fine-grained substrates within the low-gradient alluvial reaches, and the fining of formerly coarse-grained substrates within the steeper reaches in the uplands); (3) the reduction of the longitudinal and planform channel morphologic and the salmonid habitat complexity—especially involving pools—along stream reaches providing riverine summer rearing habitat, and winter rearing habitat, starting in the 1860s; (4) the severe disturbance of boulder-cobble streambed substrate, known to provide riverine winter rearing habitat for salmonids in steep stream channels in about 30% of the Pescadero-Butano Watershed area, which is underlain by competent, cobble-boulder-substrate producing bedrock (i.e. Mindego Basalt, Vaqueros Sandstone, and Butano Sandstone geologic units), starting in the 1860s in limited areas during the 19th century timbering activities and in the 1920s across half of the watershed during the 20th century timbering activities; (5) the transformation of the watershed's deep-water estuary into a shallow creek delta, starting in about 1920, due to the deposition of up to 5.7 millions tons of sediment, and involving a 60% reduction in the size of Pescadero Marsh and a 85% loss of the tidal prism within the lagoon, with the associated adverse effects on the estuarine summer rearing habitat for salmonids; (6) the triggering of legacy sediment sources, namely those of channel incision and hillside gullying, which persistently supply elevated loads of sediment; and (7) frequent flooding within the town of Pescadero since about 1940, most notably since 1990.

Absent of any sediment management and watershed rehabilitation and/or restoration actions, the ongoing legacy channel incision-turned-widening and hillside gullying processes, as well as the industrialized agricultural activities, are likely to maintain this elevated sediment delivery of 100-130% over the natural background levels across the watershed, as well as sediment delivery to the Pescadero Marsh/Lagoon Complex (including the historic tidal reaches), for decades to come.

The geomorphic, land-use, and sediment source assessments built upon the following: (1) the assembling, review, and interpretation of several dozen historical, technical and research documents and reports developed by multiple agencies, inter-disciplinary programs, consultants, contractors, non-profit organizations, and private citizens for this watershed over the past 35 years; (2) the acquisition of historic documents, maps, and ground and aerial photographs spanning the past 240 years; (3) numerous interviews and anecdotal accounts of watershed events and land-use history from private citizens and business owners, many of whom are long-time residents over 85 years of age; (4) extensive field reconnaissance across the Pescadero-Butano Watershed, including numerous private properties and the San Mateo

County and State parks; (5) the high-resolution geomorphic mapping of the Holocene alluvial valley floor, the alluvial fan and other natural and land-use related depositional landforms; (6) the delineation of the Quaternary deep-seated bedrock slide terrain; (7) the mapping of planform changes (i.e. channel shifting) along the alluvial-valley reaches of Pescadero and Butano creeks over the past 150 years; (8) the delineations of areas of land-use specific disturbance over the past 190 years; and (9) the development of digital terrain models (DTM), based on the San Mateo County's high-resolution digital elevation model (DEM)(San Mateo County 2005), of erosion, mass wasting, sediment delivery, and sediment transport and deposition across the Pescadero-Butano Watershed and the Pescadero Marsh/Lagoon Complex.

The assessments resulted in additional benefits with regard to both engineering and academic concerns. Some of the results related to the historic transformation of the natural channels and floodplains, and the associated erosion and sediment supply, in the watershed supported a hydrologic, hydraulic, and hydrodynamic study, aimed at developing solutions to reduce flooding along lower Butano Creek and Pescadero Road (cbec, inc. eco engineering 2014). Other results related to the historic physical transformation, excessive sedimentation, and the associated loss of tidal prism within the Pescadero Marsh/Lagoon Complex (namely the lagoon) informed the doctoral research on bio-physical coupling in an intermittent estuary by Eric Huber, Ph.D. Candidate at Department of Environmental Science, Policy & Management, University of California, Berkeley (Huber and Carlson 2012). Lastly, some of the results related to the sediment source analysis and the historic distribution of salmonid winter rearing habitat informed the master's research on predicting the occurrence of the cobble-boulder bedded channels in stream networks by Eric T. Donaldson, P.G. (Donaldson and Sklar 2010, Donaldson 2011).

The results are presented on the following pages of this memorandum: Introduction and Overview of Results, on pages 1-5; Executive Summary, on pages 6-24; Acknowledgments, on pages 25-27; Section 1: Purpose and Study Approach, on pages 28-29, providing a brief overview of scope and methods; Section 2: Assembled and Reviewed Literature, on pages 30-47, providing a complete list of historical, technical and research documents and reports developed by multiple agencies, inter-disciplinary programs, consultants, contractors, non-profit organizations, and private citizens for this watershed over the past 35 years, assembled and reviewed by Martin Trso, P.G.; Section 3: Geomorphic and Land-Use History Mapping, on pages 48-63, featuring geologic, geomorphic, and land-use history interpretation maps developed by Martin Trso, P.G.; Section 4: Evidence of Historic Geomorphic Response, on pages 64-106, featuring numerous historic documents, maps, and ground and aerial photographs spanning the past 240 years prepared by Martin Trso, P.G., to illustrate evidence in support of hypotheses concerning the natural state of sediment delivery and sediment transport, stream channels, floodplains, and the Pescadero Marsh/Lagoon Complex, as well as Martin Trso, P.G.'s field observations of geomorphic response to land-use; Section 5: Sediment Budget Analysis, on pages 107-112, providing the results of the sediment source analysis results and the sediment budgets developed by Martin Trso, P.G. for the pre-1820, 1820-1920, 1920-1970, 1970-1990, and 1990-2010 periods; Section 6: Management Recommendations, on pages 113-116, featuring cost-effective and efficient short-, medium-, and long-term solutions recommended by Martin Trso, P.G. for the management of sediment delivery and transport; Section 7: Limitations, on pages 117-118; and Section 8: References, on pages 119-139, providing all literature cited, including recently published new technical reports (post-2012).

Due to the substantial amount of data collected and the required in-depth and extensive scope of the quantitative and qualitative analytical assessments, as well as the budgetary constraints associated with the original scope of work prepared by the San Francisco Bay Regional Water Quality Control Board staff in 2009, the results of Balance Geo's geomorphic, land-use, and sediment source assessments could not be presented in a full-fledged technical report. Instead, the results are presented in a results-summary memorandum format only, containing only a fractional subset of the information collected on the watershed geology and Quaternary/Holocene geomorphology, the land-use history, the geomorphic response to land-use, and the results of the sediment budget analysis (including historic trends).

Should more funds become available, the abbreviated-text sections would be fully and adequately expanded, so as to provide additional spatially-explicit information to inform the future sediment management and watershed rehabilitation and/or restoration actions. Specifically, the technical report would feature more historic pictorials of stream channel, valley, and hillside conditions over the past 150 years, and ground photographs capturing present-day stream channel, valley, and hillside conditions across the watershed; details on the methods employed (including confidence levels) in and the results of the quantitative assessment of the type-specific sediment sources and their deliveries to watercourses across the watershed, including hillside gully mass wasting and partial sediment delivery, channel incision/widening and complete sediment delivery, and road surface erosion and partial sediment delivery; details on the methods employed on and the results of the quantitative assessment of sedimentation within the Pescadero Marsh/Lagoon Complex; and details on topographic-geomorphic assessments documenting land-use-related small- and medium-scale sediment deposit sites across the watershed, and flood-prone areas along the alluvial reaches of Pescadero and Butano creeks, including the alluvial-terrace areas suitable for cost-effective reconnection and habitat enhancement.

EXECUTIVE SUMMARY

The Pescadero-Butano Watershed (208.4 km^2, 80.5 mi^2, or 52,000 acres) is located in the Santa Cruz Mountains, within the central California Coast Ranges physiographic province, an area of active tectonic deformation, which is characterized by steep hillside terrain, frequent earthquakes, and fractured and weathered sand-producing bedrock. Prior to the Spanish colonial contact around 1770, the coastal scrublands within the watershed were occupied for at least 3,000 years (and possibly up to 8,000 years) by the local Ohlones, a Native American people also known as Costanoan people. The Ohlones subsisted mainly as hunter-gatherers and harvesters, practicing land management and uses such as burning ("slash-and-burn") the coastal scrublands and old-growth forests in order to protect natural valley bottoms and increase the yield of native grasses on hillslopes, in order to increase food sources for themselves and the wildlife they hunted. An estimated hillside area of over 4,500 acres (18 km^2) had been converted by the Ohlones in the Pescadero-Butano Watershed. During the subsequent Spanish colonial era, from about 1770 to 1830 (the "Mission Period"), the native human populations abruptly declined over 90%, in response to a disruption of their way of life imposed by the Spanish Franciscan missionaries and soldiers, as well as European diseases brought in by the Spanish. The lifestyle changes mainly involved forcing the Ohlones from their ancestral lands and resettling them to live and work in missions, which were founded between 1770-1797. During this period, slash-and-burn practices were abandoned by the Spanish, in favor of allowing for the natural re-vegetation of the landscape to create pastures for their horses and mules, and firewood used in the missions. In about 1820, the expulsion of the Spanish colonists and the arrival of Mexican land-owners following Mexico's independence from Spain, marked a 30-year period of extensive ranching activities (the "Rancho Period") in the coastal watershed areas, with over four thousand head of cattle. Under Mexican rule, the missions system was dissolved, and its lands privatized.

Since the end of the Mexican-American War and California's admission to the United States, as well as the arrival of Euro-American (in about 1850) and European (about 1860) settlers, the Pescadero-Butano Watershed has experienced the widespread extraction of its natural resources, notably fish, terrestrial wildlife, timber, water, ore minerals, and oil and gas over a majority—about 70%—of its landscape. The dominant land-uses in the watershed have involved extensive agricultural activities (ranching, dairy farming, dryland farming, and industrialized farming) since 1820 (11,200 acres); extensive timbering and deforestation on private and State lands from 1850 to 1970 (25,500 acres); the protection of cattle, agricultural crops, settlers, and seasonal loggers by eradicating mountain lions, the grizzly bear, and deer, and the poaching of other native wildlife and fish by ranchers, loggers, and bandits (1860-1920); weekend tourism and associated organized wildlife hunting and fishing from 1860 to 1940 in the lower parts of the watershed, including Pescadero and Butano valleys, the Pescadero Marsh/Lagoon Complex, and Pescadero Beach; the near elimination of industrial timbering activities; and a gradual decrease in industrialized crop farming; and weekend tourism, seasonal camping, and low-intensity hiking across the middle and upper watershed since about 1990. The population immigration in the watershed (excluding seasonal loggers, poachers, bandits, and the like) is estimated to have changed from a few residents in 1820, to 50 in 1847, 400 in 1870, 500 in 1940, and 700 presently. The land-use history of the Pescadero-Butano Watershed in the period 1850-1920 (between the 1848 California gold rush and the 1906 San Francisco earthquake) is strongly linked to the rapid growth, massive urban development, and reconstruction of San Francisco, which depended heavily on the watershed's natural resources. This included the rise of the upper middle class, the nouveau riches, banks, industries, and institutions in the San Francisco Peninsula, many of which still exist to the present day.

During the 1850-1920 period, the ranching, dairy farming, and dryland farming took place over 4,500 acres (18 km^2), an area which had been formerly converted by the local Ohlone populations, and used as extensive grazing lands by the Mexican land-owners from 1820-1850. The ranching and dairy farming additionally involved the continuing conversion of the native vegetation on hillsides and along alluvial stream corridors over 8% (about 4,000 acres, or 16 km^2) of the watershed in the 1850s, and the introduction of dozens of thousands of livestock (cows, sheep, and horses) to the newly cleared areas. The crop agricultural activities—which included growing bean, flax, grain/wheat, oats, and barley—involved the following: land reclamation (by draining) within the swampy valley bottoms along the Pescadero and Butano creeks over 3% (about 1,300 acres, 5 km^2) of the watershed by the 1870s; building water diversions in the uplands; and flood-control projects (comprising channelization, and the removal of in-channel large woody debris and riparian vegetation) in the 1880s and 1890s. The timbering activities involved the manual clearcutting and downhill yarding of old-growth redwood-Douglas fir forests along easily accessible medium-order watercourses, building in-channel skid roads and 19 on-channel shingle mill dams over 7% (3,600 acres, or 15 km^2) of the watershed, employing oxen, mules, and horses (later replaced by steam-powered logging engines, i.e. steam donkeys) to skid logs along the intermittent watercourses, operating seasonal splash dams to float timber logs along Pescadero Creek, and the pervasive sluicing of sawdust into the running streams. These early timbering activities, also referred to as 19th century logging, were especially pronounced during the period 1860-1890. An estimated 72.5 kilometers (45 miles) of roads existed in this period, including the present-day Pescadero and Cloverdale roads.

During the period 1850-1920, ranching, agricultural, and timbering activities also involved poisoning and/or killing mountain lions and the grizzly bear to protect livestock and human lives, and deer to protect agricultural crops, as well as the poaching of other native wildlife and fish by ranchers, loggers, and bandits. Crop agriculture also entailed a State program for the incentive-based eradication of the ground squirrel during the period 1880-1920, to further protect agricultural crops. The weekend tourism, the year-round land-use activities, and the associated wildlife hunting and fishing activities during the period 1860-1890 across the lower, middle, and upper watershed escalated the systemic elimination of wildlife, leading to the massive extraction of coho salmon, steelhead trout, frogs, quail, rabbit, deer, mountain lions, and the grizzly bear. The fishing activities also involved harvesting for mussels and shell-fish along the sea shore at Pescadero Beach, harvesting for crab and angling for steelhead trout in the Pescadero Lagoon, and hunting sea lions along the tidal reach of Pescadero Creek and along Pescadero Beach. Prospecting for oil and gas, which took place in the uplands in the eastern part of the Pescadero-Butano Watershed, ended by about 1890, leaving behind over 250 mine shafts, of which about 150 are unaccounted for. In part due to the acts of the Spanish missionaries and soldiers, as well as the land-use practices of the Euro-American and European settlers, the Ohlone population was virtually extinct by 1890. The near elimination of native fish populations by the 1890s led to large-scale hatchery efforts by the Federal and State governments, which resulted in the restocking of 0.5 million coho salmon and 15 million steelhead trout smolt during the period 1900-1930.

The period 1920-1970 was marked by the severe mechanized deforestation of old- and second-growth redwood-Douglas fir forests due to industrial timbering activities over 43% (22,000 acres, 89 km^2) of the watershed, the building of over 400 kilometers (250 miles) of new unpaved haul roads and skid trails (an increase of the road network by a factor of 6.5), the damming of ten small catchments, all of which drain Butano Ridge, over an area of 1,300 acres (5.5 km^2) in tandem with the construction of a major timber haul railroad/truck road ("Old Haul Road") along the canyon reach of Pescadero Creek (1920-1950), the conversion of mixed conifer-oak woodlands due to ranching expansion over 5% (2,800 acres, 11 km^2) of the watershed, the introduction of mechanized irrigation crop agriculture in and around the coastal areas that were subject to ranching, dairy farming, and dryland farming in the 19th century, the establishment of several dozen seasonal campgrounds for girl scouts, boy scouts, and public retreat sites along the canyon reaches of Pescadero and Butano creeks (1930s),[1] the construction of Highway 1 across Pescadero Marsh by the California Department of Transportation (Caltrans)(1941), continuing land reclamation within Pescadero Marsh (including the building of levees, and the channel modifications) and the lower valleys of Pescadero and Butano creeks due to the expansion of industrialized crop farming (1940s-1960s), and the re-construction of several bridges across Pescadero and Butano creeks (Cloverdale Road bridge, Pescadero Road bridge, and Pescadero Cutoff Bridge), and the significant associated modifications (straightening) of the creek channels at and near these locations (1950s-1960s). The industrialized crop farming has depended heavily on groundwater and surface water withdrawals from the alluvial valleys of Pescadero and Butano creeks. In response to continuing population growth and increasing land-use demands, as well as seeking revenue and maximizing income, San Mateo County pursued massive development plans in the watershed starting in the 1960s. These included developing Pescadero Creek Park as a major new recreational asset with campgrounds, a visitor center, picnic grounds, trails and interpretive programs, as well as transforming the lower Pescadero Valley into a town of 70,000. As part of these plans, in the late 1960s, the U.S. Army Corps of Engineers (USACE) proposed developing a 230-foot-tall earthen dam (Loma Mar No. 2 Dam), with a 80,700 acre-foot reservoir, to provide enough water for the new residents in Pescadero and agricultural activity on the coastside.[2] These plans fell through due to the opposition of conservationists, anti-development groups, and local citizens.[3,4] The passage of Proposition 13 in 1978 terminated the

[1] Numerous seasonal and permanent check dams were built along the alluvial-fan and swampy-meadow reaches of Pescadero and Butano creeks in the 1930s and 1940s, to create dry-season ponds for recreational, agricultural, and residential water supply purposes (Rob Skinner, personal communication 2014). The dams by the native beaver populations along the alluvial-fan reach of Pescadero Creek were utilized for the same purposes (Steve Simms, personal communication 2014). Numerous seasonal ponds were also maintained in the canyon reach of Pescadero Creek starting in the 1930s, which were used by fish anglers and as swimming holes by the campground visitors and tourists.

[2] The Loma Mar No. 2 Dam on Pescadero Creek would have created a lake that would have flooded everything below 400 feet elevation from Loma Mar for 10 kilometers (6 miles) to Portola Redwoods State Park, stretching between Loma Mar and Fall Creek (after CWDR 1966). A smaller dam and reservoir (a 190-foot tall Worley Dam with a 27,000 acre-foot reservoir) would flood everything below 400 feet elevation from Worley Flat for 6 kilometers (3.5 miles) to Portola Redwoods State Park, stretching between Jones Gulch and Fall Creek (after CWDR 1966).

[3] The dam and the lake plan was canceled after a series of public hearings in the 1970s. During the hearings, the local citizens expressed concerns that the availability of cheap irrigation and domestic water would spur agricultural and residential development. The California Department of Parks and Recreation (CDPR) also objected to the projected destruction of 440 old-growth and 2nd-growth redwoods trees.

[4] Similarly, the development of Pescadero Creek Park into a major recreational area was cancelled as it called for the selective harvesting of timber as a means of restoring the forest and providing income for the San Mateo County General Fund. Environmental groups were opposed to the logging plan claiming that the County provided no guarantees that they would pursue forest restoration. The local citizens also expressed concerns that the park would attract additional visitors to the area, causing traffic and population issues.

San Mateo County plans to develop Pescadero Creek Park as well as expand the town of Pescadero. Following the introduction of beavers in the lower (historic deep tidal) reach of Butano Creek by the California Department of Fish and Wildlife (CDFW) in the 1930s,[5] near Pescadero Road Bridge, and the partial burial of the floodplain with engineered fill as part of the construction of Pescadero Road and the CAL FIRE station in the early 1960s, the channel of Butano Creek has experienced a significant aggradation (i.e. burial) with sediment and a reduction of flood and sediment transport capacity (after Cook 2002).

The period 1970-2010 was characterized by the significant reduction of industrial timbering activities (to about 1,000 acres within the second- and third-growth redwood-Douglas fir forests), the creation of public lands (by converting most of the timberlands into public parks), the introduction of low-intensity seasonal camping and hiking tourism over 27% of the watershed, a gradual decrease in industrialized crop farming, an increase in the management—and the abandoning—of former ranching and dairy farming areas in the west of the watershed, and the limited conversion of former ranching areas to vineyard agriculture in the east of the watershed. Since the passing of the California's Z'Berg-Nejedly Forest Practice Act in 1973 (CPRC 2012), the remainder of the timberlands (about 1,000 acres) experienced sustainable forestry practices, while the area of the active land-uses decreased to 23% of the watershed area. Since the 1990s, nearly all seasonal (e.g., wooden-plank, filter bale) and permanent check dams and beaver dams have been removed by CDFW (Steve Simms and Rob Skinner, personal communication 2014), eliminating the dry-season ponds in the alluvial reaches. An estimated 42 kilometers (26 miles) of new roads across the watershed were built in this period. Under the present conditions, the length of the road network is estimated to be 514 kilometers (320 miles), of which 64% is surfaced with gravel, 27% is paved with asphalt, 7% is grassed, and 2% is native. There are an estimated 1,380 road-watercourse crossings, of which 70% are with unpaved roads and trails.

In response to the land-use post-1820, a profound geomorphic transformation took place over the subsequent 190 years across the entire Pescadero-Butano Watershed, its channel network, and its estuary. The majority of the land-use related impacts and the associated geomorphic transformations had already occurred by 1920. Many of these are likely irreversible without a drastic intervention employing watershed rehabilitation and/or restoration actions. The effects included the conversion of native hillside vegetation across a significant portion of the watershed, coupled with a pronounced denudation (starting in about 1860)—surface erosion and loss of soil, gullying, and mass wasting—of the hillsides; a near total transformation of the flood-prone alluvial floors, involving pronounced channel shifting and progressive channel incision, and the associated formation of alluvial terraces, along the alluvial reaches of Pescadero Creek (starting in about 1860) and Butano Creek (starting in about 1920);[6] the severe fragmentation of natural channel connectivity, including notable changes in the stream channel substrate; an increase of about 100% in the total sediment delivery to stream channels across the watershed, including the transformation of long-term geomorphic sediment sink landforms (Holocene alluvial valley fills and alluvial fans along the trunk streams in the lower watershed, amounting

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[5] It was expected by CDFW that the beaver dams would create ponds to benefit area farmers (after ESA 2004).

[6] Following notable shifting across the Pescadero and Butano alluvial-fan and swampy-meadow valleys, as recorded on the San Mateo County Office of Public Works historic surveyor maps, the non-tidal channels of the Pescadero and Butano creeks have maintained their present-day trace since about 1900, as recorded by the USGS and USACE topographic quadrangle maps and aerial photography, but have deepened due to the effects of land-use induced incision and flood-control measures (including channelization).

to an estimated 99 millions tons of fine-textured and unconsolidated sediment)[7] to sediment sources and the formation of new fine- and coarse-textured unconsolidated land-use-related sediment deposits across the watershed; and the transformation of the watershed's deep-water estuary into a shallow creek delta, starting in about 1920, and involving a 60% reduction in the size of Pescadero Marsh and a 85% loss of the tidal prism within the lagoon.

In detail, the impacts entail a 99% loss of flood-prone swampy meadow valley floors (1,550 acres, 6 km^2) by the 1870s (note: a small portion of the upper valley floor of Bradley Creek has remained relatively undisturbed to the present) and the abandonment of 99% of the natural floodplains (490 acres, 2 km^2) by the 1940s, due to deep channel incision and channelization (Pescadero Creek downcut 5 meters or 16 feet on average since 1860, and Butano Creek 10 meters or 33 feet on average since 1920. In terms of channel length, the channel incision amounts to 16 kilometers—10 miles—within the formerly swampy meadows, and 11 kilometers—7 miles—within the alluvial-fan floodplains); an estimated 100% increase in channel density in the soft-rock, scrub grassland hillsides that were subject to intense ranching and crop agriculture in the past; the increased connectivity of tributaries to the Pescadero and Butano creeks along the formerly swampy meadow, due to channelization; the decreased connectivity of tributaries along the canyon reach of Pescadero Creek, likely due to an incision-related evacuation of the minor alluvial bottom,[8] the construction of the timber haul railroad/truck road in the 1920s, and the burial of tributary junctions by debris-flow deposits and cut wood related to timbering activities during the period 1920-1970; the coarsening of formerly fine-grained riverine substrates within the alluvial valley floors, and the fining of formerly coarse-grained riverine substrates within the uplands; the severe disturbance of boulder-cobble substrate in areas underlain by competent bedrock (i.e. Mindego Basalt, Vaqueros Sandstone, and Butano Sandstone geologic units), involving the direct impact of skid-construction and livestock (oxen, mules, and horses) trampling over 30% (10 kilometers, or 6 miles) of the area during the 1850-1920 timbering activities, the scouring and burial by debris flows along most of the remaining boulder-cobble substrate reaches during the 1920-1970 timbering activities, and the El Niño years in the subsequent period 1970-2010 within the areas deforested during the period 1920-1970; the depositional settling of up to 9 million tons of fine- and coarse-textured and unconsolidated sediment across the watershed, and another 5.7 million tons of fine-textured sediment within the Pescadero Marsh/Lagoon Complex; and frequent flooding within the town of Pescadero since about 1940, most notably since 1990. Since 1820, as based on topographic and photographic evidence (USSG land grant maps, USC&GS, USACE and USGS topographic maps, USC&GS nautical charts, USGS earthquake maps, USGS orthophotography, and USDA-NRCS, USGS, FAS, USAF, and WAC aerial photography), and the work of Viollis (1979), there has been a loss of 50% of the historic tidal reaches of the Pescadero and Butano creeks—in response to channel aggradation associated with a doubled sediment supply from the entire watershed.[9] This involved a reduction from 3.1 to 1.1 kilometers (1.9 to 0.7 miles) on Pescadero

[7] An additional estimated 77 million tons of semi-consolidated fine- and coarse-textured sediment are stored in Pleistocene-age alluvial fans located in the canyon reaches of the trunk streams in the middle watershed. However, these long-term sediment sinks are decoupled for sediment delivery, as they hang dozens of feet above the stream channel).

[8] The loss of the 2-4-meter thick, and 15-meter-wide alluvial bottom in the canyon reach of Pescadero Creek likely began during the first round of logging as a result of the LWD removal and simplification to enable floating of logs.

[9] On Pescadero Creek, the aggradation within its historic deep tidal reach was observed to have initiated following the construction of Highway 1 across Pescadero Marsh by Caltrans in 1941 (after Ron Duarte, personal communication 2010). On Butano Creek, the aggradation within its historic deep tidal reach was noted following the introduction of beavers in the lower reach of Butano Creek by CDFW in 1938 (after Cook 2002).

Creek, and a reduction from 4.5 to 3.6 kilometers (2.8 to 2.2 miles) on Butano Creek. Due to the effects of elevated sediment supply since 1820, the loss of its flood-prone areas, and its constriction by Highway 1 in 1941, Pescadero Marsh experienced a 15% reduction, from 500 acres (of which 80-160 acres were in open water, i.e. lagoon) in 1820, to 425 acres (80 acres in open water) in 1920, and an additional 45% reduction from 425 (80) to 160 acres (27 acres) in 1970. The areal extent of the Pescadero Marsh/Lagoon Complex has remained unchanged from 1970 to the present. Based on field and anecdotal evidence, a transformation from channel incision to channel widening took place around 2005, along 17 kilometers (11 miles) of the alluvial reaches of Pescadero and Butano creeks, triggering systemic channel bank instability and associated sediment delivery.

According to the sediment source analysis, an estimated 21.2 million tons were naturally produced on the hillsides across the watershed during the period 1820-2010, and additional 25.2 million tons due to the geomorphic effects of land-use. The natural sediment sources are estimated to have provided the following loads of sediment: 16 millions tons (75%) from deep-seated bedrock slide terrain, 2.6 million tons (12%) from shallow-seated landslides/debris flows, and 2.6 million tons (12%) from shallow soil creep. The land-use related sediment sources are estimated to have provided the following loads of sediment: 11.4 million tons (45%) from surface erosion (associated with the thinning and/or loss of soil) within the areas involved with the 19th and 20th century ranching and agricultural activities, 4.3 million tons (17%) from shallow-seated landslide/debris flows within the areas affected by 19th and 20th century timbering activities, 3.5 million tons (14%) from the channel incision along the trunk streams of Pescadero and Butano creeks, 2.6 million tons (10%) from road-watercourse crossing related hillside gullying within the areas affected by all land uses in the 20th century, 2.4 million tons (10%) from hillside gullies within the areas affected by the 19th and 20th century ranching and agricultural activities, and 0.7 million tons (3%) from road surface erosion within the areas affected by all land uses in the 20th century.

Of the natural sediment production and delivery, an estimated 0.5 million tons (2%) were deposited across several dozen large-scale Quaternary/Holocene landforms, such as debris-flow fans, alluvial fans, alluvial valleys, and the (former) trunk-stream swampy meadow valleys. Of the land-use related sediment production and delivery, an estimated 9.1 million (36%) were deposited in a scattered manner at thousands of sites across the watershed and in association with various land uses: 4.6 million tons (51% of the total deposition) were deposited in small-scale shallow-seated, fine- and coarse-textured gully and landslide deposits within the areas affected by the 20th century timbering activities; 3.4 million tons (37%) in medium-scale, fine- and coarse-textured debris-flow deposits within the areas affected by the 20th century timbering activities; 0.8 million tons (9%) in medium-scale, fine-textured debris fans at the bases of hillside gullies within the areas affected by the 19th and 20th century ranching and agricultural activities; and 0.4 million tons (4%) of fine-textured sediment in the reaches of the historic tidal reaches of Pescadero and Butano creeks.

According to the sediment source analysis, the stream channels in the watershed experienced the doubling of sediment delivery due to the effects of the land-use activities: 65% over the baseline sediment loading of 111,300 tons/year (183,200 tons/year) during the period 1820-1850, 101% (224,200 tons/year) in 1850-1920, 173% (304,200 tons/year) in 1920-1970, 134% (260,900 tons/year) in 1970-1990, and 133% (259,300 tons/year) in 1990-2010. The supply of sediment from the watershed to the Pescadero Marsh/Lagoon Complex (including the historic tidal reaches) increased from an estimated 106,000 tons/year in 1820 to about 219,200 tons/year in 1920, to 193,000 tons/year under the current conditions. The sedimentation within the Pescadero Marsh/Lagoon Complex (including the historic tidal reaches) increased from an estimated 1,200 tons/year in 1820 to about 13,700 tons/year in 1920, to 37,300 tons/year under the current conditions.

Based on the watershed sediment supply predicted by the sediment source analysis, and assuming grainsize-specific sediment settling (i.e. trapping) in the estuary and the tidal channels, an estimated 5.7 million tons of fine-grained sediment have been deposited within the Pescadero Marsh/Lagoon Complex (including the historic tidal reaches) since 1820. Of this, 0.3 million tons originated from natural sediment sources, and 5.4 million tons from the land-use related sediment sources. This predicted sediment settling is corroborated by detailed stratigraphic, palynological, and topographic investigations, which indicate that about 3.05-5.14 million tons of fine-grained sediment have been deposited within the Pescadero Marsh/Lagoon Complex (including the historic tidal reaches) during the period 1820-2010. Of this, 0.66 million tons of sediment accreted within the marsh during the period 1820-1990 (after Bergolar Geotechnical 1988), about 2.07-4.14 million tons within the lagoon during the period 1820-1990 (after Smith 1990), and about 0.22-0.30 million tons in the marsh and about 0.04 million tons within the lagoon during the period 1990-2010 (after ESA 2011).[10]

Sediment delivery has decreased slightly (about 15%) since 1970, due to the significant reduction in timbering and the abandoning of former ranching and dairy farming areas. However, due to the cumulative effects of past land-use activities and the severe impairment of natural processes in the Pescadero-Butano Watershed, the ongoing legacy channel incision-turned-widening and hillside gullying processes, as well as the industrialized agricultural activities, are likely to maintain this elevated sediment delivery of 100-130% over the natural background levels across the watershed, as well as sediment delivery to the Pescadero Marsh/Lagoon Complex (including the historic tidal reaches), for decades to come. Such elevated sediment supply will persist unless active watershed management is pursued, focusing on reducing sediment supply from these three land-use related sediment sources under the present conditions: (1) 41,700 tons/year (16% of the total watershed sediment delivery in the period 1990-2010) of fine-textured sediment supply from hillside surface erosion within the areas affected by past (presently idle) and present-day agricultural activities; (2) 32,200 tons/years (12%) of fine-textured sediment supply originating from the ongoing excavation, due to legacy channel incision and widening, of the Holocene valley fills (about 3.5 million tons have been excavated since about 1860, or 3.5% of the long-term sediment storage of 99 million tons); and (3) 25,200 tons/year (10%) of fine-grained sediment supply from hillside gullying within the areas affected by past (presently idle) and present-day agricultural activities. Additional sediment delivery is

[10] The deposition of sediment in the marsh and the lagoon in the period 1990-2010 was interpreted by the author of this memorandum, based on the topographic surveys carried out by ESA-PWA in 1987, 2002, 2003, and 2011. The associated rate of sediment deposition (i.e. “observed deposition”) in the 1990-2010 period corresponds to about 30% of the value of the sedimentation predicted by the sediment source analysis (SSA) (see Section 5 for details on the sediment budget, including SSA-predicted sedimentation rates in the marsh-lagoon complex post-1820). The 2002, 2003, and 2011 re-surveys by ESA-PWA involved occupying the semi-permanent benchmarks established in 1987. As numerous 1987 benchmarks could not be located in 2011, the surveys of topographic changes within the marsh and the lagoon captured only a portion—about half—of the entire marsh-lagoon complex, potentially explaining the discrepancy between the “observed” and SSA-predicted values of sedimentation.

expected to occur in the event of the remobilization of recent unconsolidated, land-use related sediment deposits across the watershed, such as about 3.4 million tons stored in the medium-size fine- and coarse-textured debris-flow deposits associated with the 20th century timbering activities (the majority of these deposits are located in steep valleys located between Butano Ridge and Old Haul Road), and 0.8 million tons stored in medium-size fine-textured debris fans at the bases of hillside gullies within the areas affected by the 19th and 20th century ranching and agricultural activities.

Active management of these readily and potentially available sediment sources is expected to have the greatest positive medium- and long-term effect on mitigating excessive sedimentation within the lowermost reaches of Pescadero and Butano creeks and the Pescadero Marsh/Lagoon Complex, and the associated flooding within the town of Pescadero. Additional flood mitigation and aquatic habitat benefits would potentially be achieved in the short- or medium-term, with the re-establishment of floodplain functions via re-connecting downcut trunk channels to present-day alluvial terraces (i.e. the former—abandoned—floodplains), wherever it would be topographically appropriate and cost-effective.

However, caution is warranted given that active sediment management or watershed rehabilitation and/or restoration is being performed at a watershed scale, especially within such a geomorphically sensitive, responsive, and degraded area as the Pescadero-Butano Watershed. If poorly designed and/or administered by inadequately trained or experienced practitioners, such restoration activities could potentially be ineffective and perhaps as damaging as the effects of resource-extraction-focused land-use, as evidenced in the literature (Kondolf et al. 2007, Pess et al. 2003, and other). As reported by the author of this memorandum, a marked difference in the effectiveness and cost/benefit between sediment yield treatments (sediment settling ponds and reservoirs), preventive sediment delivery treatments (excavation of potential sediment from unstable roads, road-watercourse crossings, landings, and ephemeral watercourses), and active sediment source restoration activities (erosion control by means of re-vegetation) has been found in the Grass Valley Creek watershed, a 96-km^2 (37 mi^2) tributary watershed to Trinity River (Martin Trso, P.G. 2004). Starting in the 1960s, this watershed had experienced a 5-to-10 fold increase in sediment supply in response to timbering activities, which included a clearcut deforestation of nearly the entire watershed from the late 1940s to early 1990s. The sediment yield and the preventive treatments were found to be 5 times more cost-beneficial in terms of the cost of 1 ton of sediment saved: $30 vs. $150, in the medium- and long-term. While the preventive treatments on hillsides and along valley fills had at best a moderate efficiency in reducing erosion and sediment delivery (this is due to various adjustments following mitigation actions), the hillside toe erosion-control (re-vegetation) treatments reduced erosion and sediment delivery by a factor of 2-3 in the short-term. In total, the sediment yield treatments in the 96-km^2 Grass Valley Creek watershed amounted to an estimated cost of $31.5 million (2002 dollars) in the period 1984-2002. The preventive treatments amounted to $5.9 million in the period 1992-1997, and the re-vegetation treatments to $1.2 million in the period 1997-2002. These costs do not include land buy-outs to retire and restore timberlands. In response to these watershed restoration activities, the watershed's sediment supply decreased 30% in the period 1991-2002, as compared to the period 1975-1990. An additional 30% reduction in the watershed's sediment supply post-2002 has been reported by Gaeuman (2010), implying that a total 60% reduction in sediment supply was achieved in response to watershed restoration activities, within the medium-term, as compared to the period 1975-1990.

It is recommended that the results of the sediment budget be used to guide the development of the sediment management plan for the Pescadero-Butano Watershed and the related sediment source-specific treatments, and provide the framework for both plan design and monitoring in subsequent years. When coupled with the results of the salmonid population dynamics modeling study (Stillwater Sciences, Inc. 2015), it is recommended that the sediment budget be used to guide the watershed rehabilitation and/or restoration plan for the Pescadero-Butano Watershed. Furthermore, it is recommended that the lessons learned from other watershed sediment management projects in California be considered during the development of the sediment management plan for the Pescadero-Butano Watershed, particularly from the watersheds that are similar in terms of natural processes and geomorphic response to land-use.

Only the tested agricultural and engineering Best Management Practices (BMPs) and restoration measures should be pursued to mitigate all point and chronic sediment sources across the Pescadero-Butano Watershed. Within the active agricultural lands (16% of the watershed sediment delivery), the agricultural BMPs should include the development of high-density cover crop and the management of riparian buffers, to curb soil erosion and sediment delivery, as well as improve water quality from agricultural areas that supply fine-textured sediment to the lower Pescadero and Butano creeks and the Pescadero Marsh/Lagoon Complex. Within the active pasturelands in the coastal hills (10%), including the abandoned and degraded pastures turned to open space, gully debris-fan footslopes should be vegetated, to disconnect sediment transport across these unconsolidated sediment deposit features, and to prevent turning these into sources of sediment in the medium- and long-term. In the absence of vegetative mitigations, short-term sediment yield control actions such as temporary ponds should be employed downslope from large hillside gullies, in order to immediately reduce sediment delivery to the lower Pescadero and Butano creeks and the Pescadero Marsh/Lagoon Complex.

It is acknowledged that the most effective actions of mitigation of the ongoing channel incision and widening (12%) are cost prohibitive, and could amount to hundreds of millions of dollars. Additionally, these actions would require extensive and disruptive construction activities in areas occupied by hundreds of people. However, a decrease in sediment production and delivery from the cut terrace banks could be achieved by decreasing peak flows in the trunk streams, via a cost-effective reconnection of available and suitable alluvial terraces, by building flood bypass channels wherever possible, and by bank stabilizing bio-engineering actions.

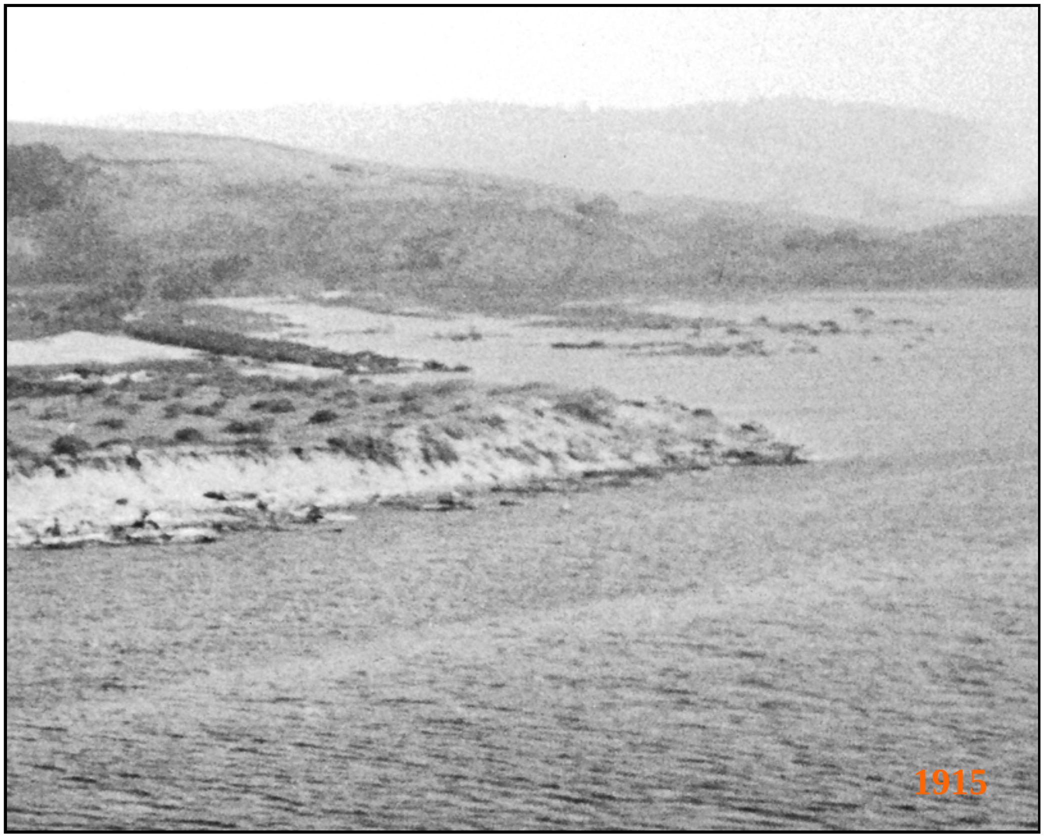
Given the empirical evidence for their high long-term effectivity along the Alder Forest reach of Butano Creek, an introduction of beavers should be considered along the perennial incised alluvial-fan and swampy-meadow reaches of Pescadero and Butano creeks, as a potential low-cost and highly efficient mechanism of building up the incised trunk channels with sediment and reducing flooding in the lower Pescadero and Butano valleys. These reaches would include the following: the alluvial-fan reach of Butano Creek from Butano Canyon to Cloverdale Road Bridge; the alluvial-fan reach of Pescadero Creek from the USGS gaging station to Pescadero Cutoff Bridge; and the swampy-meadow reach of Butano Creek from Cloverdale Road Bridge to the upstream-most extent of the historic tidal reach of Butano Creek, upstream from the present-day Alder Forest reach. Based on the recent successes in the United Kingdom, where beavers were re-introduced after 400 years in the late 2000s, as well as in the United States (New York Times 2014), this would amount to a substantial benefit to the public, by greatly reducing the cost associated with the mitigation of the ongoing channel incision and widening and the related sediment delivery.

Irrespective of the mitigation measures needed to manage the ongoing channel incision and widening and the related sediment delivery along the downcut trunk streams, it is recommended that the beavers from the Alder Forest reach be relocated and their dams removed, to enable sediment flushing of the aggraded historic tidal reach. This, however, would need to be complemented by the breaching of the sand bar in the marsh, to minimize sediment deposition within the Pescadero Marsh/Lagoon Complex.

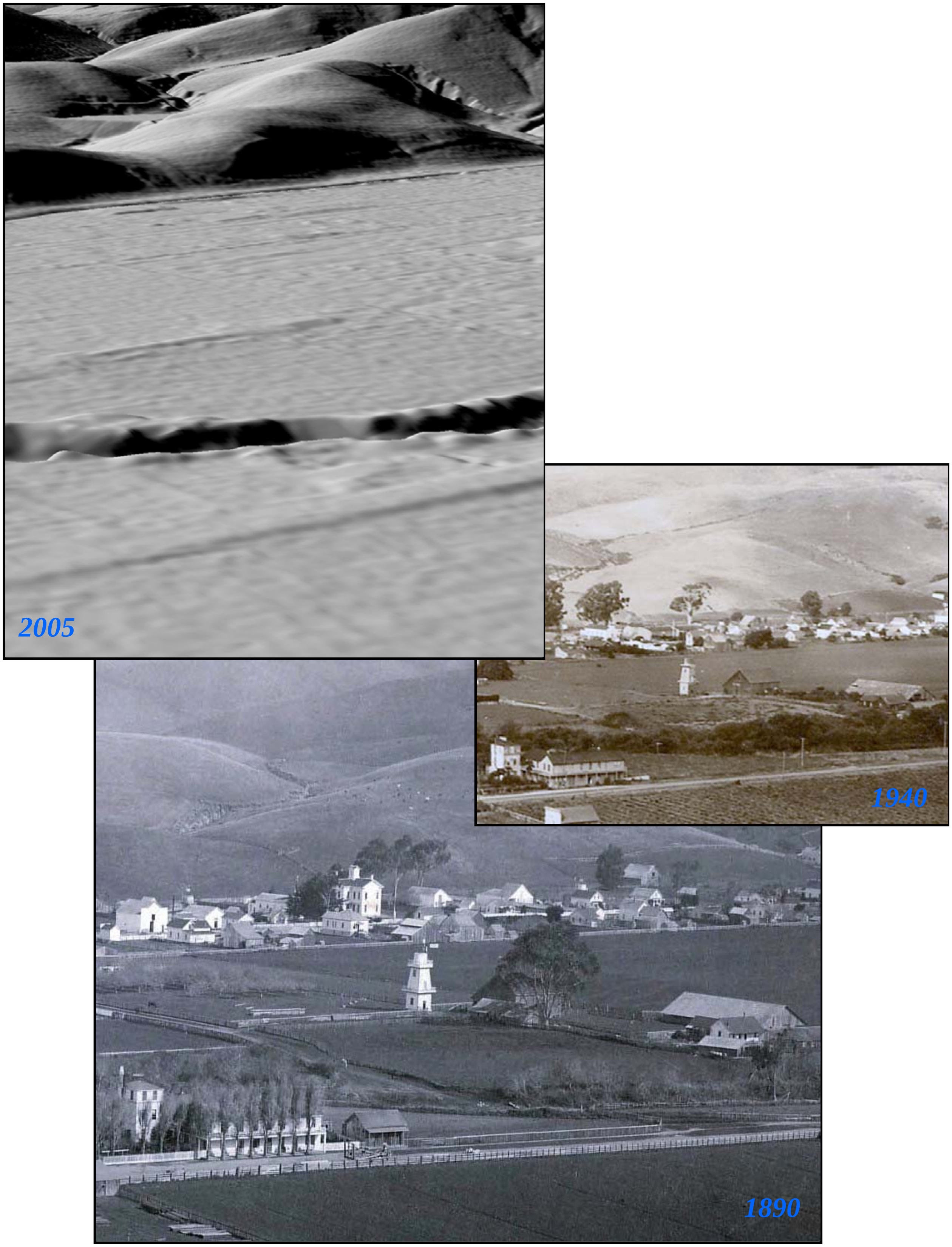
Given the sustainable forestry practices within the active timberlands post-1973, including those of Big Tree Lumber Co. and Redtree Properties, Ltd., the sediment-management treatments should be limited to seasonal management of haul roads and road-watercourse crossings. Within the former timberlands, presently State and County parks, the potential for erosion and sediment excavation from within the post-1920 timbering-related debris-flow sediment deposits should be evaluated, to identify management actions needed to prevent the remobilization of the sediment storage within these medium-scale landforms in the future.

While the road-related sediment delivery amounts of a mere fraction of the total watershed sediment delivery in the period 1990-2010 (9%), the road-watercourse crossings across the entire watershed, including the agricultural lands, timberlands, ranchlands (including abandoned), timberlands-turned-parks, and residential lands, should be upgraded, in order to improve sediment passage and reduce the potential for flow diversion and the related sediment generation and/or re-entrainment. Furthermore, special focus should be paid to the repair of the road-watercourse crossings in the areas underlain by the Mindego Basalt, Vaqueros Sandstone, and Butano Sandstone geologic units, to improve the passage of the coarse, cobble-boulder streambed substrate. It is recommended that all road and road-watercourse crossing repair activities be prioritized, utilizing the spatially-explicit Sedmodl2 maps developed for the Pescadero-Butano Watershed by the author of this memorandum.

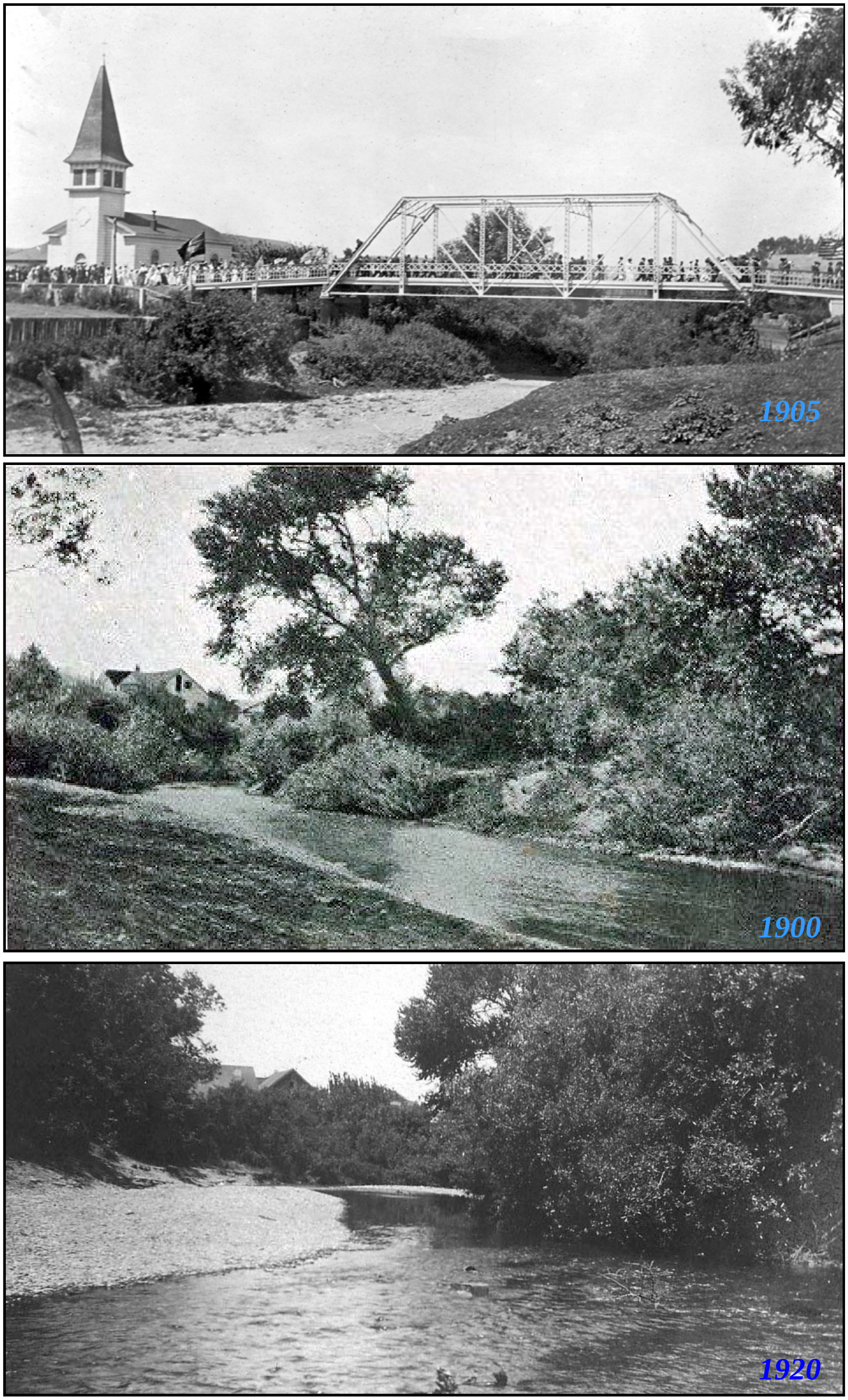
Lastly, it is recommended that the flood mitigation actions rely only on minimal dredging, unless only short-term (emergency), and instead focus on the following measures: the deployment of a cost-effective, portable and adaptable interlocking mechanical barrier-type flood containment solution (such as the Muscle Wall, and other barrier types) in the short-term, and on point-source and chronic sediment control across the watershed in the medium- to long-term. In the event of emergency dredging activities within the estuary, it is recommended that the excavated sediment be placed in the hillside gully voids, in the coastal hills in close proximity to the Pescadero Marsh/Lagoon Complex.



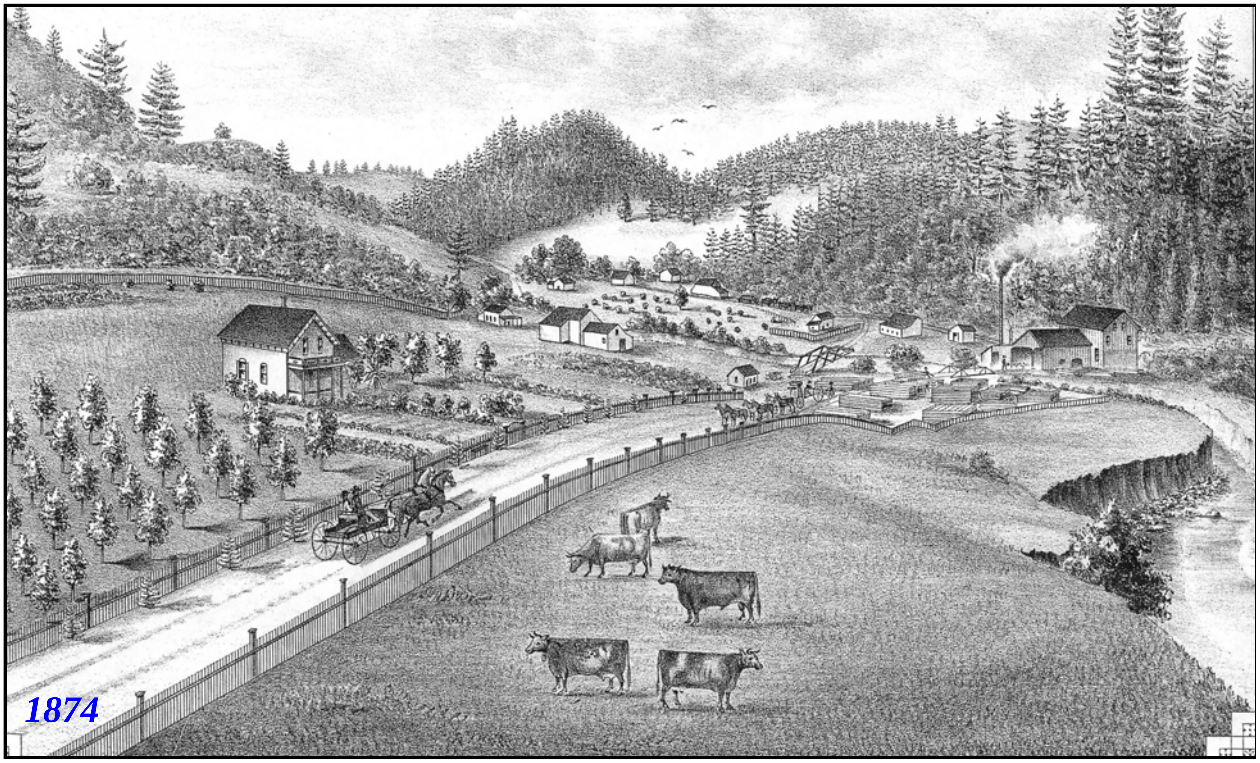
Looking east at Pescadero Marsh/Lagoon Complex from Highway 1 bridge, same view in 1915 and 2010.

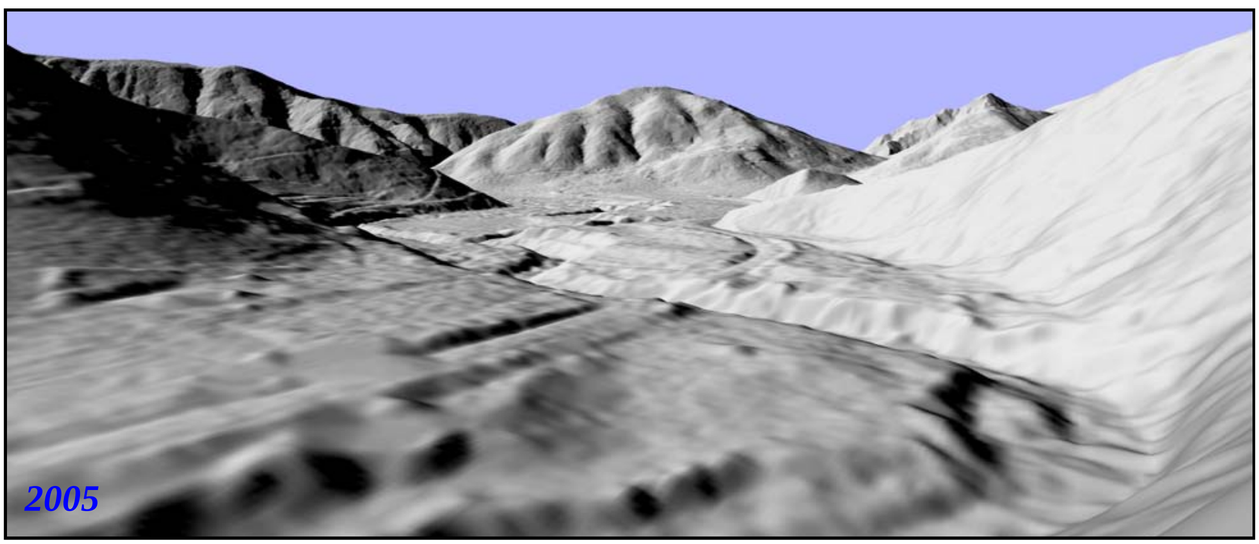


Looking northeast across lower Pescadero Valley, Pescadero Creek, and Pescadero Road. Note progressive hillside gullying and channel incision from 1890 to 2005.

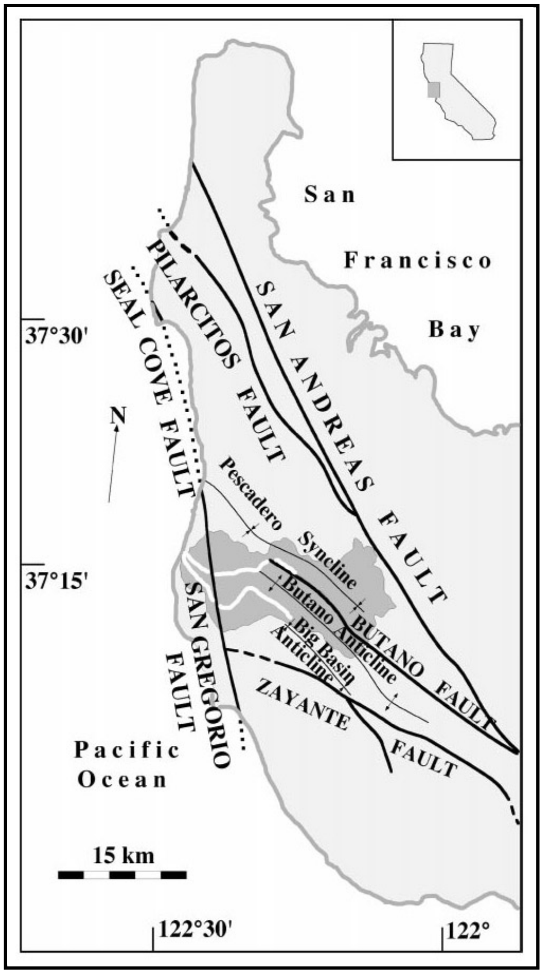


Pescadero Creek, historic tidal reach 1900-1920.





Alluvial-fan reach of Pescadero Creek at Hayward Mill site (present-day USGS gaging station) in 1874 (from Brown 1874). Compare to rendering of same view using San Mateo County LiDAR DEM (2005). Note age of timber stands on hills upstream from mill, and fresh channel incision downstream from mill in 1874. Note channel deepening and lateral migration toward valley wall from 1874 to 2005, by an estimated 1.5 meters and 15 meters, respectively.



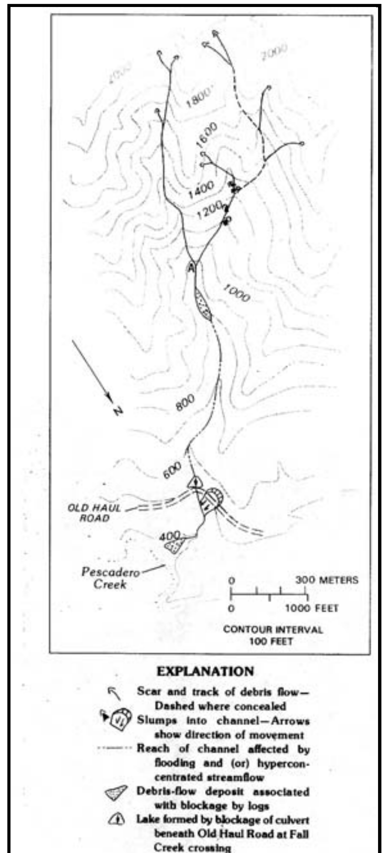


FIGURE 8.8.—Features related to slides, flows, and hyperconcentrated floods in Fall Creek drainage, San Mateo County. Two major debris-flow tracks joined at point A. Topographic base modified from map of Pescadero Creek by San Mateo County Department of Public Works.

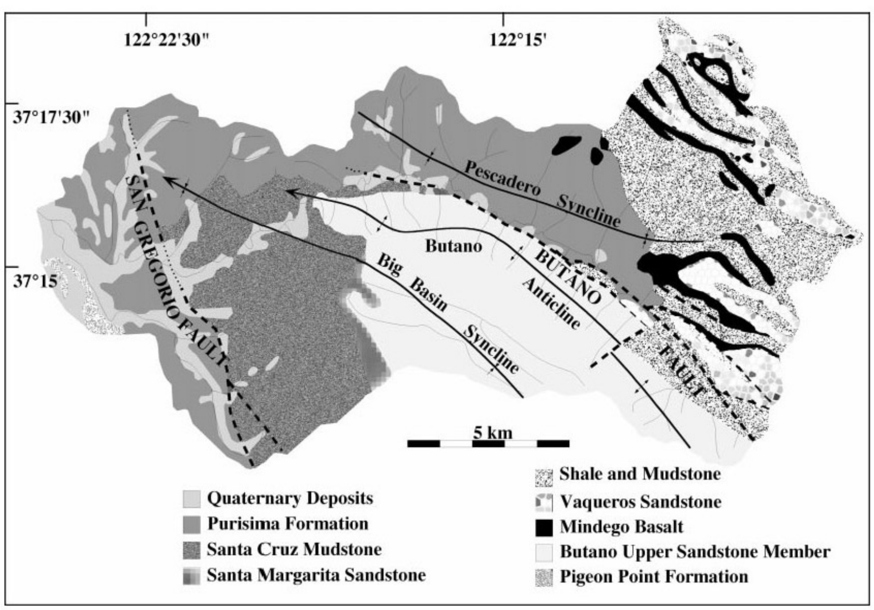
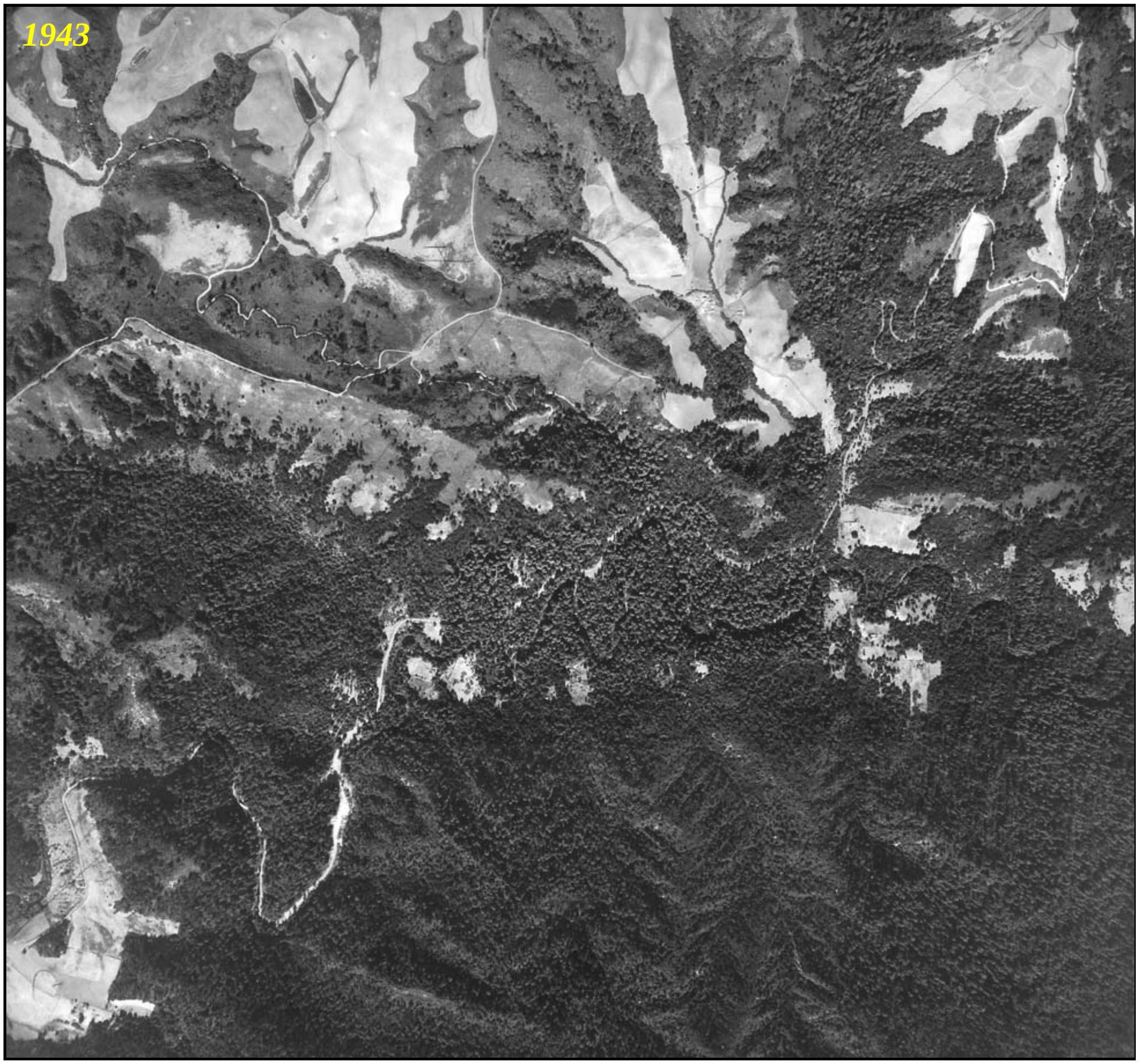


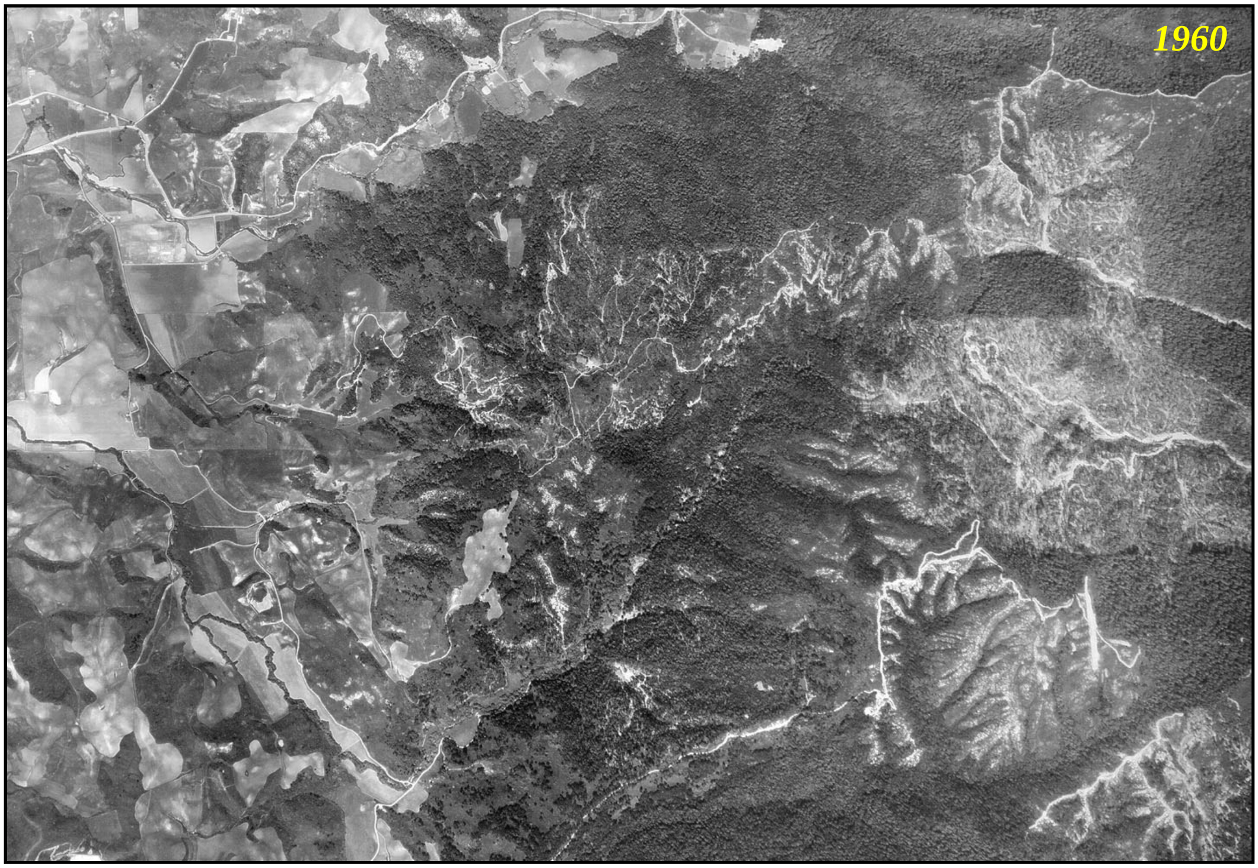
Figure 2. Geologic map of the Pescadero Creek watershed (adapted from *Brabb and Pampeyan* [1983] and *Brabb* [1989]).

Geology, faults, and tectonic setting of Pescadero-Butano Watershed.

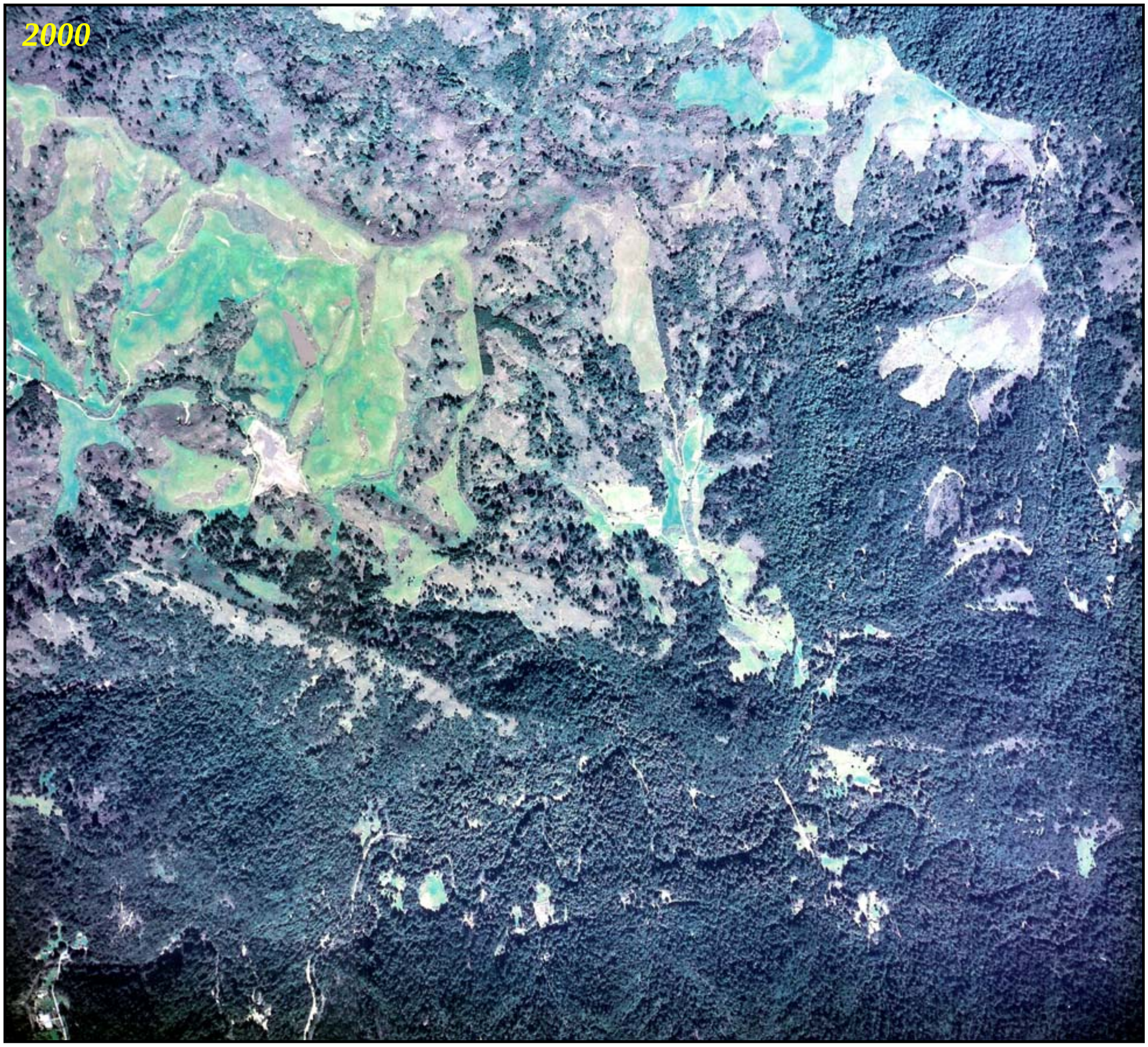


View of bedrock canyon reach of Pescadero Creek in 1943 (USDA-NRCS 1943). Note deforestation of McCormick Creek and Jones Gulch watersheds due to timbering activities starting in 1930s, and canyon benches (strath terraces) due to permanent conversion to recreational areas starting in 1930s. USGS gaging station located in (deforested) alluvial valley floor permanently converted to agricultural and ranching activities post-1860 in left lower corner of photograph.

View of alluvial-fan valley reach of Pescadero Creek (USDA-NRCS 1943), showing (deforested) alluvial valley floor permanently converted to agricultural and ranching activities post-1860. USGS gaging station located in right upper corner of photograph.



View of Butano Creek watershed (USAF 1960). Note deforestation of upper Butano Creek Sub-Watershed and lower Pescadero Creek Sub-Watershed timberlands and rangelands due to timbering activities starting in 1940s and 1950s, respectively.



View of bedrock canyon reach of Pescadero Creek in 2000 (WAC 2000). Note unchanged conditions in McCormick Creek and Jones Gulch watersheds, which were partially deforested in 1930s, due to ongoing timbering activities.

ACKNOWLEDGEMENTS

Martin Trso, California Professional Geologist No. 7216, Certified Professional Geologist No. 11475, Certified Professional in Erosion and Sediment Control No. 5590, and Qualified Stormwater Pollution Prevention Plan Developer/Practitioner No. GO7216 was the principal investigator for the geomorphic, land-use, and sediment source assessments presented in this memorandum. Martin Trso, P.G. DBA Balance Geo is a registered sole proprietorship and California registered small business owned and independently operated by Martin Trso since 2001.

In February 2010, Martin Trso was retained by William E. Dietrich, Ph.D., professor of geomorphology at the Department of Earth and Planetary Science, University of California, Berkeley, to conduct a geomorphic, land-use, and sediment source investigation for the Pescadero-Butano Watershed in San Mateo County to inform the Pescadero-Butano Watershed Sediment TMDL (Region 2 Water Board 2013a, 2013b, 2013c, 2015) and the Pescadero and Butano Creeks salmonid population dynamics modeling study (Stillwater Sciences, Inc. 2015), funded by the Cal/EPA's State Water Resources Control Board. (As part of his public service, Professor Bill Dietrich retained Martin Trso and Stillwater Sciences as independent research contractors, and provided his technical guidance on both projects.) The geomorphic, land-use, and sediment source investigation by Martin Trso to benefit the Pescadero-Butano Watershed Sediment TMDL involved the following: the development of hypotheses concerning the natural state of sediment delivery and sediment transport, stream channels, floodplains, and Pescadero Marsh/Lagoon; an assessment of the watershed's natural disturbance and land-use history since 1820; the assessment of the geomorphic response to post-1820 natural disturbance and land-use, including the transformation of the channel network, floodplains, and Pescadero Marsh/Lagoon; the identification of natural and anthropogenic sediment sources on hillsides and along the watercourses; and the construction of closed, grainsize-specific, and causal-mechanism specific sediment budgets for the pre-1820, 1820-1920, 1920-1970, 1970-1990, and 1990-2010 periods. The salmonid population dynamics modeling (the model is titled RIPPLE, Dietrich and Ligon 2009) is a digital-terrain based model (DTM) that characterizes the geomorphic and ecological processes that create and maintain freshwater salmon habitat, predicts the distribution of fish habitat conditions throughout a watershed, and simulates salmon population dynamics. The geomorphic, land-use, and sediment source investigation by Martin Trso to benefit the Pescadero-Butano Watershed RIPPLE involved, in addition to the assessment of the transformation of the channel network, floodplains, and the Pescadero Marsh/Lagoon Complex, the collection of field data on stream channel dimensions and channel morphology, as well as the development of hypotheses concerning the pre-1820 locations of rearing and spawning reaches for steelhead trout (*Oncorhynchus mykiss*) and coho salmon (*Oncorhynchus kisutch*).

Eric Donaldson, P.G., currently a Staff Geomorphologist/Hydrologist at Balance Hydrologics, Inc., and Jake Wilson, currently a Staff Environmental Scientist at San Francisco Bay Regional Water Quality Control Board, assisted Martin Trso on twenty day-long field surveys in 2010 to collect the field data used to develop the assessments of historic geomorphic change and sediment sources. Michael Napolitano, P.G., a Staff Engineering Geologist at San Francisco Bay Regional Water Quality Control Board, Professor Bill Dietrich, and Jeffrey Prancevic, currently Ph.D. Candidate at California Institute of Technology, also assisted with data collection on two day-long field surveys. Professor Bill Dietrich, Michael Napolitano, P.G., and Setenay Bozkurt

Frucht, P.E., a Staff Water Resources Engineer at San Francisco Bay Regional Water Quality Control Board, provided a review of the interim products of the geomorphic, land-use, and sediment source investigations and assessments.

Dino Bellugi, Ph.D. (currently a Postdoctoral Fellow at Massachusetts Institute of Technology) and Ionut Iordache (currently a Software Engineer at Google, Inc.) of Professor Bill Dietrich's research group provided GIS (Geographic Information Systems) modeling, DTM, and production assistance to Martin Trso as it related to the resampling and application of the LiDAR (Light Detection and Ranging) 2-meter DEM (digital elevation model) of the Pescadero-Butano Watershed (San Mateo County 2005). Rafael Real de Asua, a Senior GIS Analyst at Stillwater Sciences, Inc., provided some interim GIS and DTM products to Martin Trso, which additionally helped with scoping and planning the field effort on the geomorphic investigation, and with GIS modeling of sediment delivery.

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Tess Black with Rob Skinner provided invaluable historic ground photography documenting valley and channel conditions in the lower Pescadero Valley (i.e. historic swampy meadow) spanning the period 1865-1920, and Al Sollars provided vital personal accounts of the valley and channel conditions in the middle Butano Valley (i.e. alluvial-fan reach of Butano Creek) spanning the period 1919 (when he was three years old) to 2010.

I would also like to express my appreciation to many former graduate students, academics, consultants, and concerned citizens for their outstanding contributions to a better understanding of natural geomorphic processes, ecological history, and land-use history of the Pescadero-Butano Watershed. Their published contributions provided much insight and inspiration to my own geomorphic, land-use, and sediment source investigations. In particular, I would like express a special appreciation, in alphabetical order, to Albion Environmental (2004); Balance Hydrologics, Inc. (2003a); Bergolar Geotechnical Consultants (1988); Grafton T. Brown (1878);

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1 PURPOSE AND STUDY APPROACH

In February 2010, Martin Trso was retained by William E. Dietrich, Ph.D., professor of geomorphology at the Department of Earth and Planetary Science, University of California, Berkeley, to conduct a geomorphic, land-use, and sediment source investigation for the Pescadero-Butano Watershed in San Mateo County to inform the Pescadero-Butano Watershed Sediment TMDL (Region 2 Water Board 2013a, 2013b, 2013c, 2015) and the Pescadero-Butano Watershed salmonid population dynamics modeling study (Stillwater Sciences, Inc. 2015), funded by the Cal/EPA's State Water Resources Control Board. (As part of his public service, Professor Bill Dietrich retained Martin Trso and Stillwater Sciences as independent research contractors, and provided his technical guidance on both projects.) The salmonid population dynamics modeling (the model is titled RIPPLE, Dietrich and Ligon 2009) is a digital-terrain based model (DTM) that characterizes the geomorphic and ecological processes that create and maintain freshwater salmon habitat, predicts the distribution of fish habitat conditions throughout a watershed, and simulates salmon population dynamics.

Martin Trso's assessments focused on the assessment of historical channel, floodplain and estuarine changes, watershed sediment delivery, and watershed sediment yield.

Specifically, the geomorphic, land-use, and sediment source investigation by Martin Trso to benefit the Pescadero-Butano Watershed Sediment TMDL involved the following: the development of hypotheses concerning the natural state of sediment delivery and sediment transport, stream channels, floodplains, and Pescadero Marsh/Lagoon; an assessment of the watershed's natural disturbance and land-use history since 1820; the assessment of the geomorphic response to post-1820 natural disturbance and land-use, including the transformation of the channel network, floodplains, and Pescadero Marsh/Lagoon; the identification of natural and anthropogenic sediment sources on hillsides and along the watercourses; and the construction of closed,[11] grainsize-specific, and causal-mechanism specific sediment budgets for the pre-1820, 1820-1920, 1920-1970, 1970-1990, and 1990-2010 periods. The salmonid population dynamics modeling (the model is titled RIPPLE, Dietrich and Ligon 2009) is a digital-terrain based model (DTM) that characterizes the geomorphic and ecological processes that create and maintain freshwater salmon habitat, predicts the distribution of fish habitat conditions throughout a watershed, and simulates salmon population dynamics. The geomorphic, land-use, and sediment source investigation by Martin Trso to benefit the Pescadero-Butano Watershed RIPPLE involved, in addition to the assessment of the transformation of the channel network, floodplains, and the Pescadero Marsh/Lagoon Complex, the collection of field data on stream channel dimensions and channel morphology, as well as the development of hypotheses concerning the pre-1820 locations of rearing and spawning reaches for steelhead trout (*Oncorhynchus mykiss*) and coho salmon (*Oncorhynchus kisutch*).

The geomorphic, land-use, and sediment source assessments built upon the following: (1) the assembling, review, and interpretation of several dozen technical and research documents and

[11] A complete sediment budget can be expressed by the sediment continuity equation: $\boldsymbol{I} - \boldsymbol{\Delta S} = \boldsymbol{O}$, where: $\boldsymbol{I}$ is the volume of sediment Input to a watercourse, $\boldsymbol{\Delta S}$ is the change in sediment Storage in a watercourse, and $\boldsymbol{O}$ is the volume of sediment Output ('yield') of a watercourse (Dietrich and Dunne 1978, Lehre 1982, Dietrich et al. 1982, Reid and Dunne 1996).

reports[12] developed by multiple agencies, inter-disciplinary programs, consultants, contractors, and non-profit organizations for this watershed over the past 35 years; (2) the acquisition of historic documents, paintings, lithographs, topographic and land grant maps, and ground and aerial photographs spanning the past 240 years; (3) numerous interviews and anecdotal accounts of watershed events and land-use history from private citizens and business owners, many of whom are long-time residents over 85 years of age; (4) extensive field reconnaissance across the Pescadero-Butano watershed, including numerous private properties and the San Mateo County and State parks; (5) the high-resolution geomorphic mapping of the Holocene alluvial valley floor, the alluvial fan and other natural and land-use related depositional landforms; (6) the delineation of the Quaternary deep-seated bedrock slide terrain; (7) the mapping of planform changes (i.e. channel shifting) along the alluvial-valley reaches of Pescadero and Butano creeks over the past 150 years; (8) the delineations of areas of land-use specific disturbance over the past 190 years; and (9) the development of digital terrain models (DTM), based on the San Mateo County's high-resolution digital elevation model (DEM) (2005), of erosion, mass wasting, sediment delivery, and sediment transport and deposition across the Pescadero-Butano Watershed and the Pescadero Marsh/Lagoon Complex.

[12] The technical and research documents and reports focused on the following issues: bedrock geology; soils; hillslope geomorphology and processes; tectonic uplift; seismicity; geologic time-scale landscape denudation; watershed hydrology and processes; fluvial geomorphology; human and wildlife population histories; land-use history; historic and recent erosion, sedimentation, and sediment yield; and the Pescadero Marsh/Lagoon Complex.

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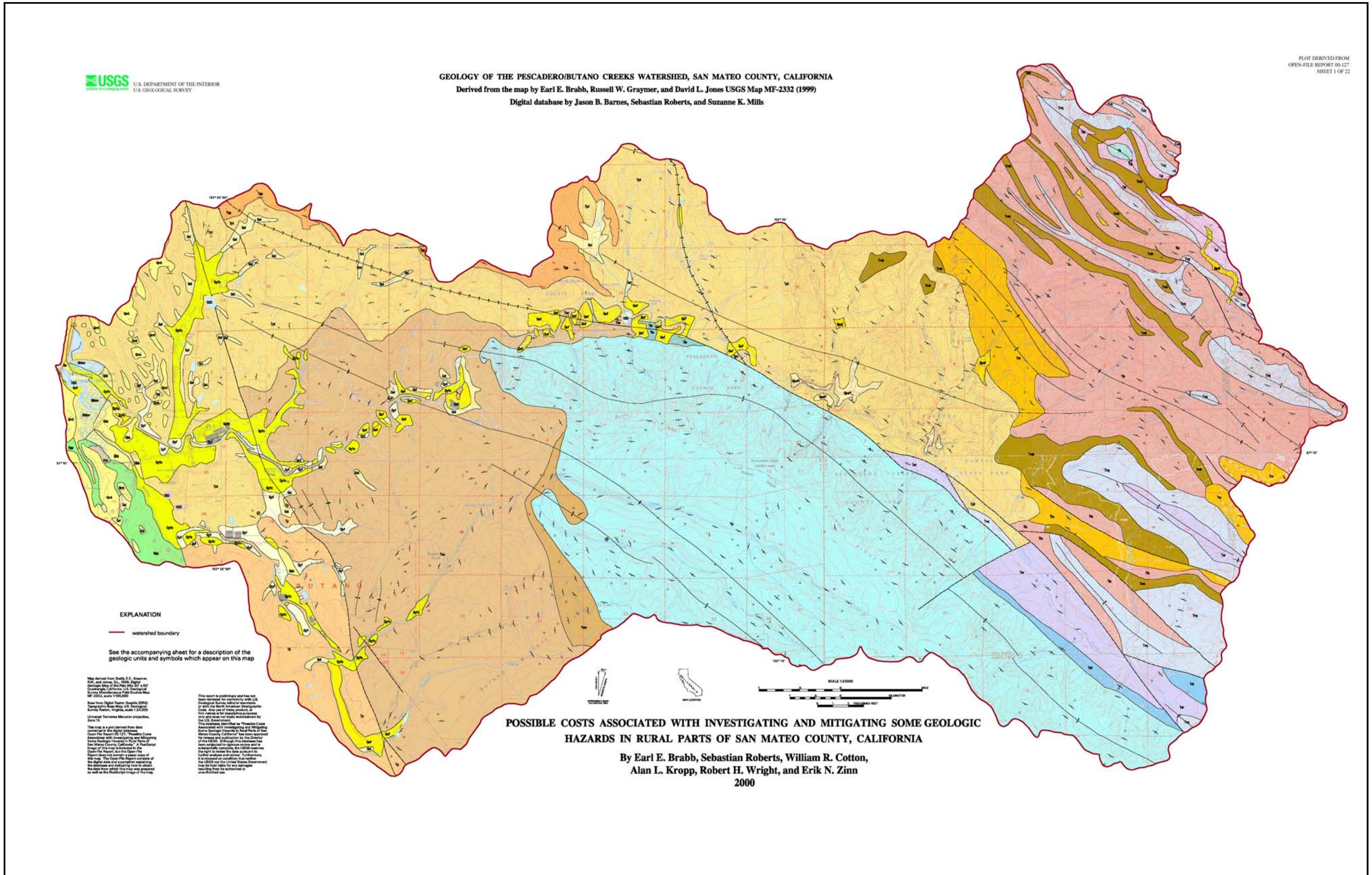
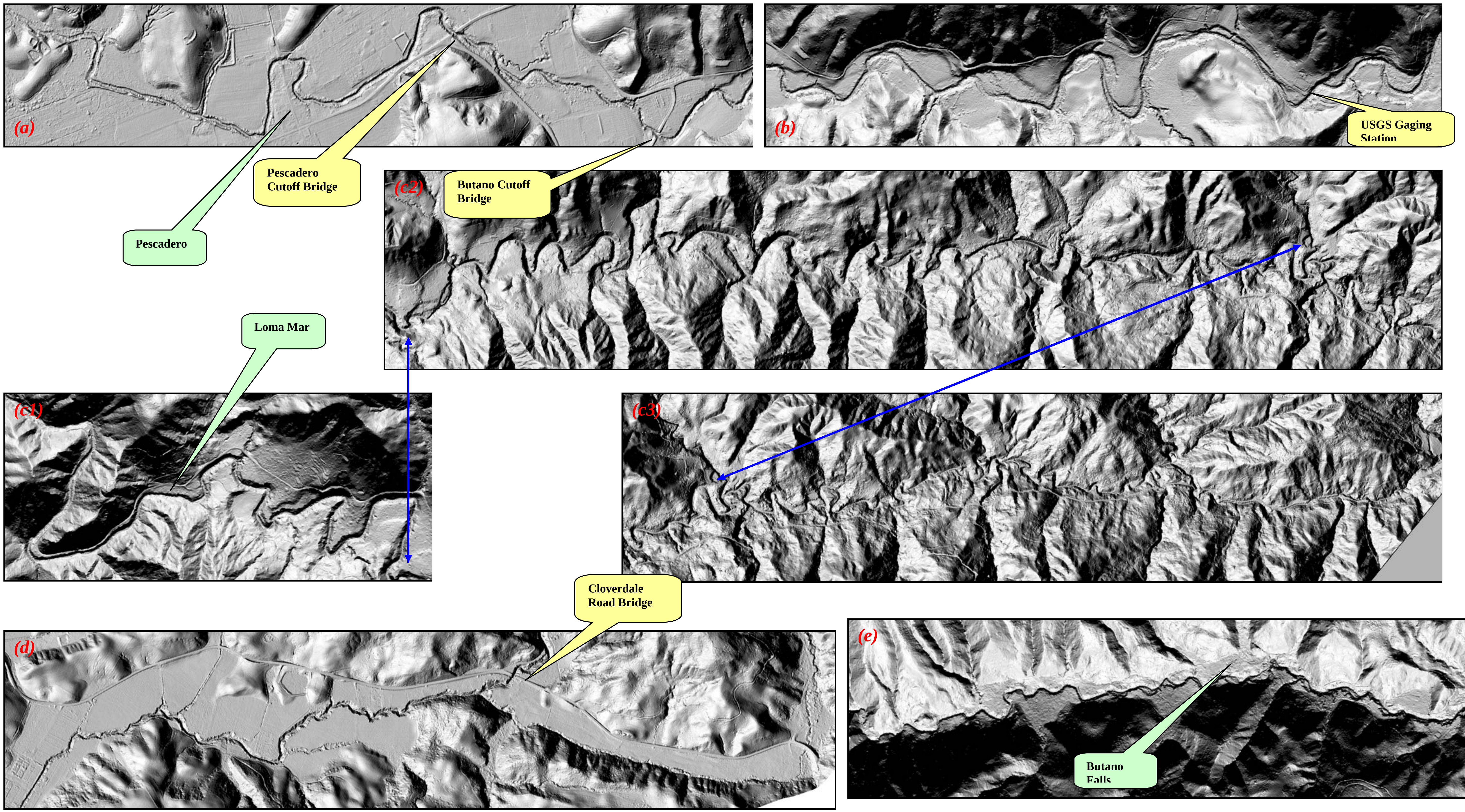
3 GEOMORPHIC AND LAND-USE HISTORY MAPPING

The following section presents the previously disseminated geomorphic synthesis maps, featuring geologic, geomorphic, and land-use history interpretation maps developed during the period February 2010-June 2012 (Martin Trso, P.G. 2012a, 2012b, 2012c).

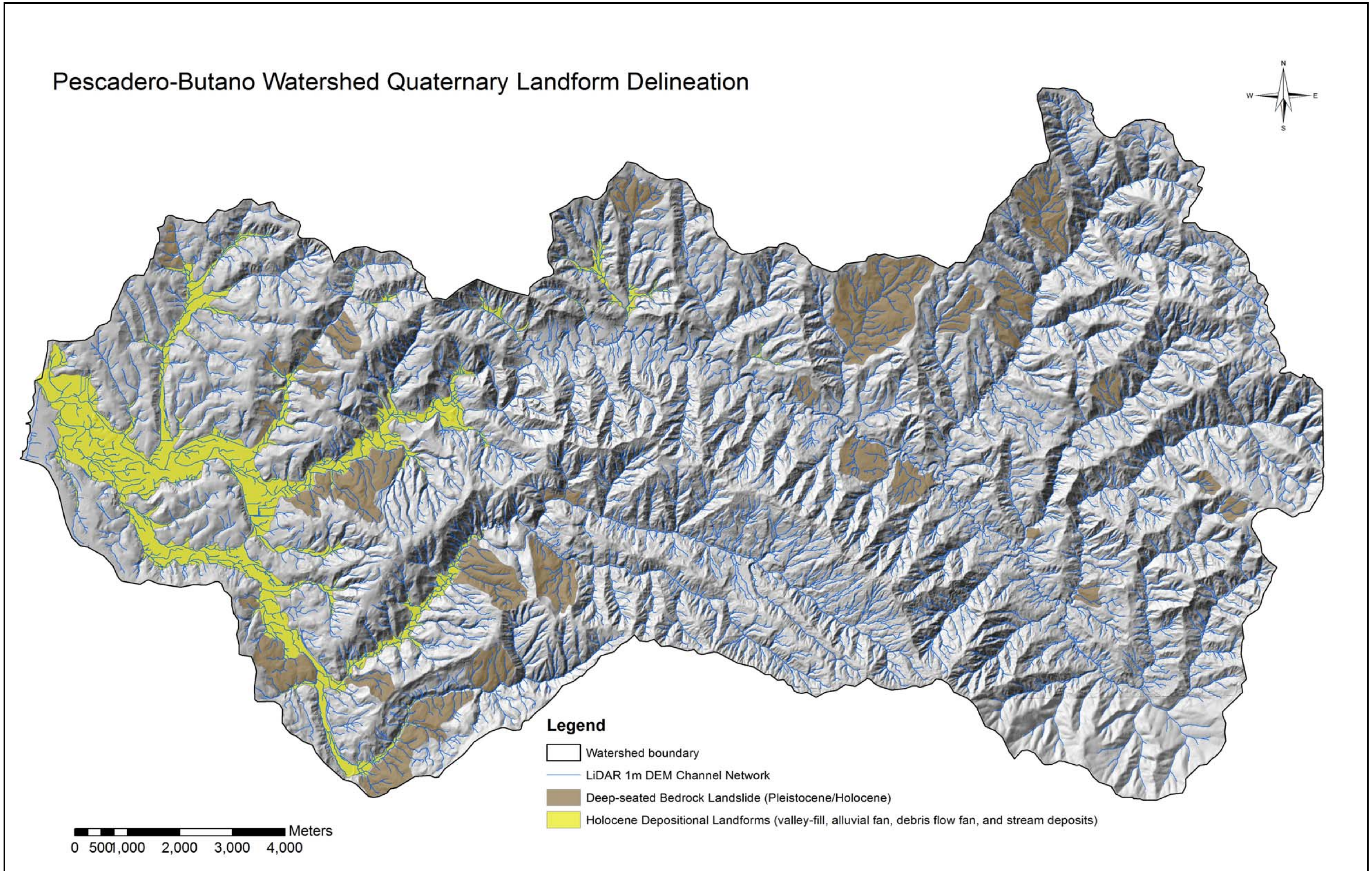


Geology of Pescadero-Butano Watershed (from Brabb et al. 2000).

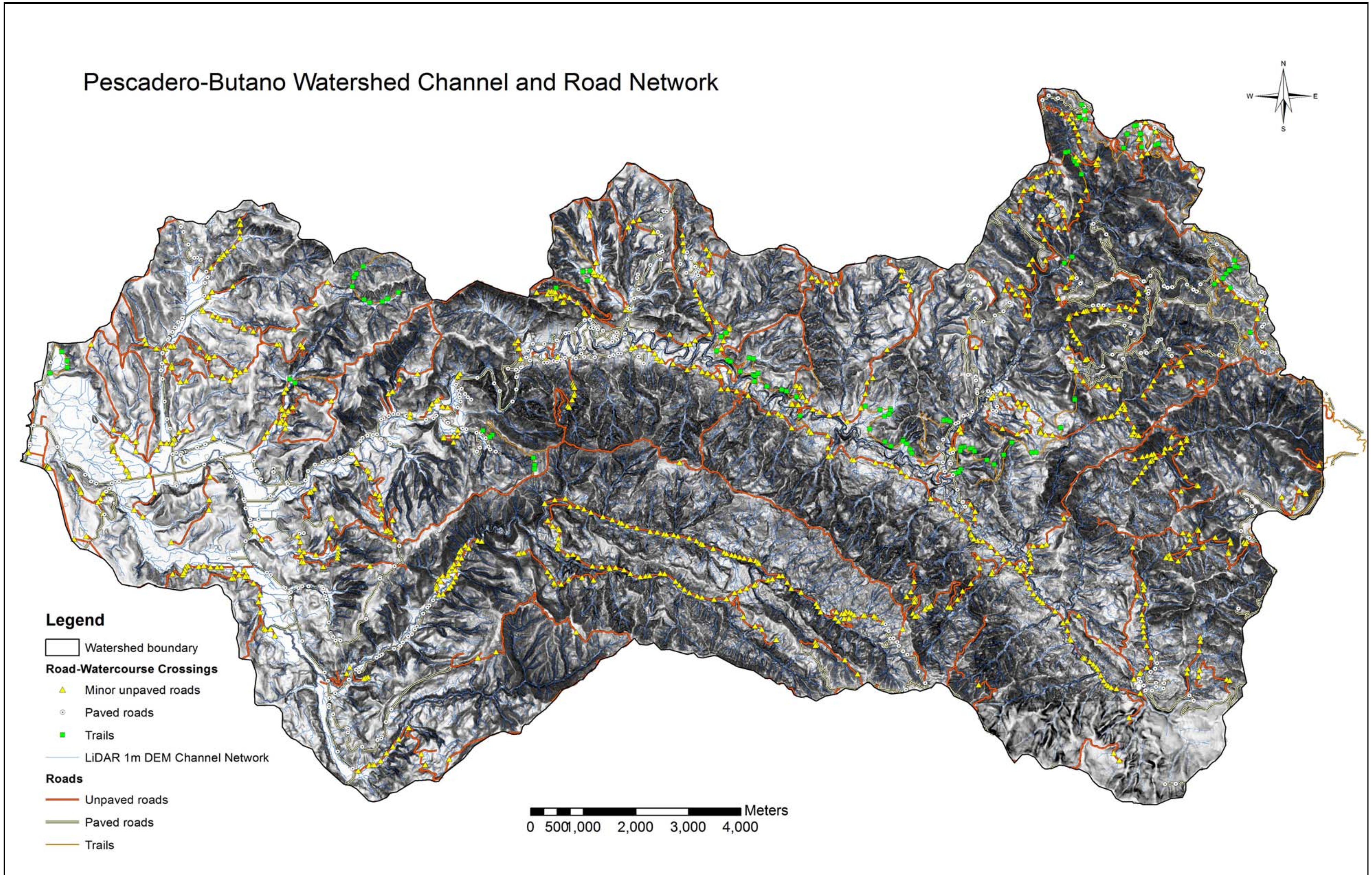


LiDAR 2-meter DEM shaded relief of Pescadero-Butano Watershed: swampy-meadow (a), alluvial-fan (b), and canyon (c1-3) reaches of Pescadero Creek, and swampy-meadow (d) and alluvial-fan (e) reaches of Butano Creek.

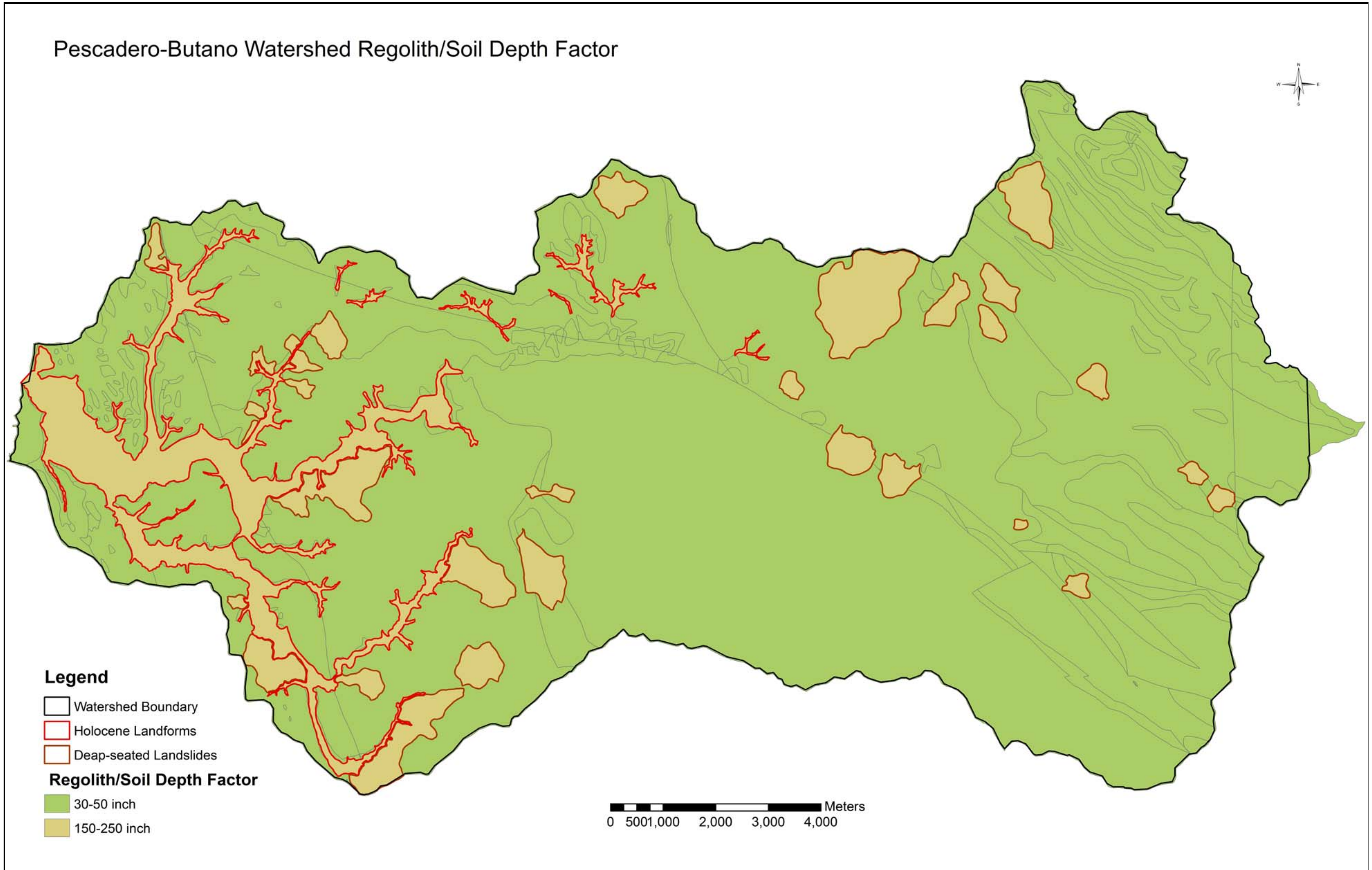
Slope analysis for Pescadero-Butano Watershed (LiDAR 2-meter DEM).



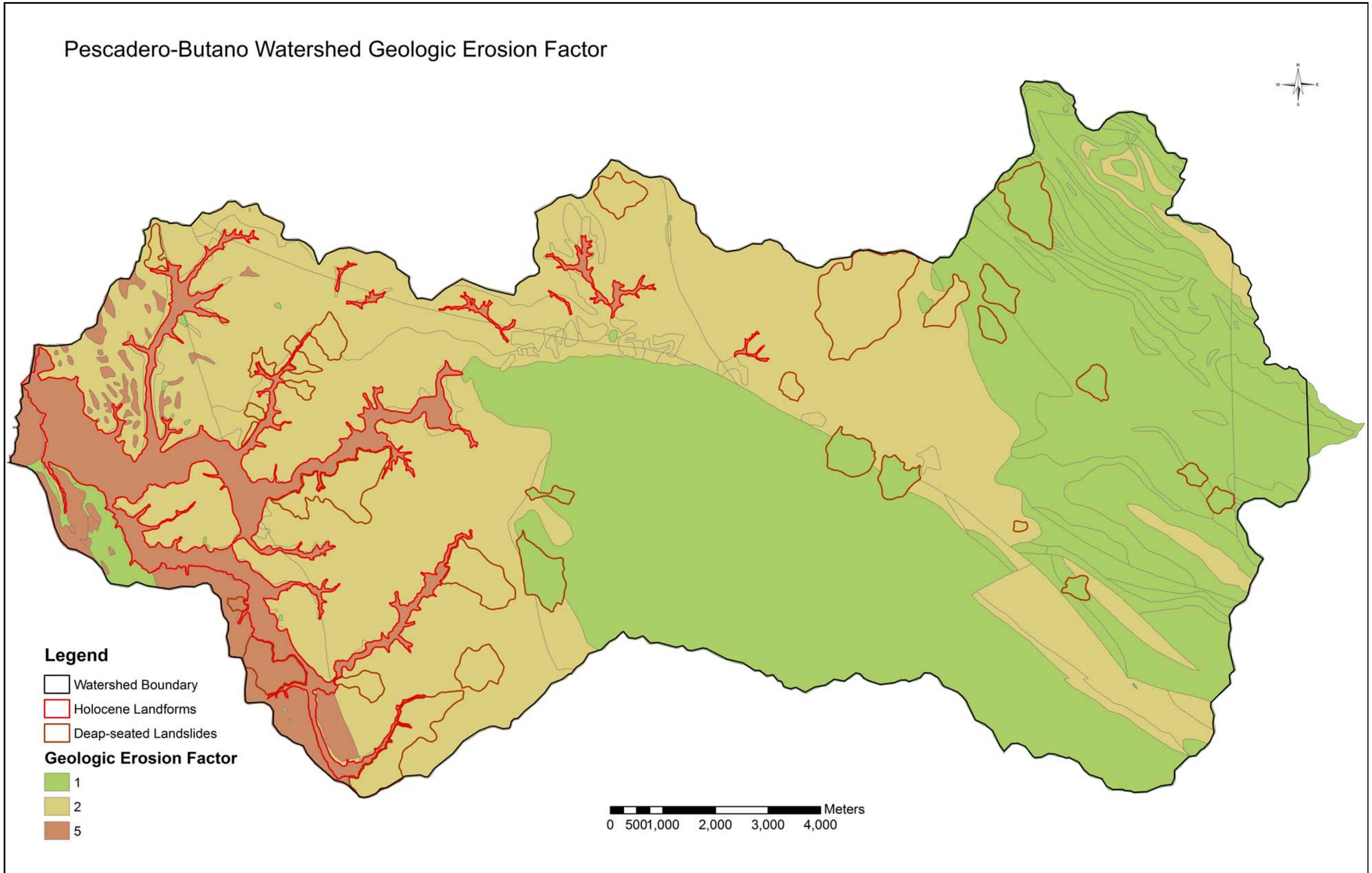
Modeled channel network and Quaternary/Holocene landforms in Pescadero-Butano Watershed: deep-seated bedrock slide terrain, alluvial/debris-flow fans, valley fill.



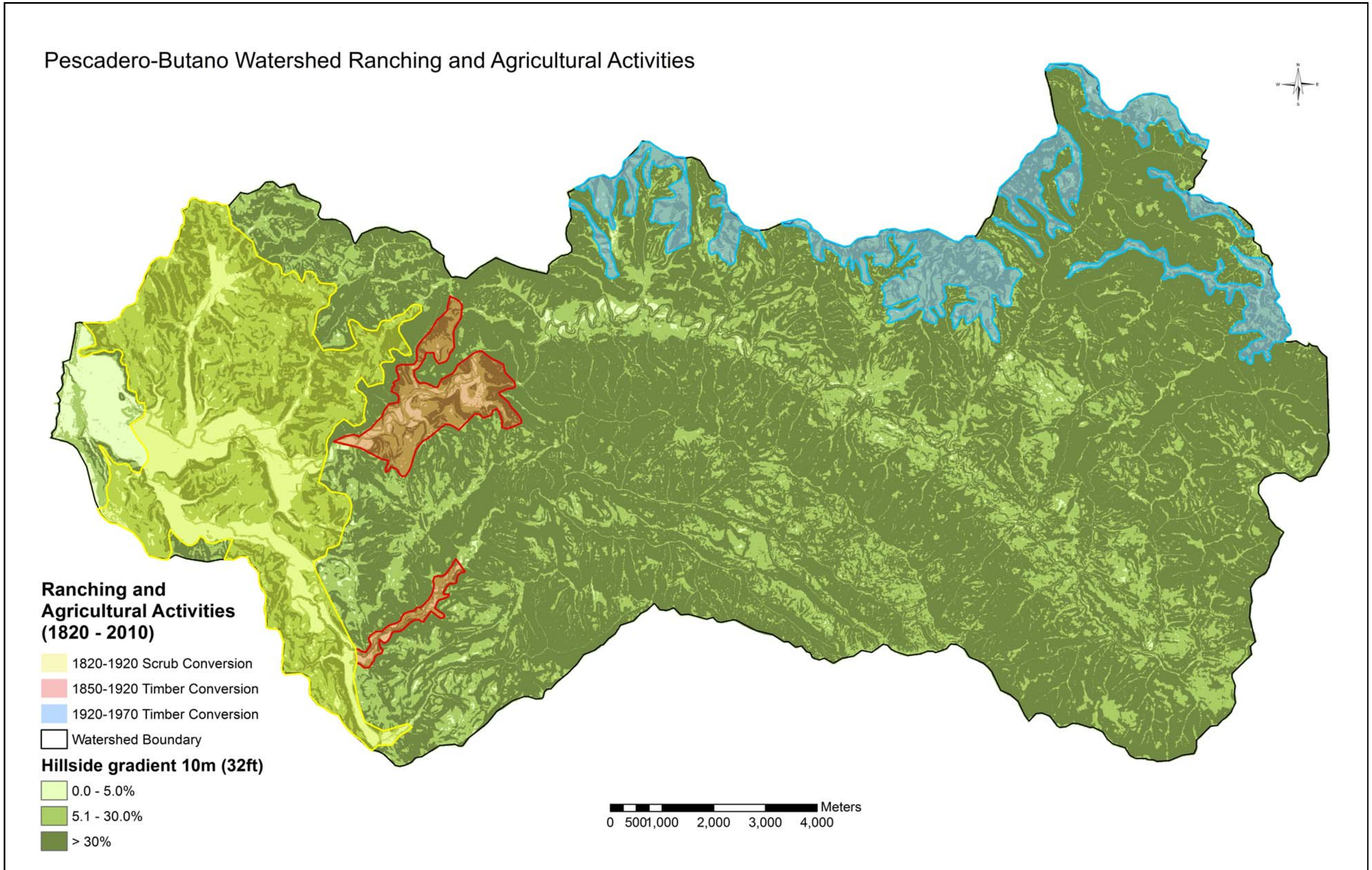
Modeled channel network, road network, and road-watercourse crossings in Pescadero-Butano Watershed (LiDAR 2-meter DEM).



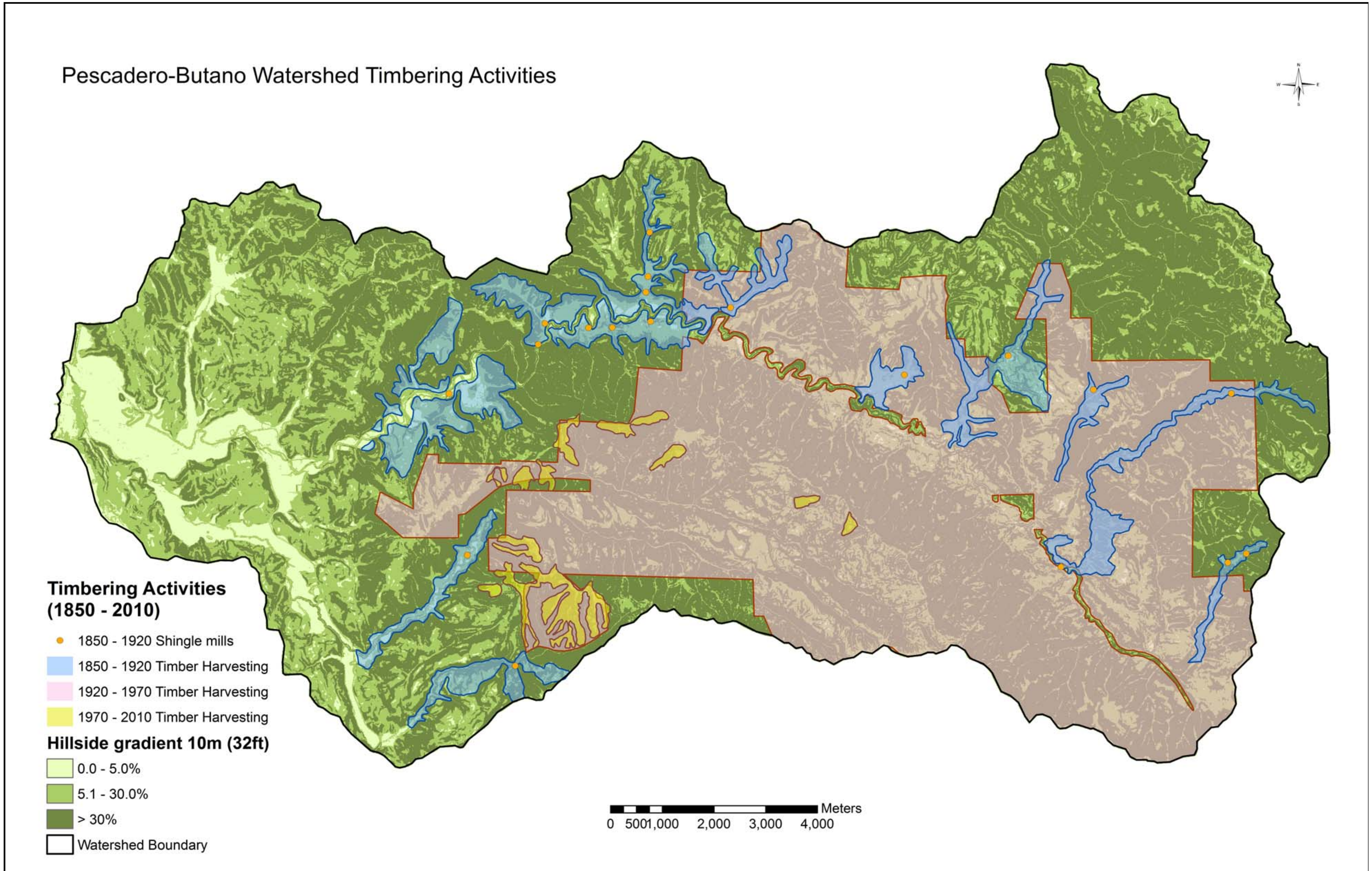
Soil depth in Pescadero-Butano Watershed (SEDMODL2 factor).



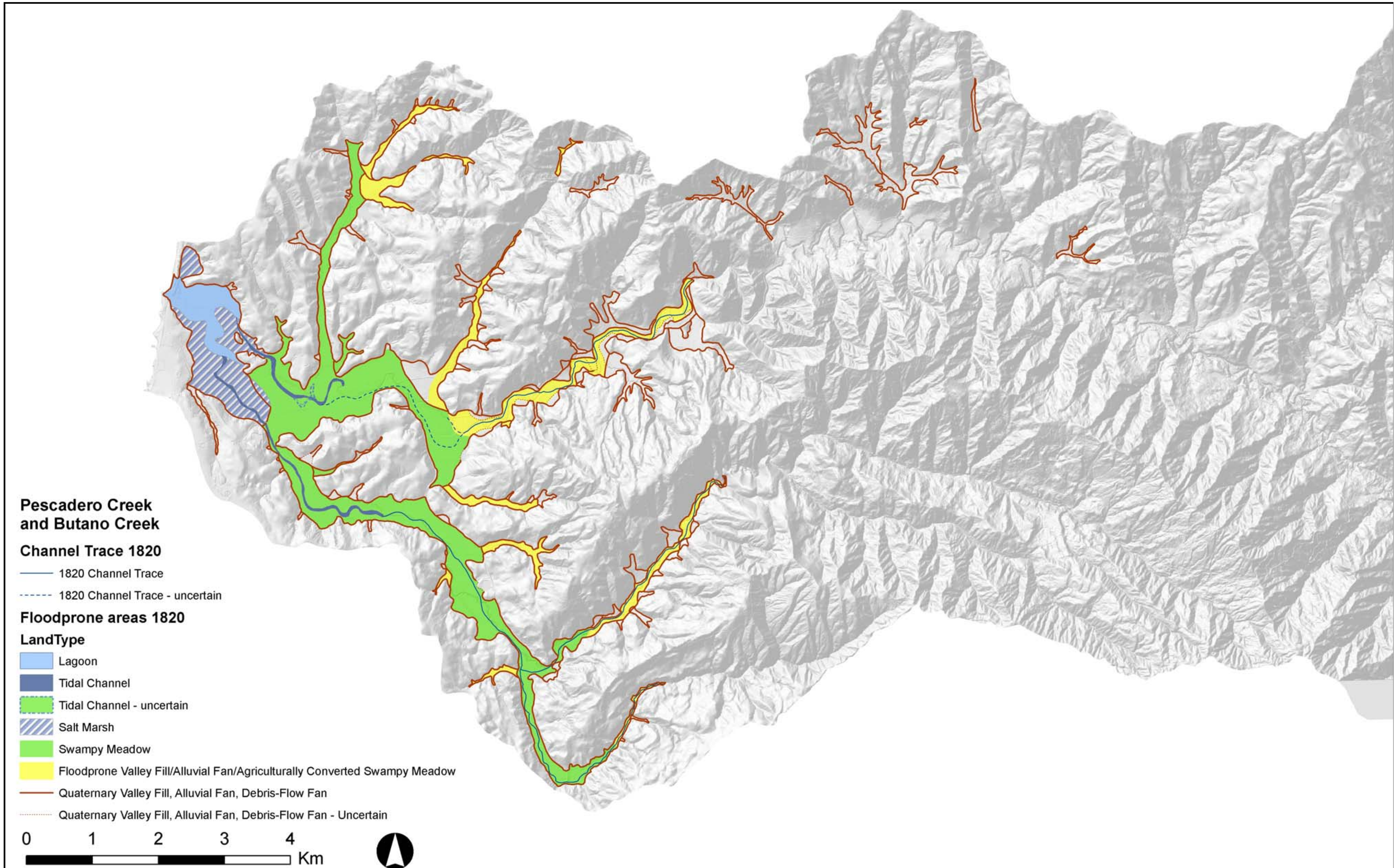
Geologic/bedrock erosion in Pescadero-Butano Watershed (SEDMODL2 factor).



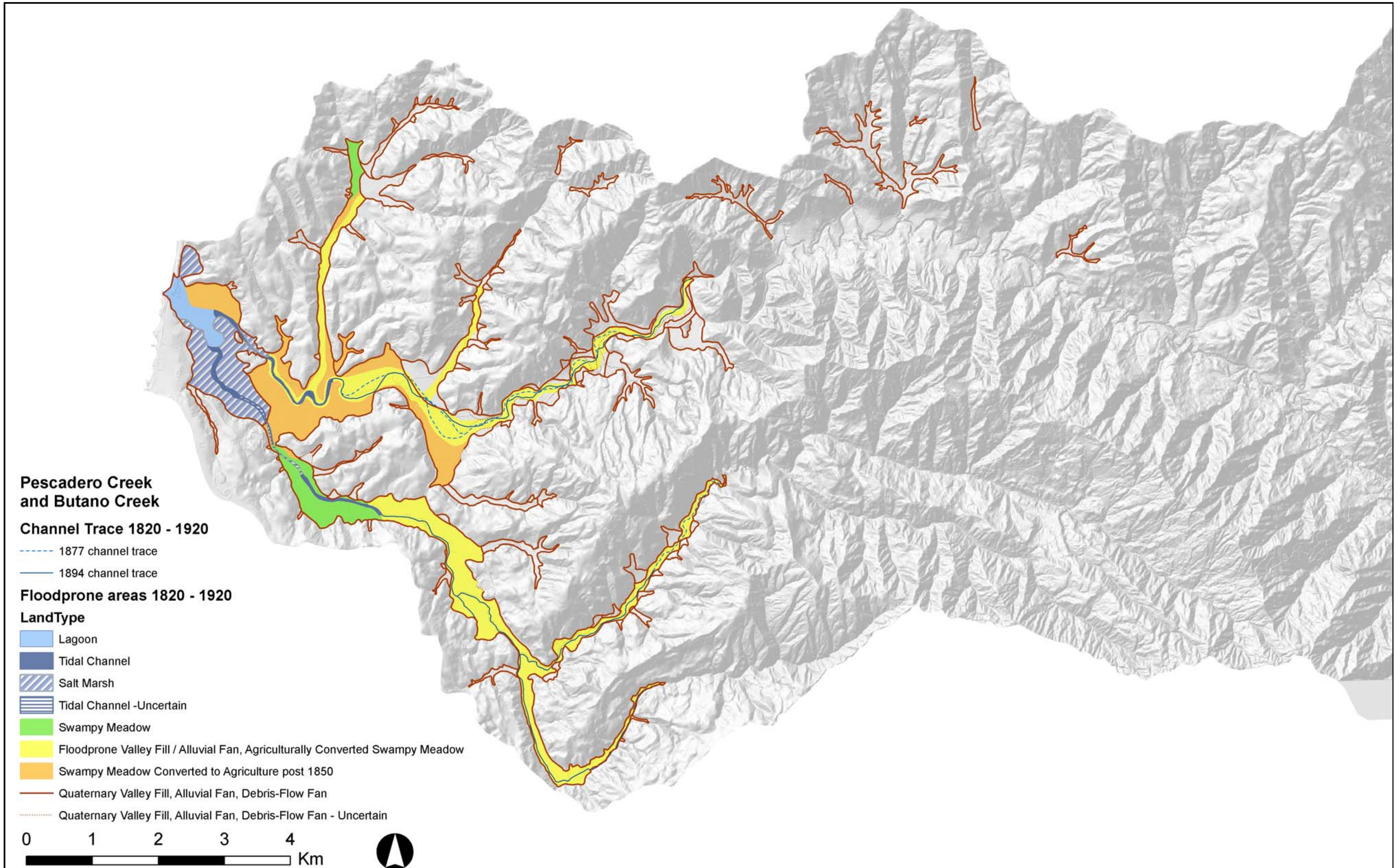
Ranching and agricultural land-use history in Pescadero-Butano Watershed.



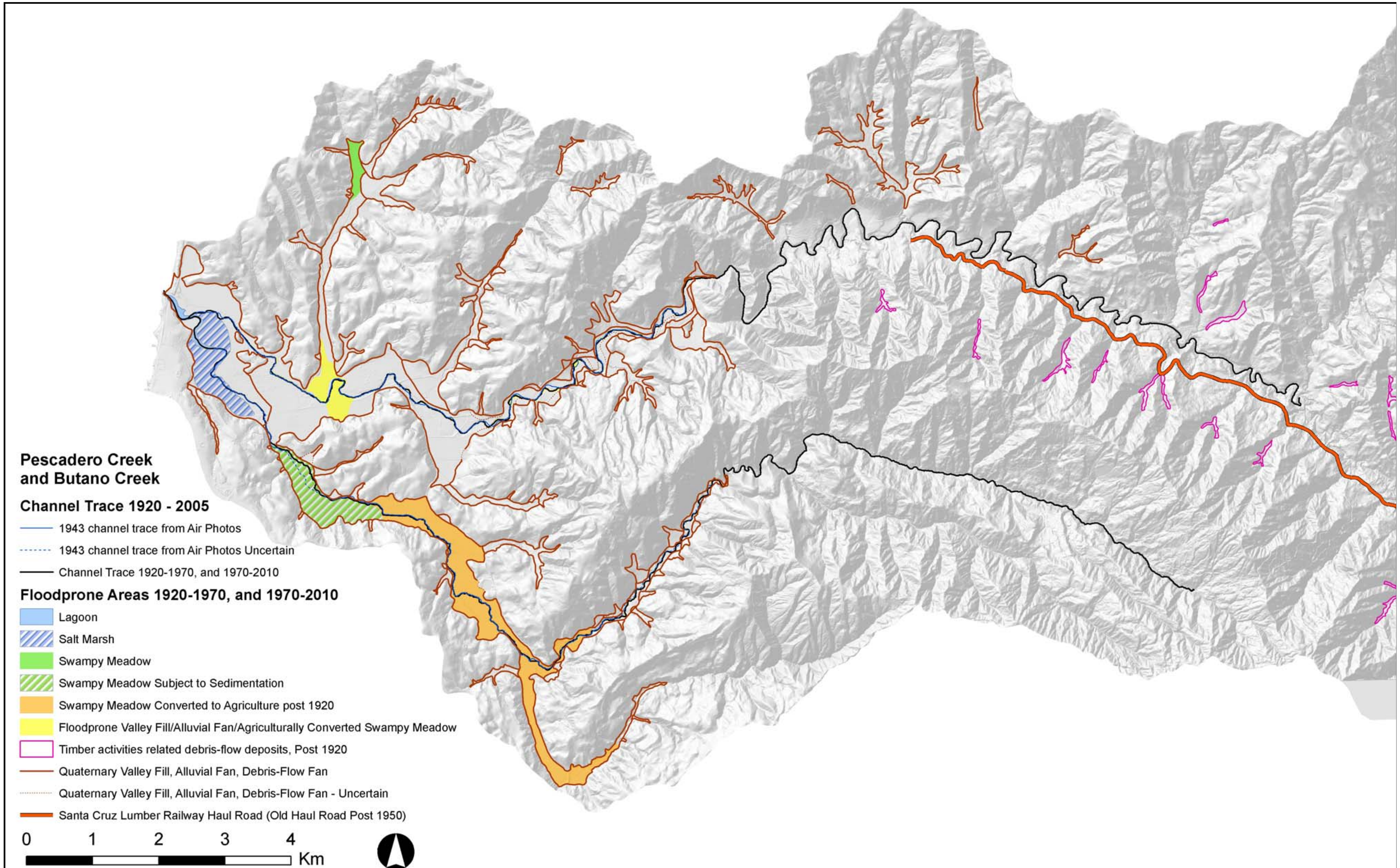
Timbering land-use history in Pescadero-Butano Watershed.



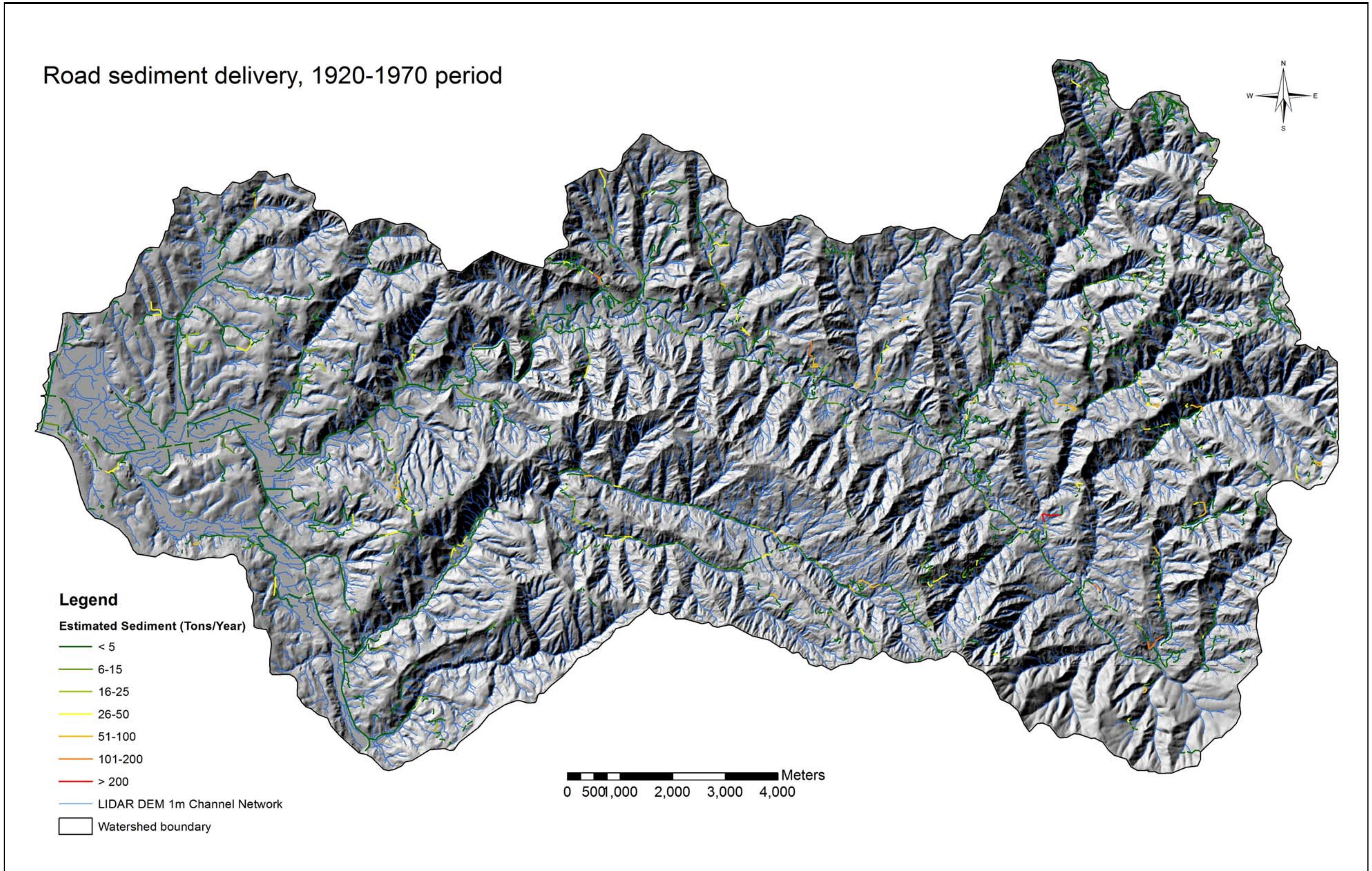
1820 channel, floodplain, and estuarine conditions in Pescadero-Butano Watershed.



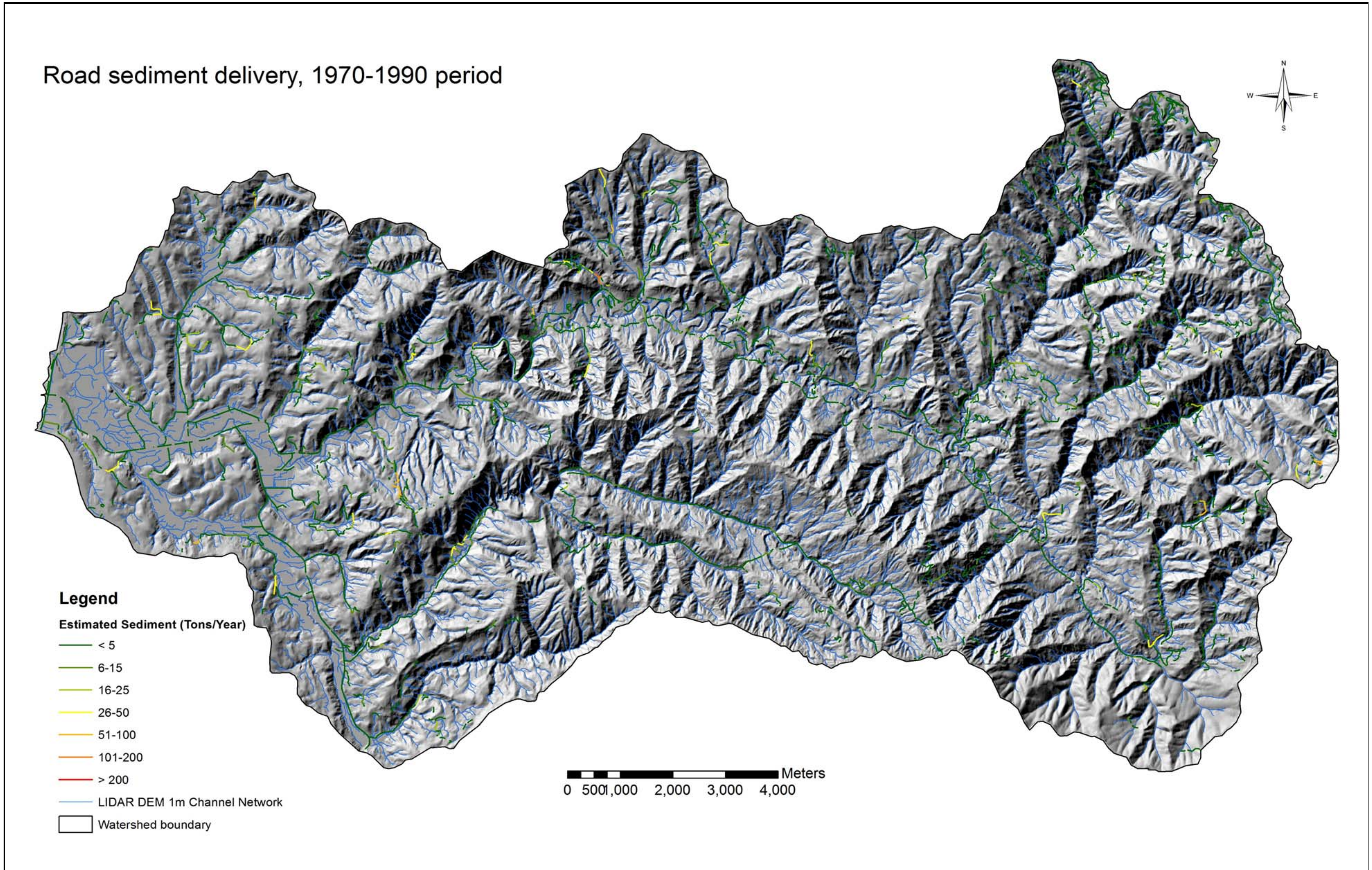
1820-1920 channel, floodplain, and estuarine conditions in Pescadero-Butano Watershed.



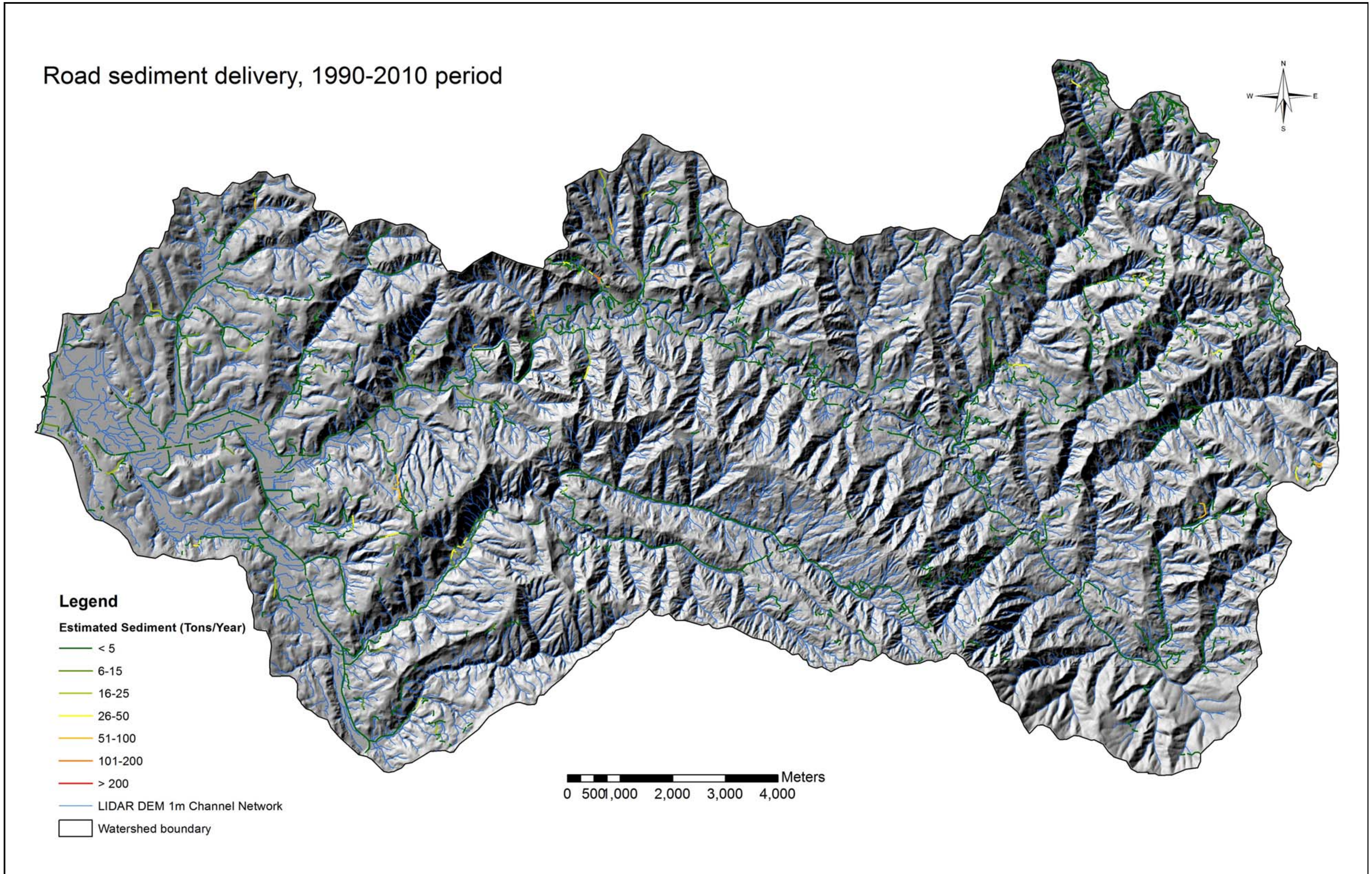
1920-2010 channel, floodplain, and estuarine conditions in Pescadero-Butano Watershed.



Road surface erosion and sediment delivery in Pescadero-Butano Watershed, 1920-1970 (SEDMODL2).



Road surface erosion and sediment delivery in Pescadero-Butano Watershed, 1970-1990 (SEDMODL2).



Road surface erosion and sediment delivery in Pescadero-Butano Watershed, 1990-2010 (SEDMODL2).

4 EVIDENCE OF HISTORIC GEOMORPHIC RESPONSE

The following section is compiled from the previously disseminated technical information, historic paintings, maps, ground photographs, science team presentations, and brief memoranda developed during the period February 2010-June 2012 (Martin Trso, P.G. 2011a, 2011b, 2012a, 2012b, 2012c).

Key Conclusions:

1. **Prior to disturbance, large extensive swampy meadows occurred along lower Pescadero and lower Butano creeks adjacent to the marsh. Along Pescadero, the swampy meadows were drained and mostly disconnected by 1870s. The same impact occurred approx. 50 years later along lower Butano Creek.**

Evidence:

- Interpreted LIDAR DEM generated shaded-relief (SHD), LIDAR DEM 1-meter contour, and LIDAR DEM slope topographic maps; inferred that valleys adjacent to lower mainstem Pescadero and lower Butano are very flat (and hence would be very slow to drain) from valley wall to valley wall; valley walls are comprised of bedrock hills, toes of Quaternary deep-seated bedrock landslides (DSL), or late Pleistocene/Holocene alluvial fans (AF). The DSL and AF landforms are delineated, *see maps PBFloodplainsChannels_1820conditions.jpg, the 1820-1920 and the 1920-1970 floodplains and channels maps, and LandformMapping_template.jpg*);
- Observed features in the lower valleys that appear to be historic—pre-1820—overbank deposits and remnant channels or side channels, indicating that the present-day channels, which are deeply incised and narrowly confined, are not the pre-1820 reference state;
- Noted dark organic rich soils in the lower valleys;
- Produced LIDAR DEM valley/channel transects that also show many of these overbank deposit features; additionally, the transects also reveal absence of uplifted valley-floor surfaces, implying recency as well as the extent of the depositional processes across the entire extent of the lower, swampy valley fills;
- The Butano Creek valley bulges, and the valley fault depression suggest this creek was actively aggrading prior to recent disturbances (all indicative of swampy meadow setting);
- Compiled, reviewed, and interpreted early sketches and property diseño maps (1833-1861), the 1854 USC&GS survey map, early paintings (1855, 1884), and Brown lithographs (1874), all of which are indicative of swampy meadows in the lower valleys;
- Early settler accounts of cattle stranded in mud, and frequent flooding;
- Accounts from the first Spanish expeditions in 1769 (Capt. Gaspar de Portola) and 1774 (Capt. Rivera), who attempted to cross the swampy meadows but failed…they ended up using a native Ohlones trail, which cut across the location of the present-day town of Pescadero, going north along the eastern valley wall of the Bradley Creek valley…they describe the floor vegetation cover, beside grass, as: cottonwoods, alders, willows, and live oaks. They noted that the floors have much good arable land, which could be easily irrigated with the water from Pescadero and Butano creeks (*see report prepared by ESA 2004*);
- Accounts of historic floods, notably those of 1852 and 1862, which inundated the entire valley and destroyed most of the newly-built town of Pescadero; this led to the following immediate response: building a creek crossing on the Coast Road, where it crossed Butano Creek, and shifting the town of Pescaderos' administrative center by a few hundred feet (*after Gregory Timm 2006*);

- All early (1850s) crops in the lower valleys were dry-farmed: barley, wheat and oats;

- Early ground photographs (1867, 1890, 1900), and the Brown lithographs (1874) show channel of Pescadero Creek (it is currently incised 5 meters) within the town of Pescadero; in fact, the channel appears to be unconfined and shallower than 1 meter, both immediately upstream and downstream of the town center;

- The Brown lithograph (1874) showing the Moore Ranch in the Bradley Creek valley reveals that no creek channel existed on the swampy-meadow valley floor in 1874, only an unconfined overland flow pathway;

- The Brown lithograph (1874) showing the Hayward Mill site on Pescadero Creek, at the location of the present-day USGS station, reveals a fresh channel incision downstream of the mill; the mill site is in the alluvial-fan reach of Pescadero Creek; the channel has a rectangular shape, with dimensions estimated at 3 by 3 meters (under the current conditions, the channel dimensions are 4.5m by 15m); given the mill was built in 1855, the incisional process could have been initiated at that time; the area of the then 3-meter-high abandoned terrace appears to have a topographic expression of a natural floodplain;

- Mainstem Pescadero Creek channel ("historic tidal reach") reached as far as the outer extent of the marsh/lagoon, as shown on the 1833-1861 diseño maps; along and downstream of the town of Pescadero, it was ditched/straightened starting in the 1880s, as a flood-control measure; this likely lead to accelerated channel incision and floodplain isolation in the upstream reaches;

- The historic county maps of private ranchos and water works (San Mateo County Office of Public Works 1874, 1877, 1894, 1909, 1927) reveal that the trace of Honsinger Creek was straight, as if ditched; the creek is deeply entrenched in the valley-fill of Pescadero Creek under the current conditions, about 3 meters; based on field observations (vegetation), 1 meter of incision would have been accomplished by about 1940, and the additional 2 meters since then; the top 1 meter of incision may be equivalent to the ditching that may have taken place in the period 1870-1927, while the lower 2 meters (post-1940) may have been basally-induced by the incision of the mainstem Pescadero Creek; interestingly, the degree of the post-1940 incision of Honsinger creek (i.e. 2 meters) matches the observed post-1940 2-4 meter incision (depending on the location) on the mainstem Pescadero Creek along its entire alluvial-fan reach, and the swampy-meadow reach upstream of the town of Pescadero;

- Conducted interviews with several valley-bottom property owners, including Clifford Moore, whose ancestors were the very first settlers in Pescadero, who confirmed that his greatgreatgrandfather manipulated the channel of Pescadero Creek on their property, which is located several hundred feet upstream of town of Pescadero; Mr. Moore confirmed that these efforts continued until only a few decades ago (*see the 1820-1970 planform changes map);*

- Reviewed numerous scientific and historic documents on sedimentation rates within coastal lagoons/estuaries in the central California Coast Ranges, which overwhelmingly indicate the presence of swampy meadows everywhere 200 years ago;

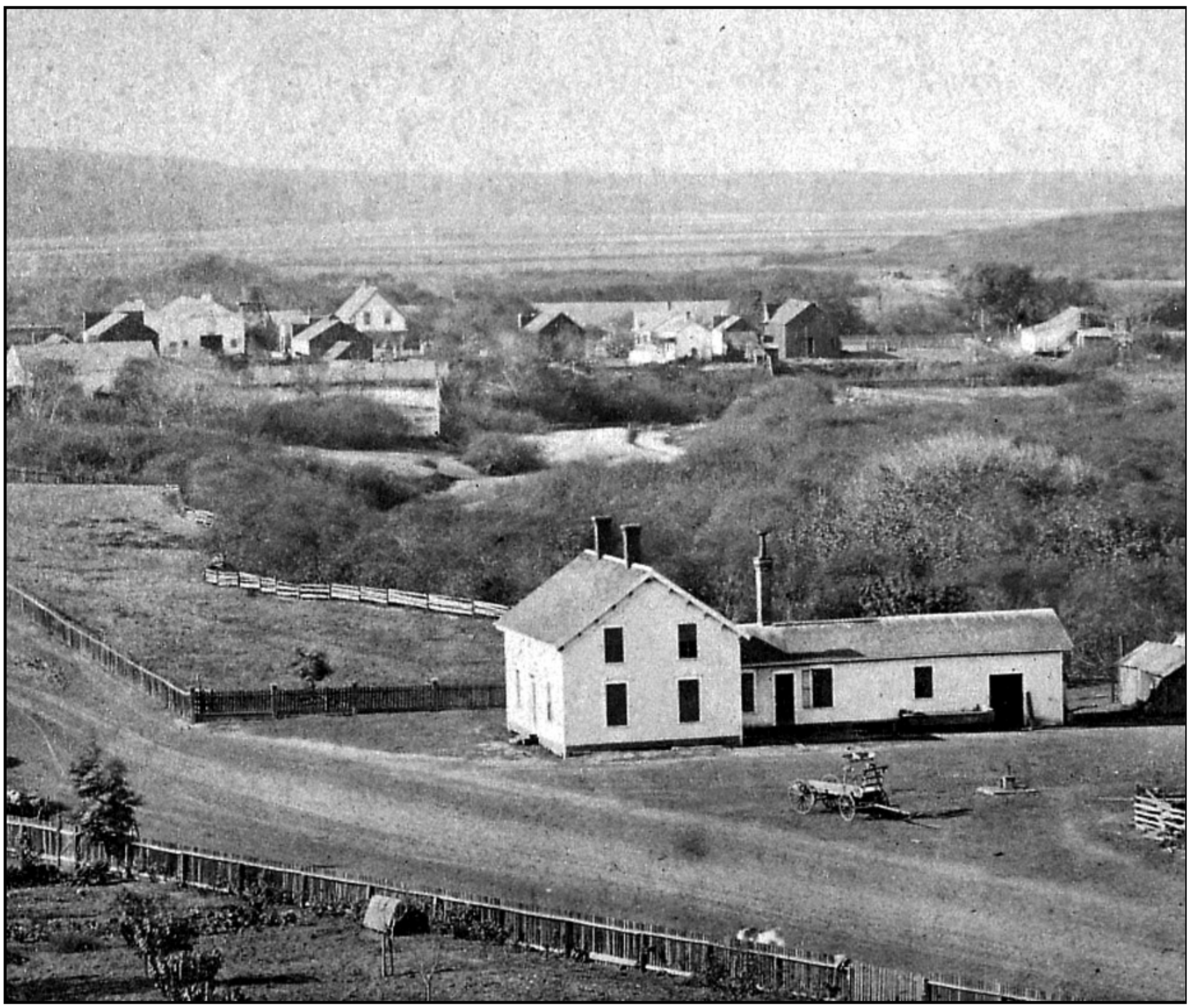
- Documented progressive channel incision, channel switching, and the narrowing of the meander belts along the alluvial reaches of Pescadero and Butano creeks, using historic county maps of private ranchos and water works (San Mateo County Office of Public Works 1874, 1877, 1894, 1909, 1927), the 1874 Brown lithographs, aerial photography (1943, 1953, 1960, 1964, 1970, 2000), and the 2005 Lidar DEM SHD; channel incision on Pescadero Creek initiated around 1860; the present-day entrenched channels of the alluvial-fan and the swampy-meadow reaches of Pescadero and Butano creeks have a vastly different trace compared to their respective channel traces from around 1850-1900 (*see the 1820-1970 planform changes map)*;

- The boundaries of the historic swampy meadows and the historic floodplains were determined using the Lidar DEM SHD imagery, the historic documents described above, and field reconnaissance; the original Pescadero Road was built along the northern valley wall of the Pescadero Creek valley, along the boundary between the valley wall and the floodprone valley fill;

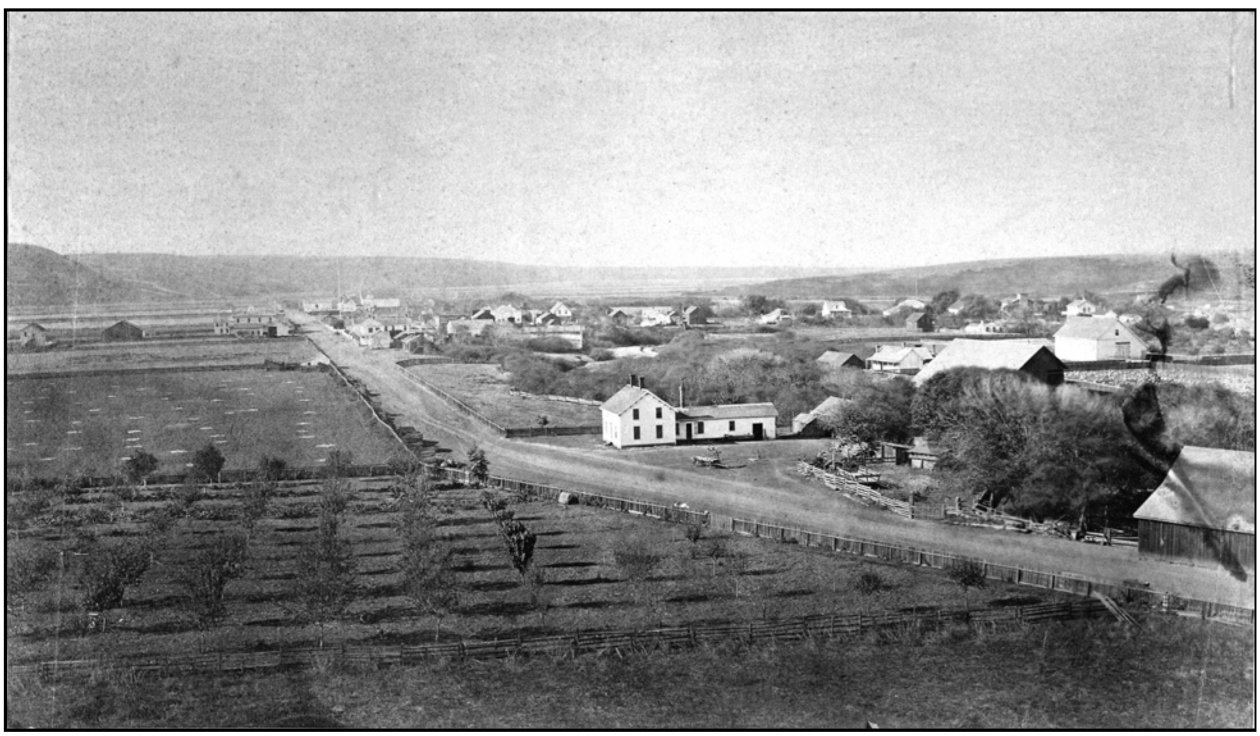
- The current-floodplains mapping involved the following: 1) the assumption that the creeks do not spill from their bank--into the agricultural lands--along the deeply entrenched reaches (this assumption was verified by my interviews with landowners, and the absence of any field data/flood marks); 2) interviews with landowners in the town of Pescadero, who delineated the remaining floodprone areas, located upstream of the marsh; and 3) the field surveys, which revealed that swampy areas still occur in the upper Bradley Creek valley (*see the 1920-1970 floodplains and channels map*);

- Conducted numerous interviews on historic conditions, notably of the following individuals: 1) Rob Skinner ([redacted]); 2) Al Sollars ([redacted]); 3) Meg Delano ([redacted]); 4) Carol Peterson ([redacted]); 5) Gregory Timm ([redacted]); 6) John Vonderlin ([redacted]); 7) Tess Black ([redacted]);

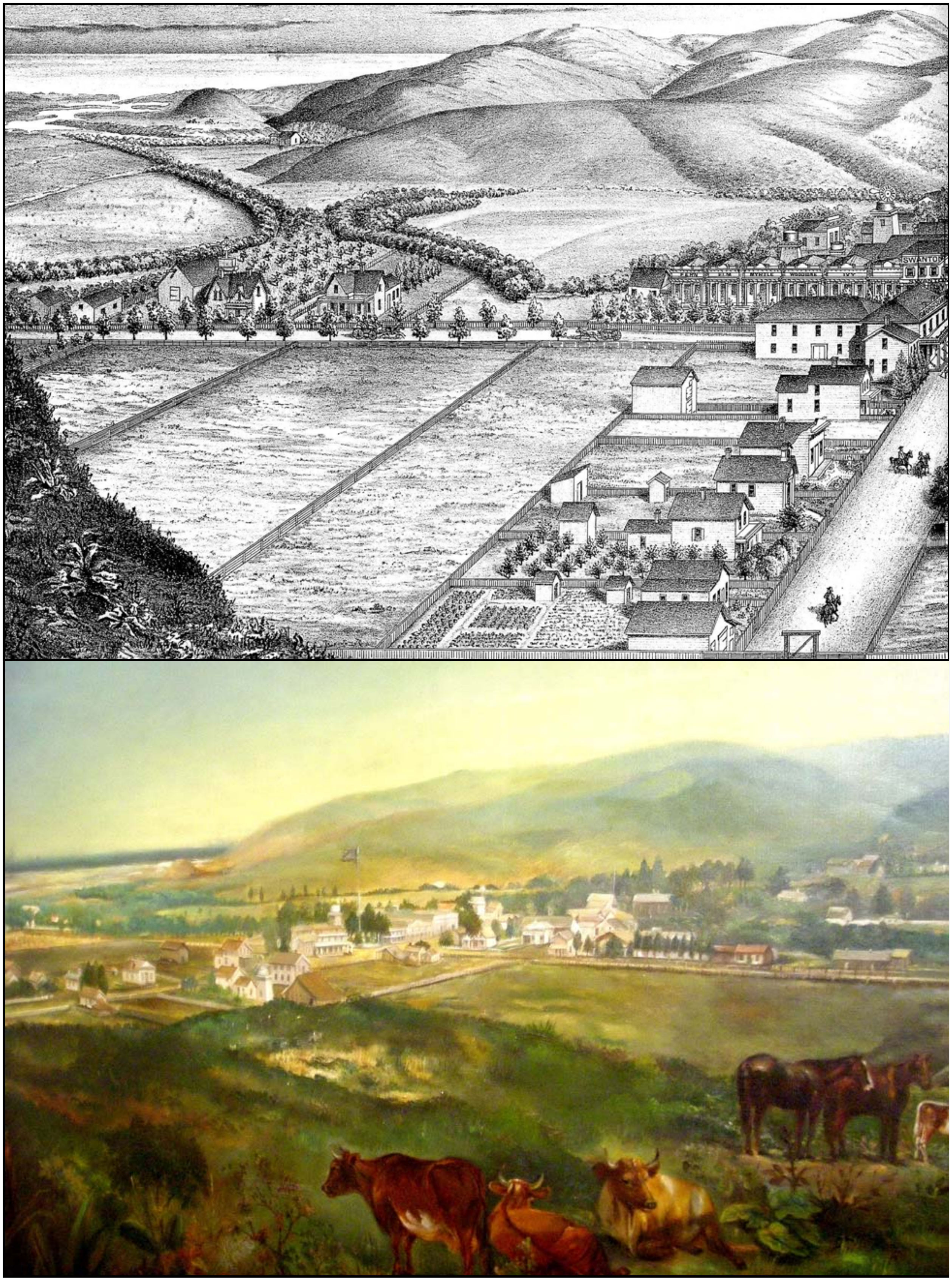
- See hard copies of the Laminated Field Maps for details on the field surveys and locations of the photographic sites, and see the Field Photographs folder for the 2010 ground photographs.



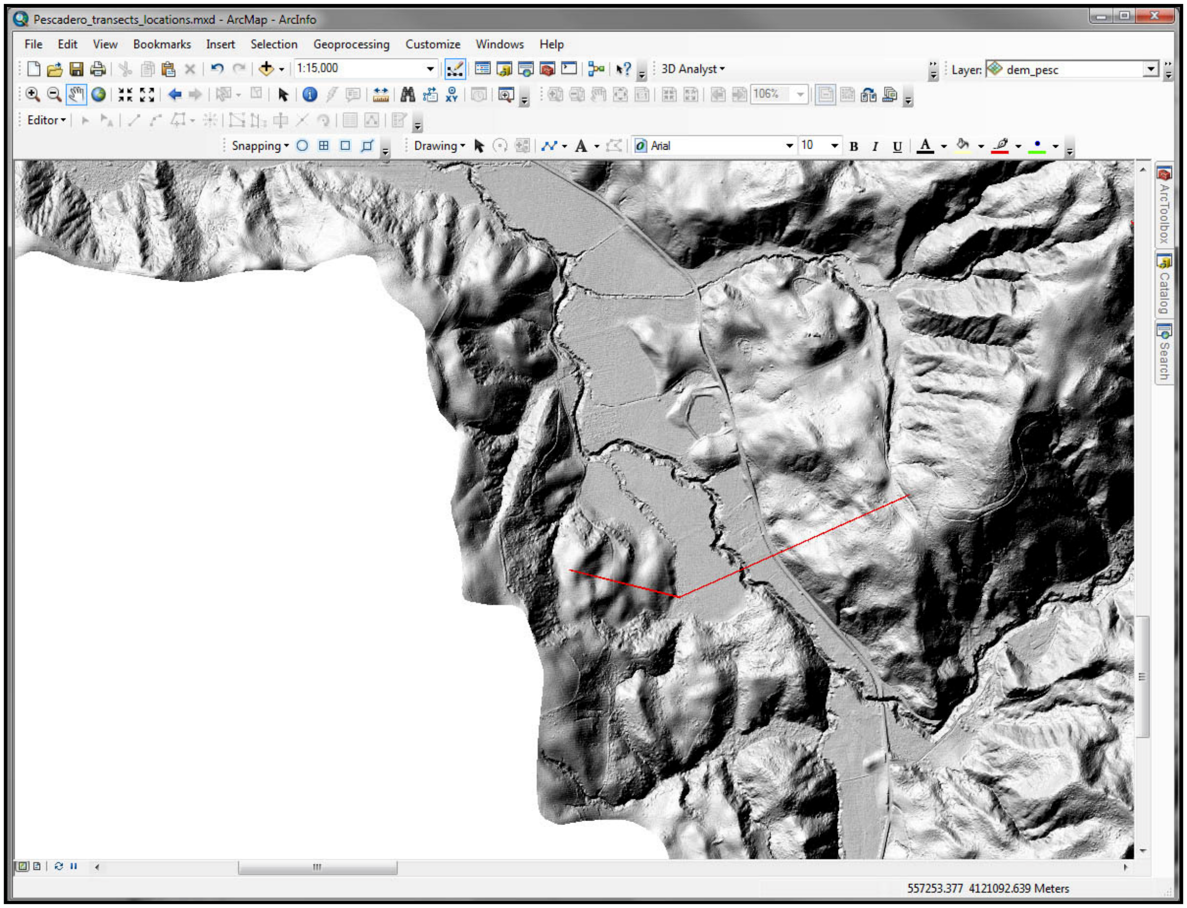
View of Pescadero in 1867, looking west along Pescadero Road. Note unentrenched and shallow unconfined channel of Pescadero Creek.

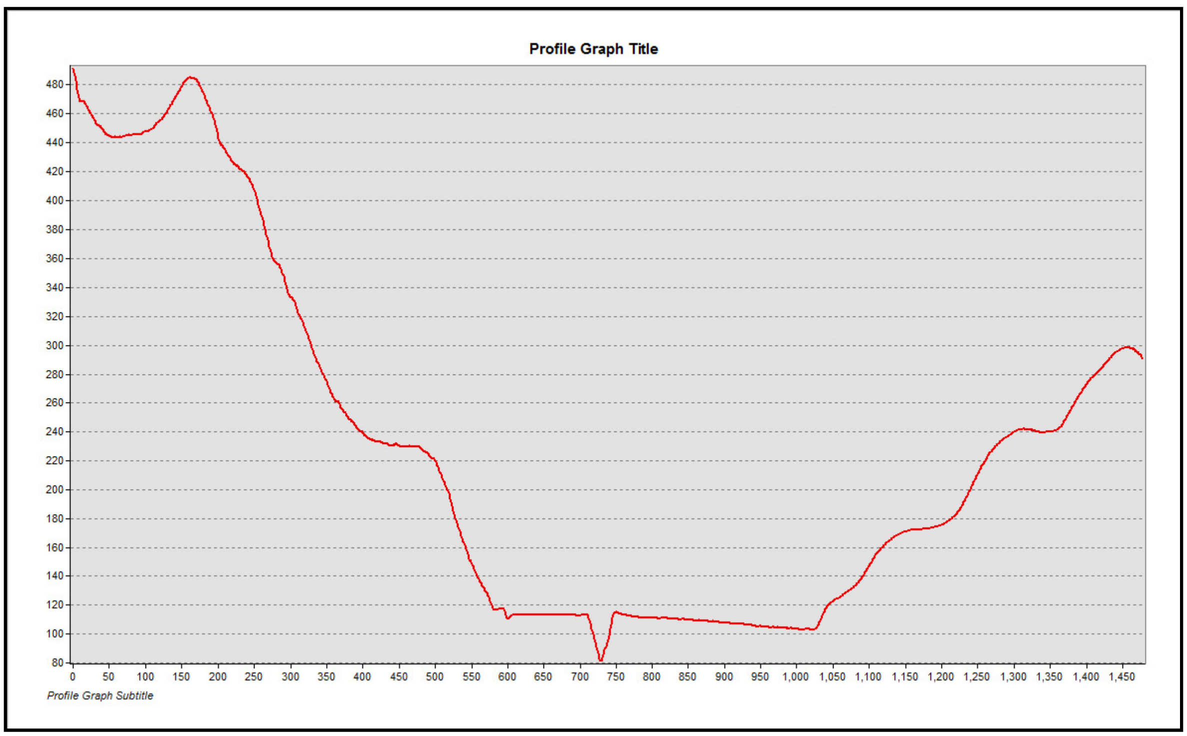


View of lower Pescadero Valley, 1855 (above) and 1867 (below), looking west.

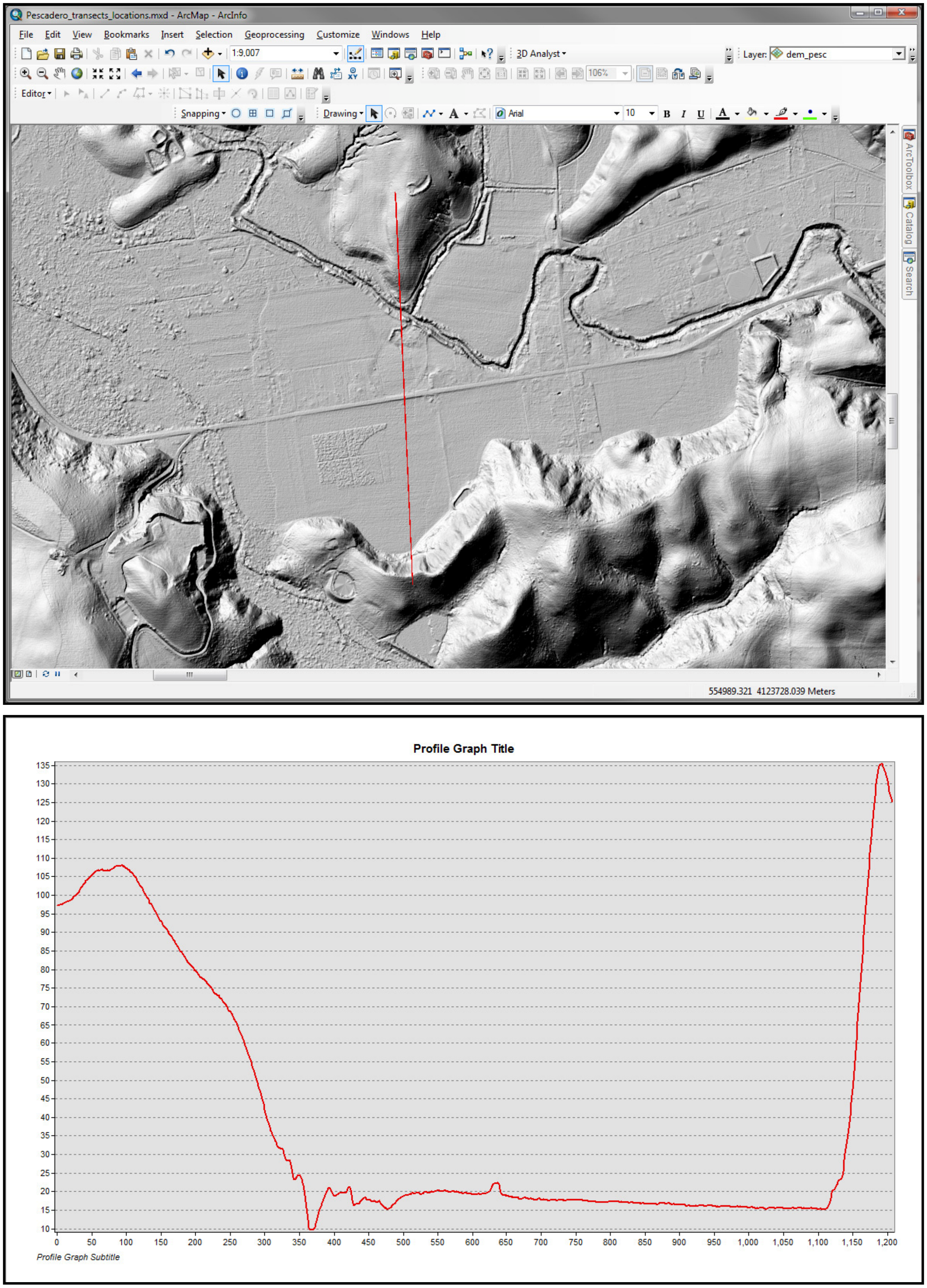


View of lower Pescadero Valley, 1874 (above) and 1884 (below), looking northwest.





LiDAR DEM valley transect across lower Butano Valley (i.e. swampy-meadow reach). Note aggradational valley topography and deeply entrenched channel of Butano Creek.



LiDAR DEM valley transect across lower Pescadero Valley (i.e. swampy-meadow reach). Note aggradational valley topography, entrenched channel of Pescadero Creek, and Pescadero Road.

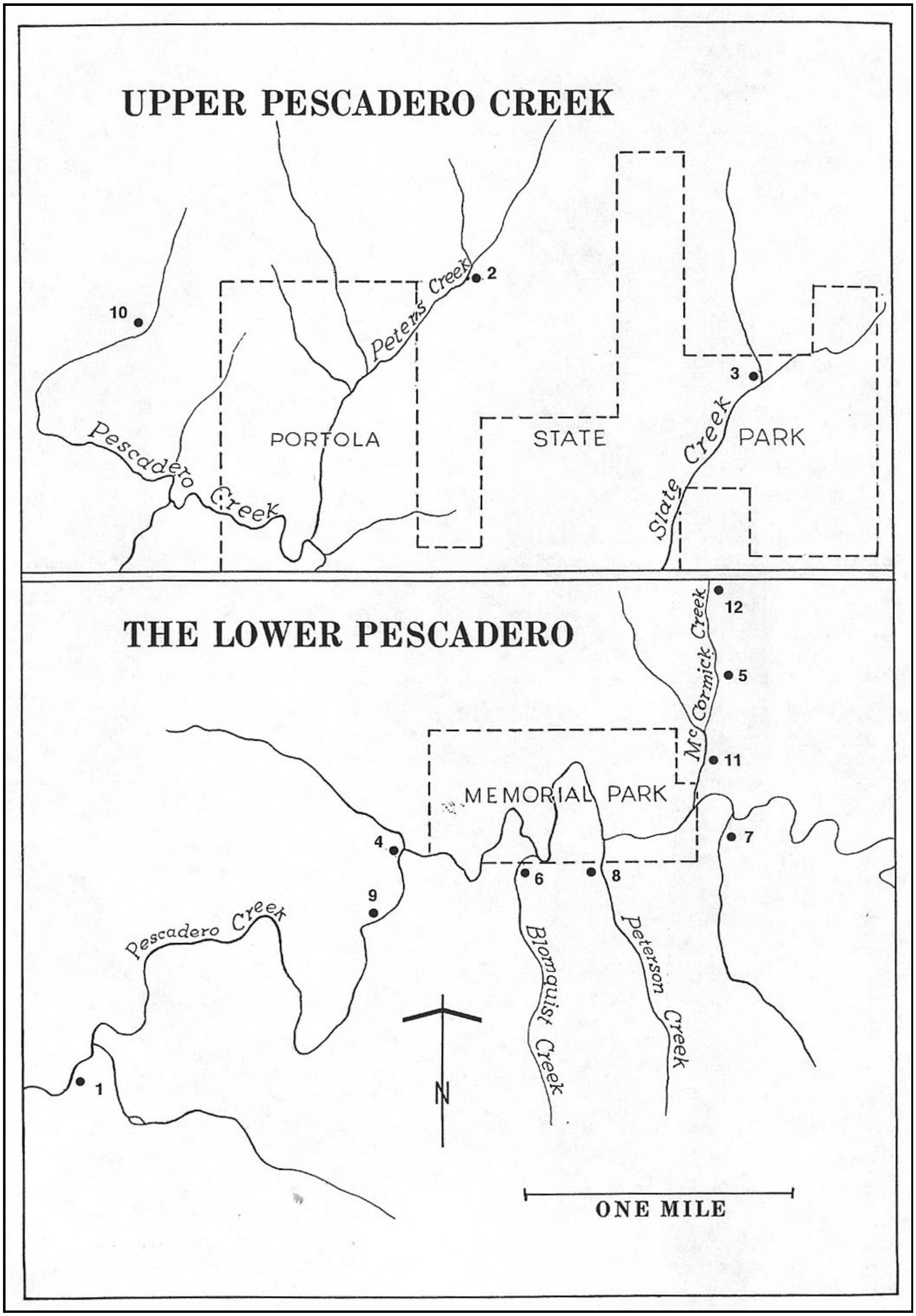
View of Moore Ranch in middle Bradley Creek valley in 1874 (from Brown 1874). Compare to rendering of similar view to capture conditions in 2005 using San Mateo County LiDAR DEM (2005). Note that Bradley Valley swampy meadow naturally supported an unconfined channel (Bradley Creek), presently an enlarged ditch-channel.

View of remainder of natural swampy meadow in upper valley of Bradley Creek.

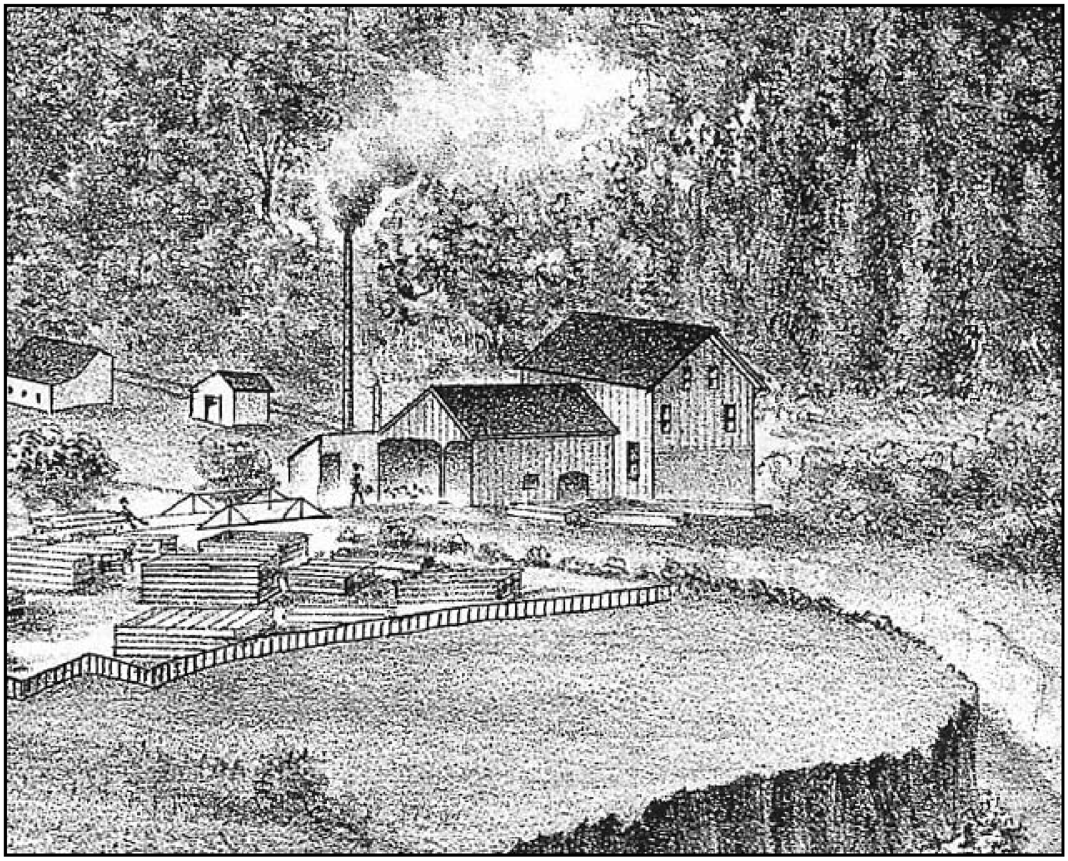
2. Splash dam logging, in-channel skidding, livestock trampling, and channel simplification on tributaries McCormick Creek, Jones Gulch, Peters Creek, Slate Creek and Oil Creek occurred primarily between 1860 and 1890.

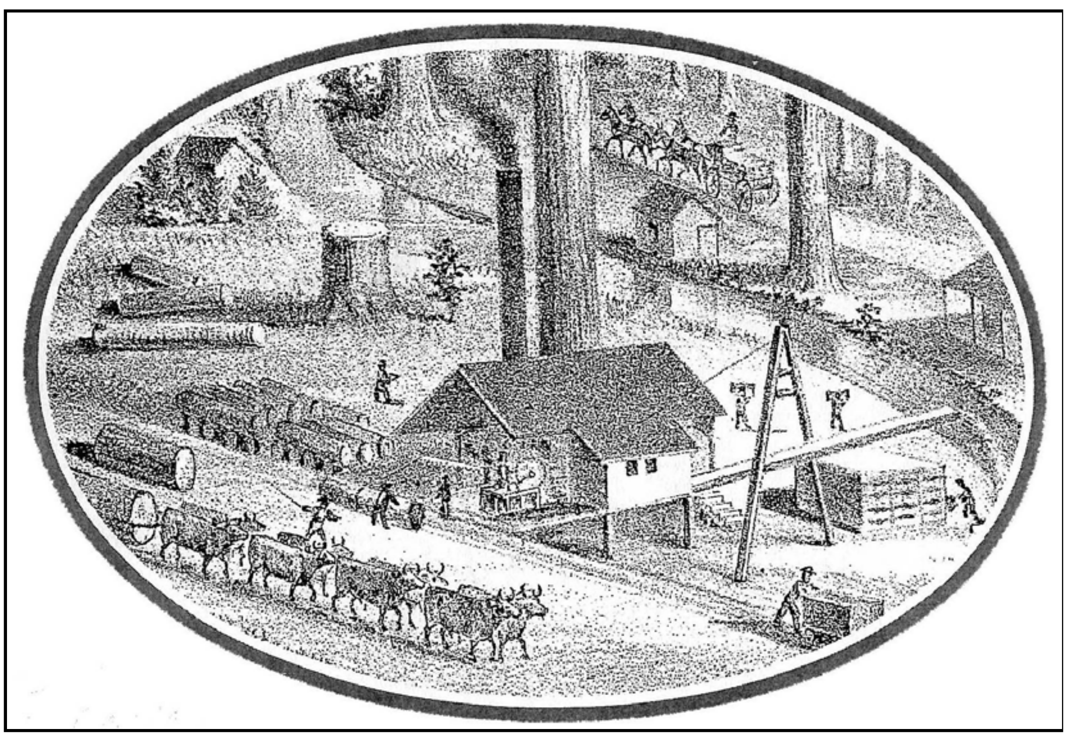
Evidence:

- Conducted interviews on land-use history with Rob Skinner, Meg Delano, and the McCormick family (Rob Skinner and his son have long-time property related connections in the McCormick watershed);
- Conducted extensive field surveys along McCormick and Jones Gulch creeks, and made a few limited stops at Peters, Slate and Oil creeks; the surveys revealed remainders of in-channel skid rows and wooden structures on locations of past splash dams and/or shingle mill dams; the surveys also revealed that the channels downcut 1-3 meters (depending on location), somewhat reducing the natural channel sinuosity in the narrow alluvial floors in these tributary creeks; in some reaches, the surveys revealed, the skid rows were buried by about 1 meter of post-logging sediment;
- Accounts of past shingle mills and their sites originate from Frank M. Stanger, Sawmills in the Redwoods (1967), published by the San Mateo County Historical Association;
- Delineated areas of past timber and agricultural-conversion activities, 1850-1920, using the following resources: 1) Stanger 1967; 2) 1874 Brown lithographs, which depict forest cover conditions at several locations along the Pescadero valley and adjacent hills; 3) Ty Liles M.S. thesis (1994); 4) Frank Viollis M.A. thesis (1979); 5) 1943 aerial photographs (which show young, 20-40 years old forest stands along Butano Creek); and 6) historic accounts of early logging practices, such as Early Lumber Industry in San Mateo County, prepared by A.S. Kalenborn (1944);
- Early photographs of livestock trampling/in-channel skidding (1852, 1870s, etc.);
- See hard copies of the Laminated Field Maps for details on the field surveys and locations of the photographic sites, and see the Field Photographs folder for the 2010 ground photographs (for McCormick Creek, see the photographs in the 2010-09 and 2010-10 folders: 1167-1235 in the 2010-09 folder, and 1315-1367 in the 2010-10 folder);
- See the Shingle Mills subfolder in the Logging History folder, for the locations of 1850-1930 single mills located on these creeks;
- See the photograph Early Logging 1850-1920 subfolder in the Logging History folder, for the ground photographs depicting logging practices in the early period, notably 1850-1890 in the tributaries in the Pescadero Sub-Watershed.

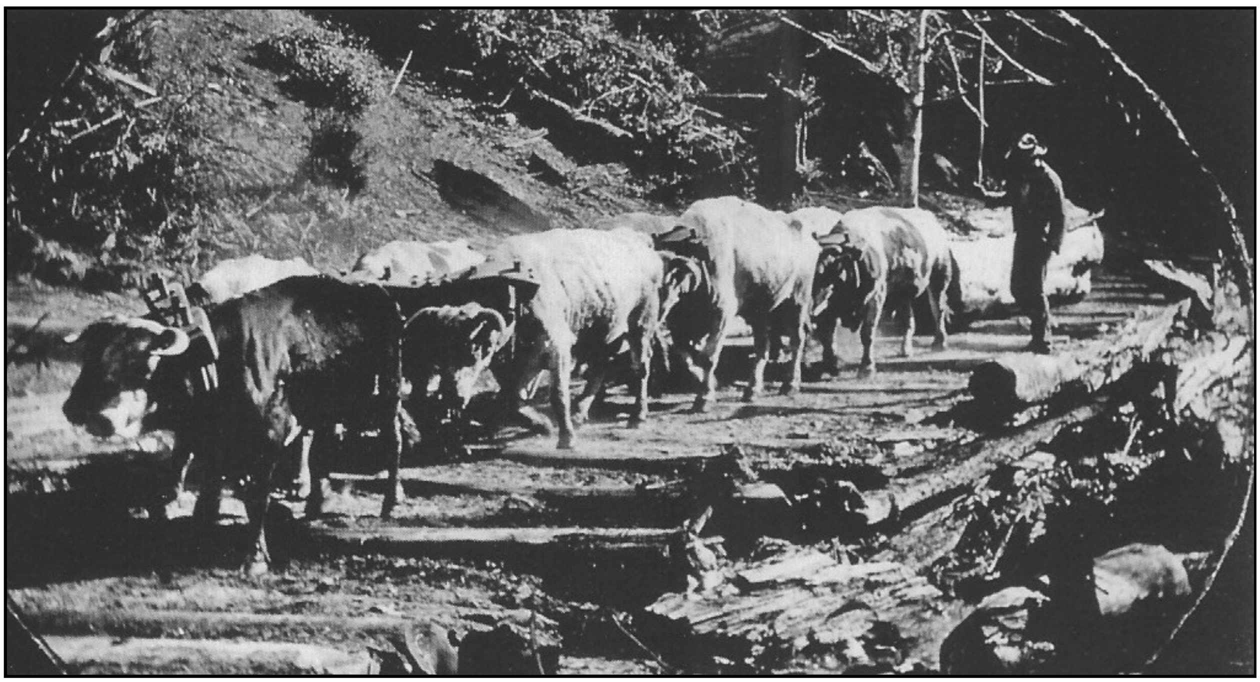


Locations of 1850-1920 single mills in Pescadero-Butano Watershed (from Stanger 1967).





Hayward Mill on mainstem Pescadero Creek (above) and Purdy Pharis Mill on Purisima Creek (below) (from Brown 1874). Note channel downcutting on Pescadero Creek, and sluicing of sawdust into Purisima Creek.



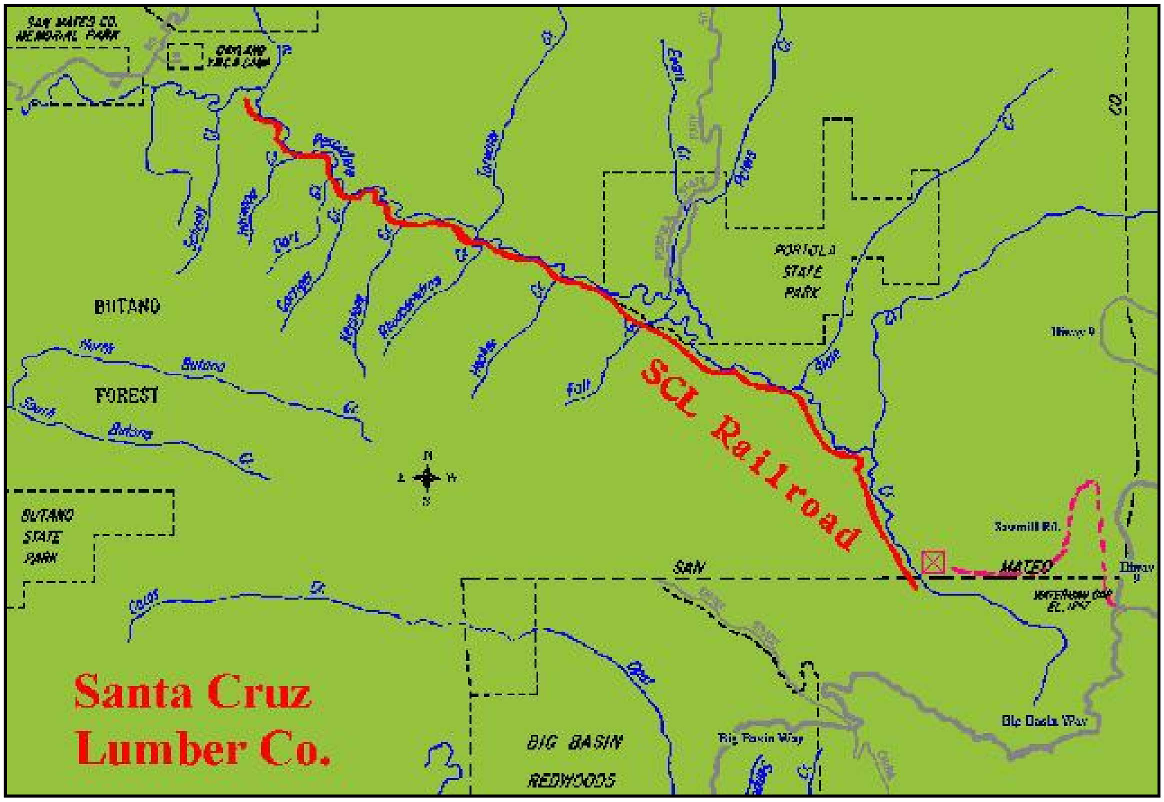
In-channel log skidding, livestock trampling, and channel simplification in 1860s-1890s.

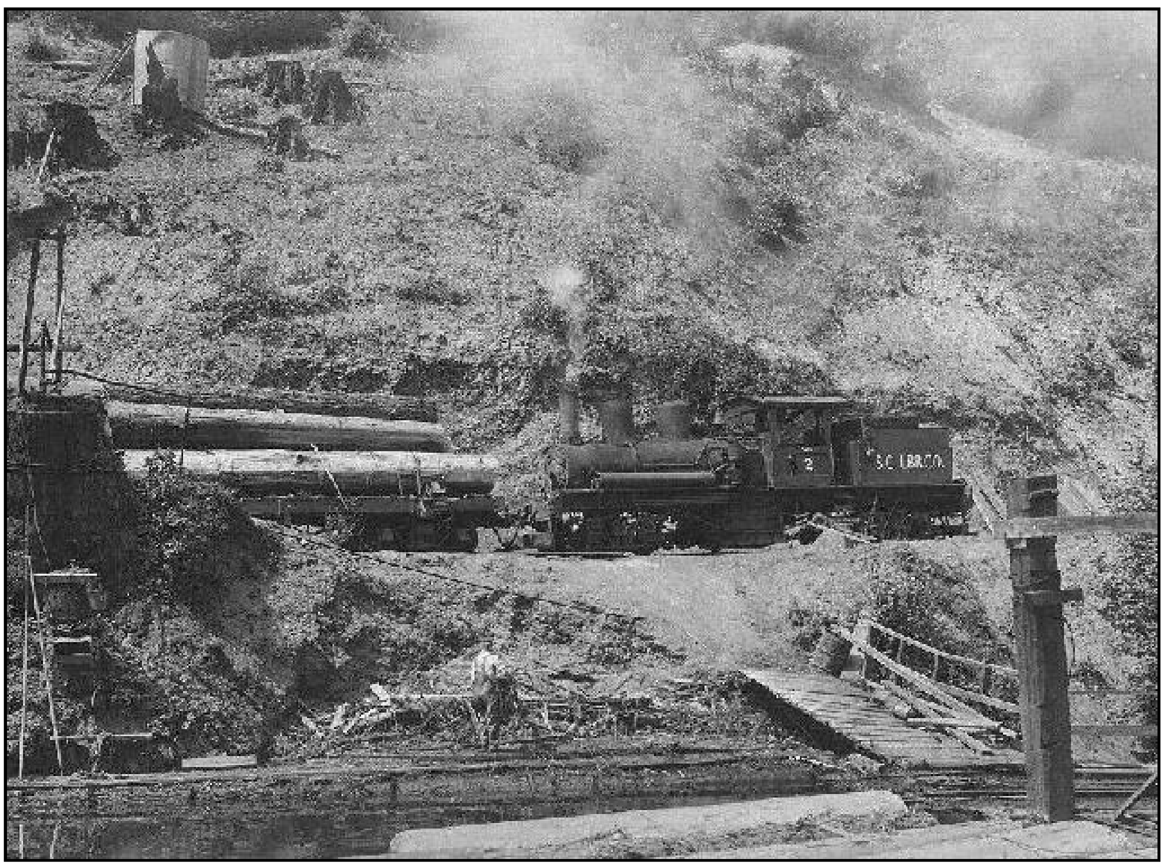
In-channel log skidding, livestock trampling, and channel simplification in 1860s-1890s.

3. The Santa Cruz Lumber Haul Railroad was constructed in (or completed by) 1920-1940 generally without provision for fish passage or sediment routing across as many as 23 tributary creeks. Since construction, even despite rebuilding the road into a truck haul road in 1950s, which also involved rebuilding some of the road-watercourse crossings, passage up/down stream of the road in 14 major, cobbler-boulder substrate tributaries (all of which drain Butano Ridge) to Pescadero Creek has been blocked. The blockage materials include earthen dams and huge quantities of woody debris.

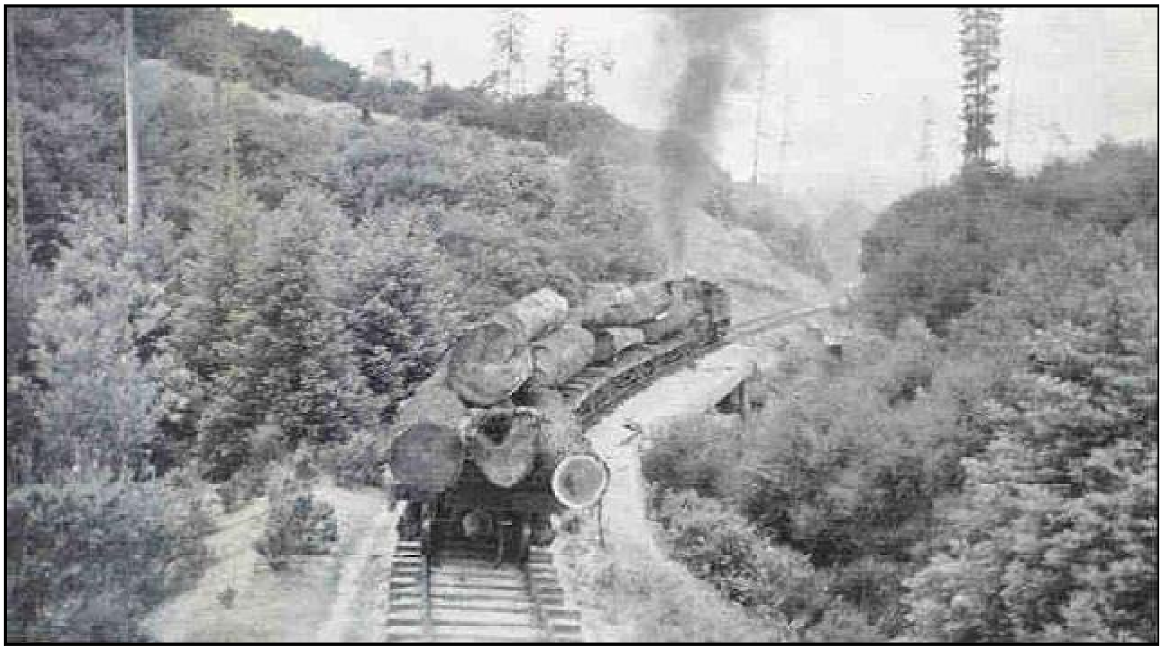
Evidence:

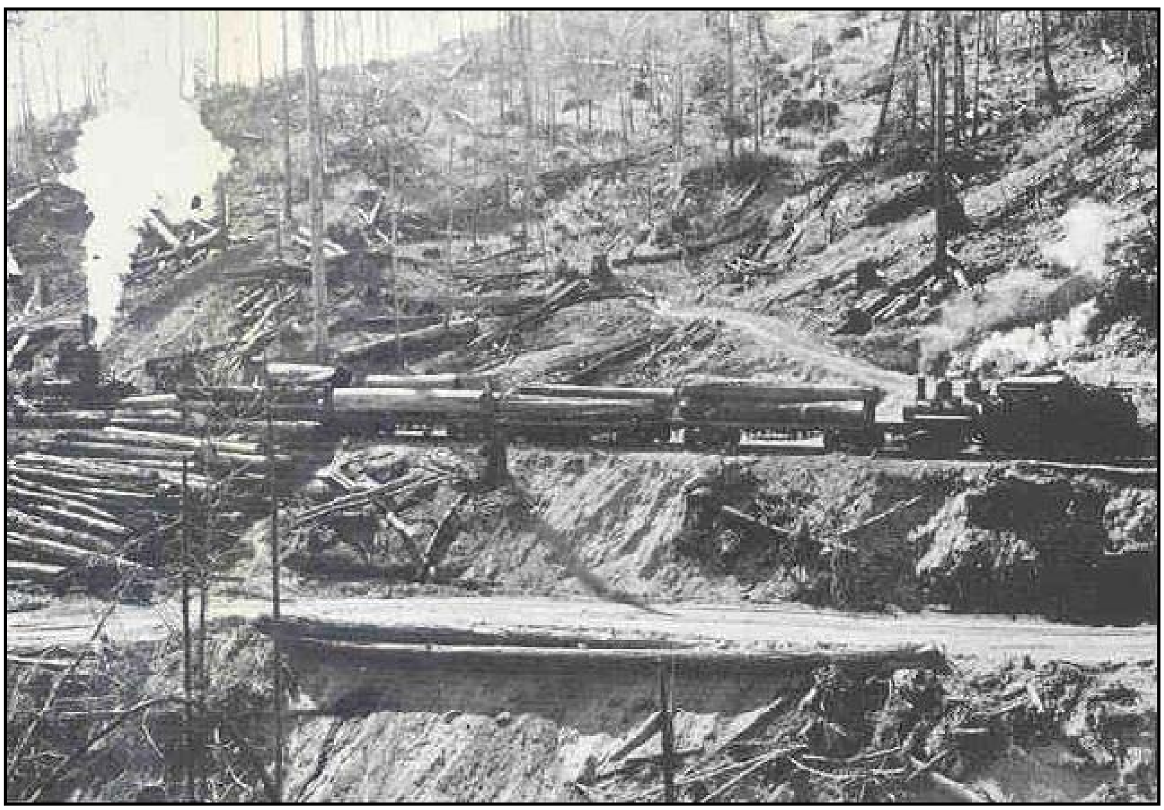
- Reviewed historic documents on the Santa Cruz Lumber Company (currently Redtree Properties, Ltd.), including The Santa Cruz Lumber Company 1923-1989, prepared by John R. Cummings 1999;
- Contacted Sam Herzberg of San Mateo County Parks Department, who provided a list of old timers in the watershed who knew the history of SLC Railroad, and history of the repair activities along the Old Haul Road in 1980s and 1990s, following the 1982 and 1997 El Niño storm damage; contacted Meg Delano, who provided Notes from the CRMP Pescadero Upper Watershed Tour (June 4, 1999);
- Surveyed the entire length of the Old Haul Road, and inspected each road-watercourse crossing; nearly all tributaries upstream and downstream of the haul road were found to be “blown-out” and incised by up to 7 meters; the passage along these tributary creeks is very low due to the presence of in-channel cut large woody debris (LWD); there are many post-1920 debris flow deposits located on the narrow valley bottoms of the tributary creeks;
- The historic accounts of logging upstream of the haul road revealed that logs were pulled down the creek beds with tractors, all the way to the haul road (after Notes from the CRMP Pescadero Upper Watershed Tour (June 4, 1999);
- See hard copies of the Laminated Field Maps for details on the field surveys and locations of the photographic sites, and see the Field Photographs folder for the 2010 ground photographs;
- See the Shingle Mills subfolder in the Logging History folder, for the locations of 1850-1920 single mills located on these creeks;
- See the Santa Cruz Lumber 1920-1970 subfolder in the Logging History folder, for the details on the railway haul road construction and operations.



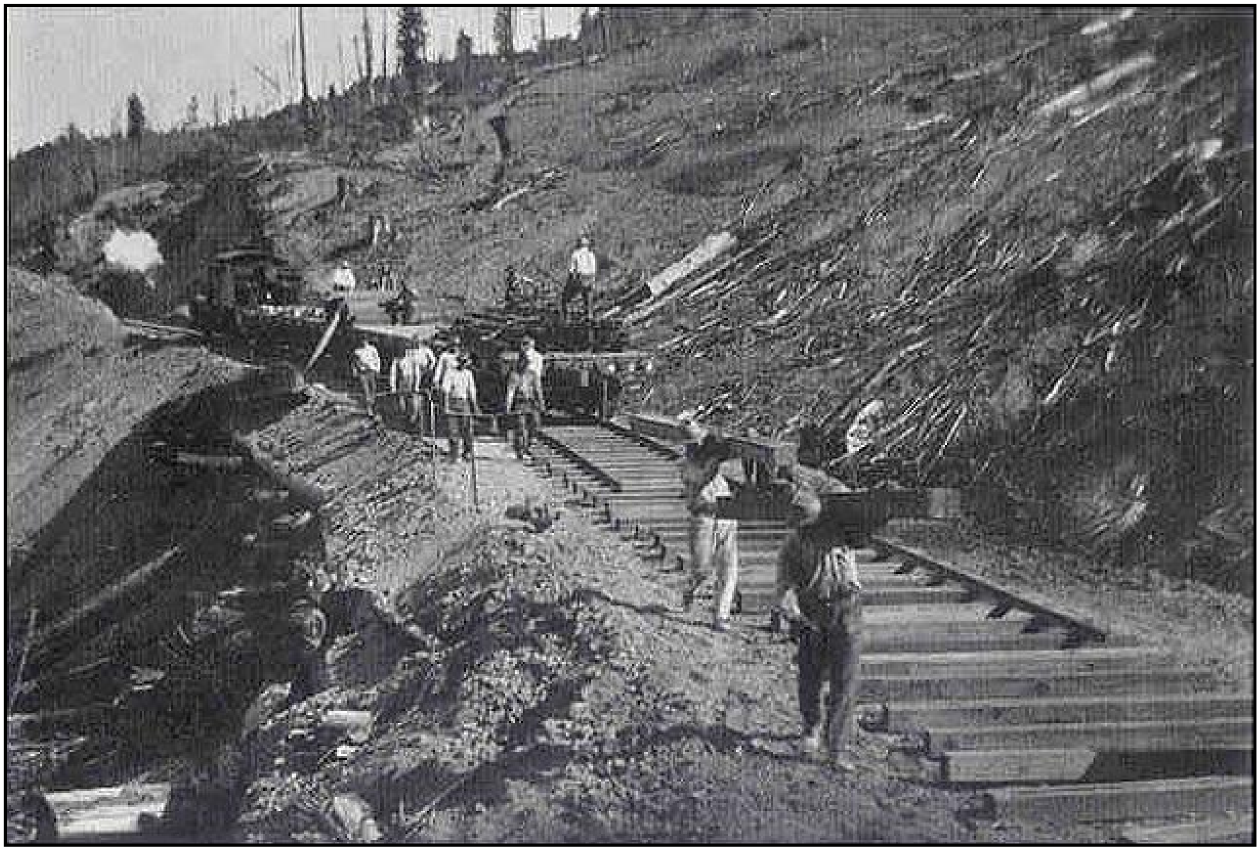


Santa Cruz Lumber Co. railroad along upper Pescadero Creek, in 1930s-1940s.





Santa Cruz Lumber Co. railroad along upper Pescadero Creek, in 1930s-1940s.



Santa Cruz Lumber Co. railroad along upper Pescadero Creek, in 1930s-1940s.

4. Incision, or evacuation of 2-4 meter deep alluvium, in the canyon reach of Pescadero Creek began during the first round of logging, *likely* as a result of the LWD removal and simplification to enable floating of logs (ALL of the evidence is very tentative, as there are only subtle alluvial terracettes left along the dominantly bedrock walls of the Pescadero canyon). Many or most of the canyon-reach tributaries (Bloomquist to Trestle), north and south, are now perched (2 to 4 meters).

Evidence:

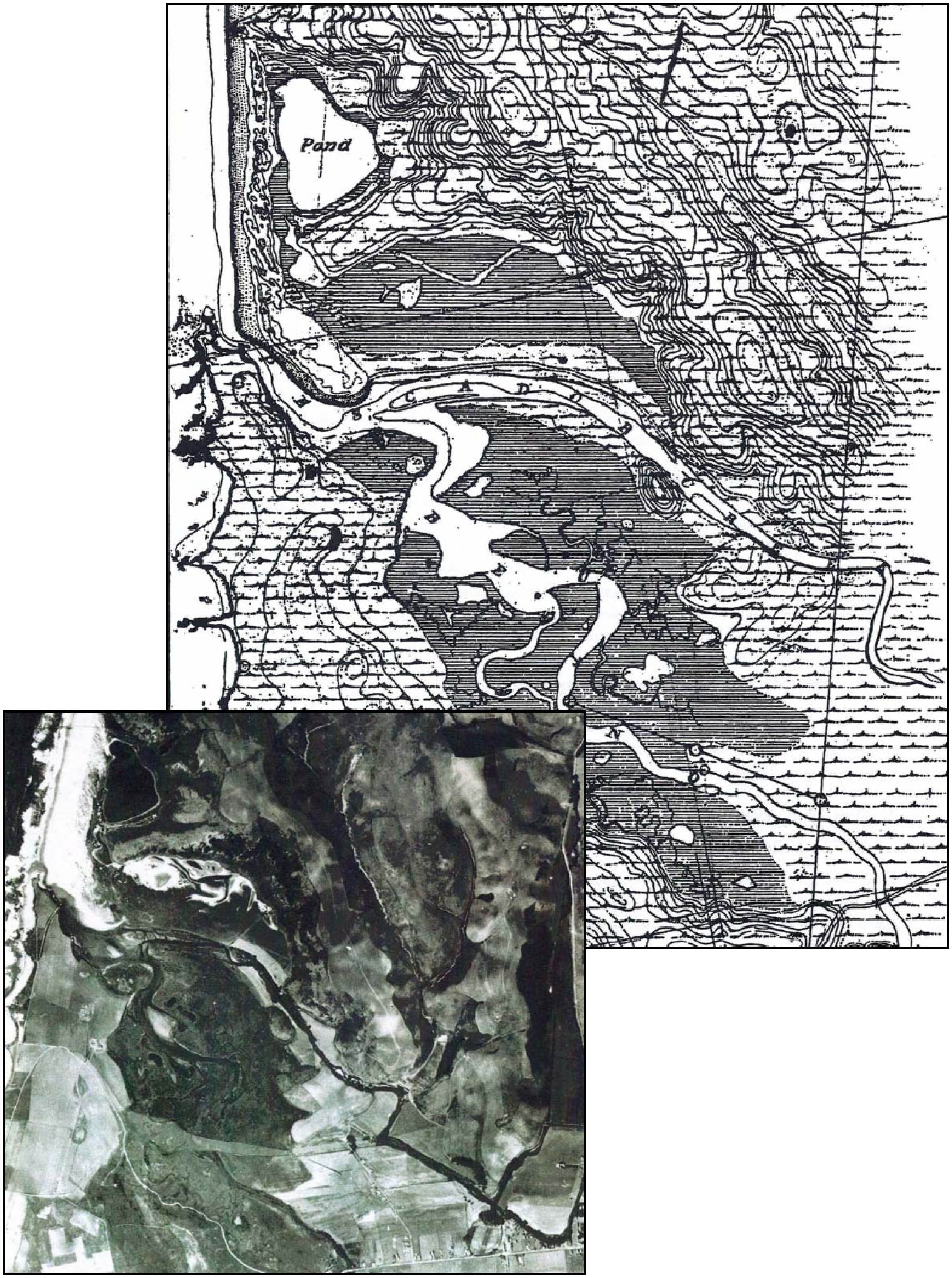
- See discussion in Conclusions (2) and (3);
- Clarification: While the evidence is very tentative, there are many subtle alluvial terracettes left hanging at up to 4 meters above the channel bottom under the current conditions, in the canyon reach; these sites occur both in the meander bends (usually in association with alluvial fan terraces on the inside of the bend), or even in straight reaches; see the 2010-07 subfolder in the Field Photographs folder, and view, among many, the following photographs: 2372, 2373, 2374, 2376-2382, 2456, 2467, 2472, 2474, 2479, 2483, 2491, 2457 (I can provide a detailed review of my field maps to pinpoint these terracette locations, if requested). Note: many of my other photographs show a similar feature on the valley walls in the canyon; however, these are associated with either the (recent) landslide dams, i.e. they are cut landslide deposits, or have been formed by corrasion in association with pond backwater (numerous seasonal ponds existed for decades in the canyon reach, from about 1930 to about 1990, both for anglers and as swimming holes for the campground/YMCA users/tourists);
- See the YMCA East Bay site, "Redwood Site," located immediately downstream of Hoffmann Creek: see the Laminated Field Map PC 6, "Redwood Site" location on the front, and the site sketch on the back of the laminated map;
- See hard copies of the Laminated Field Maps for details on the field surveys and locations of the photographic sites, and see the Field Photographs folder for the 2010 ground photographs;
- *NOTE: I will provide a list of photographs which show the hanging tributaries, and their locations on the Laminated Field Maps. In the meantime, please use the document I prepared for the November 2011 science panel meeting, titled: Trso_PescaderoButanoGeomorphicChanges_KeyConclusions2.pdf*

Perched and downcut tributary channels at or near junctions within canyon reach of Pescadero Creek.

5. By 1860, sediment delivery to channels had increased to 70-100% above natural background and diking adjacent to the lagoon began in about 1880; however, the marsh did not really begin to fill in until 1920 (it started filling up on its own around 1900), when farmers reclaimed about 30% of the area, and after Caltrans modified its Highway 1 road crossing in 1941.

Evidence:

- Documented changes in the extent of the lagoon/marsh, using the following resources: early sketches and property diseño maps (1833-1861), the 1854 USC&GS survey map, and other 1850-1940 USC&GS nautical charts, early paintings (1855, 1884), Brown lithographs (1874), 1915 and 2010 ground photographs, historic county maps of private ranchos and water works (San Mateo County Office of Public Works 1874, 1877, 1894, 1909, 1927), aerial photography (1928, 1943, 1953, 1960, 1964, 1970, 2000), the 1960 ditching and diking plan map, the 2005 LiDAR DEM SHD; Frank Viollis M.A. thesis (1979), and The Flooding of Pescadero Road & The Restoration of Butano Creek, prepared by William H. Cook (2002);
- Conducted interviews with the following: 1) Ron Duarte ([redacted]; and 2) Steve Simms [redacted];
- Interpreted the land use/watershed history section in the ESA (2004) report, prepared by Albion Environmental (2004).



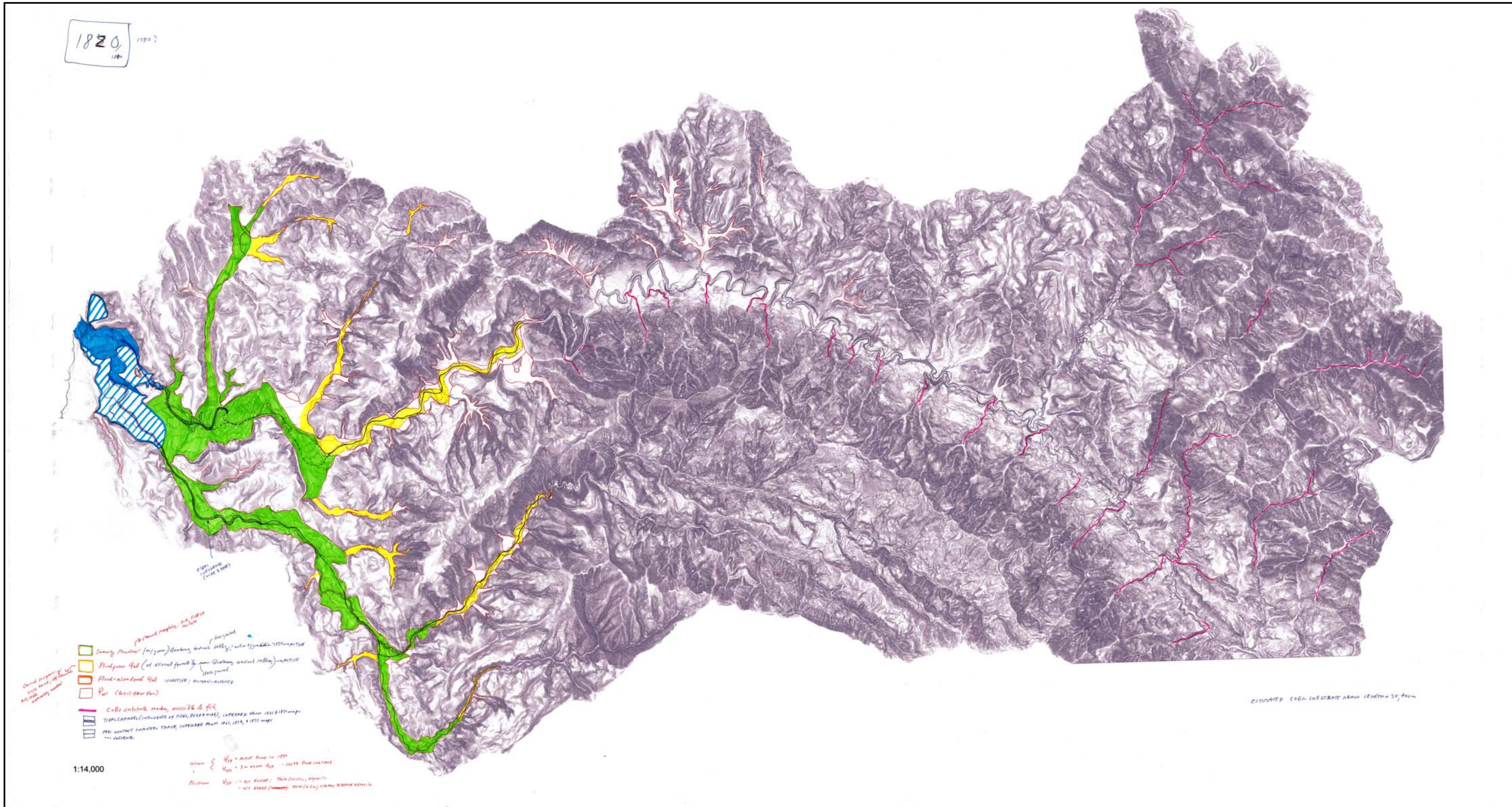
Pescadero Marsh/Lagoon Complex in 1854 (above, from USC&GS 1854) and 1928 (below).

Pescadero Marsh/Lagoon Complex in 1915 (above, from SMCHM) and 2000 (below, WAC 2000).

6. **100% of the potential steelhead habitat in southern tributaries is impaired by debris flow scour, debris flow deposition, presence of cut wood jams (remnants of the haul road), and/or clogging of coarse substrate as a result of highly elevated delivery of fine bed material. About 50% of this habitat is impaired in the northern tributaries. As presented in (Conclusion 4), tributary junctions of most of these steelhead-substrate tributaries are perched by 2 to 4 meters, amounting to fish passage blockage.**

Evidence:

- See Conclusions (2) and (3).



Working sketch map of 1820 alluvial geomorphic landforms, and channel and floodplain conditions in Pescadero-Butano Watershed (developed in 2010-2011). Note locations of cobble-boulder ("CoBo") substrate reaches (purple line), hypothesized to have occurred along 35 kilometers across Pescadero-Butano Watershed under the natural, pre-land-use disturbance conditions.

Perched and downcut tributary channels at or near junctions within canyon reach of Pescadero Creek, a legacy of 20th century timbering activities. Note cut wood jams.

Perched and downcut tributary channels at or near junctions within canyon reach of Pescadero Creek. Note absence of alluvial bed (above) and cut wood jams (below).

Downcut tributary channels draining to canyon reach of Pescadero Creek. Note skid rows in channel, a legacy of in-channel log skidding during 19th century timbering activities.

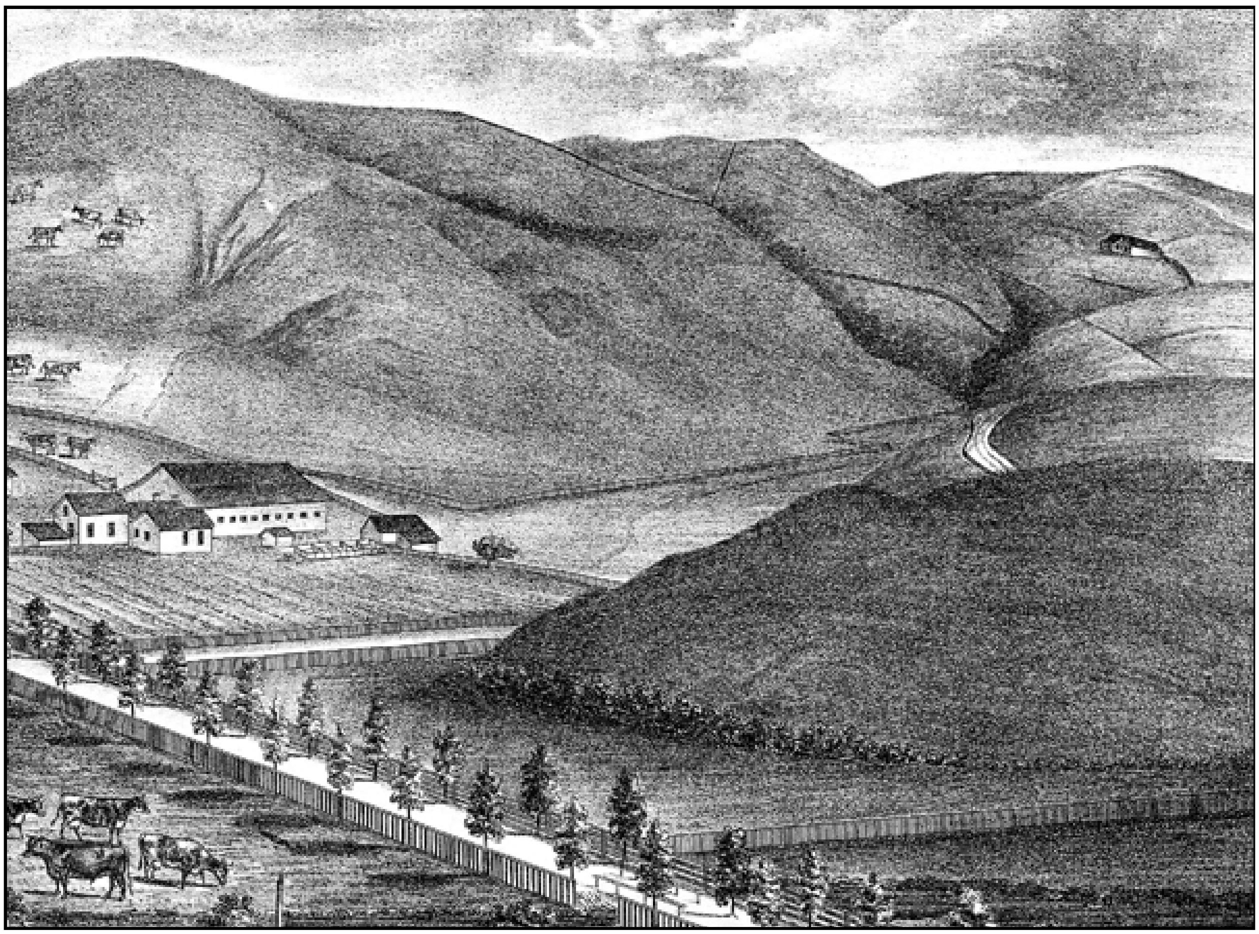
Unconsolidated debris-flow deposits in tributaries to canyon reach of Pescadero Creek, a legacy of 20th century timbering activities.

Road-watercourse crossings in former timberlands (State parks, County parks, and private lands). Note poor conditions: poorly installed and/or undersized culverts, which trap coarse substrate (including cobble-boulder substrate) and cause channel enlargement and/or hillside gullying.

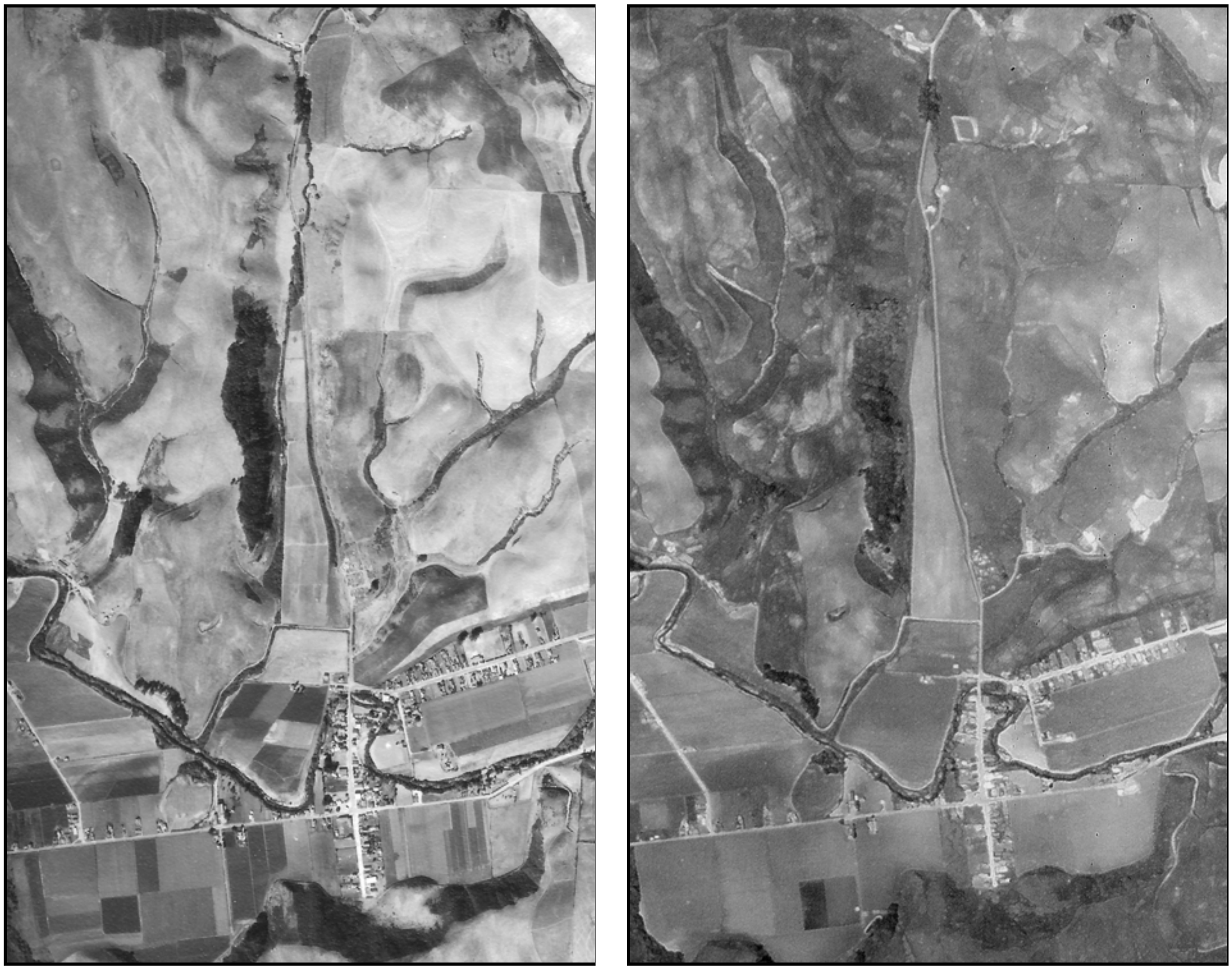
7. Although the key sources varied somewhat, for the 1820-50, 1850-1920, 1920-1970, and 1970-2010 periods, sediment delivery to channels was elevated by approx. 100% above natural background. Sediment yields to mainstem of Pescadero, mainstem Butano, and the marsh were even more greatly amplified as a result of the loss of floodplains (alluvial and swampy) and debris removal activities.

Evidence:

- See discussion on loss of floodplains in Conclusions (1) and (8);
- Sediment delivery increases are also due to hillside surface erosion and gullying within areas of agricultural and ranching activities. While rates of soil loss have decreased in the 20th century, the rates of hillside gullying have increased starting in the 1940s.



View of middle Bradley Creek valley in 1874 (from Brown 1874). Note livestock grazing on steep hills in background, and evidence of associated hillside gullying. Land-use triggered active hillside gullying in Pescadero-Butano Watershed began in about 1860.



Land-use triggered active hillside gullying in 1943 (USDA-NRCS 1943) and 1960 (USAF 1960), lower Bradley Creek watershed.

Ongoing land-use triggered active hillside gullying persistently supplies fine-textured sediment to Pescadero Marsh/Lagoon Complex under current conditions, lower Bradley Creek watershed (WAC 2000).

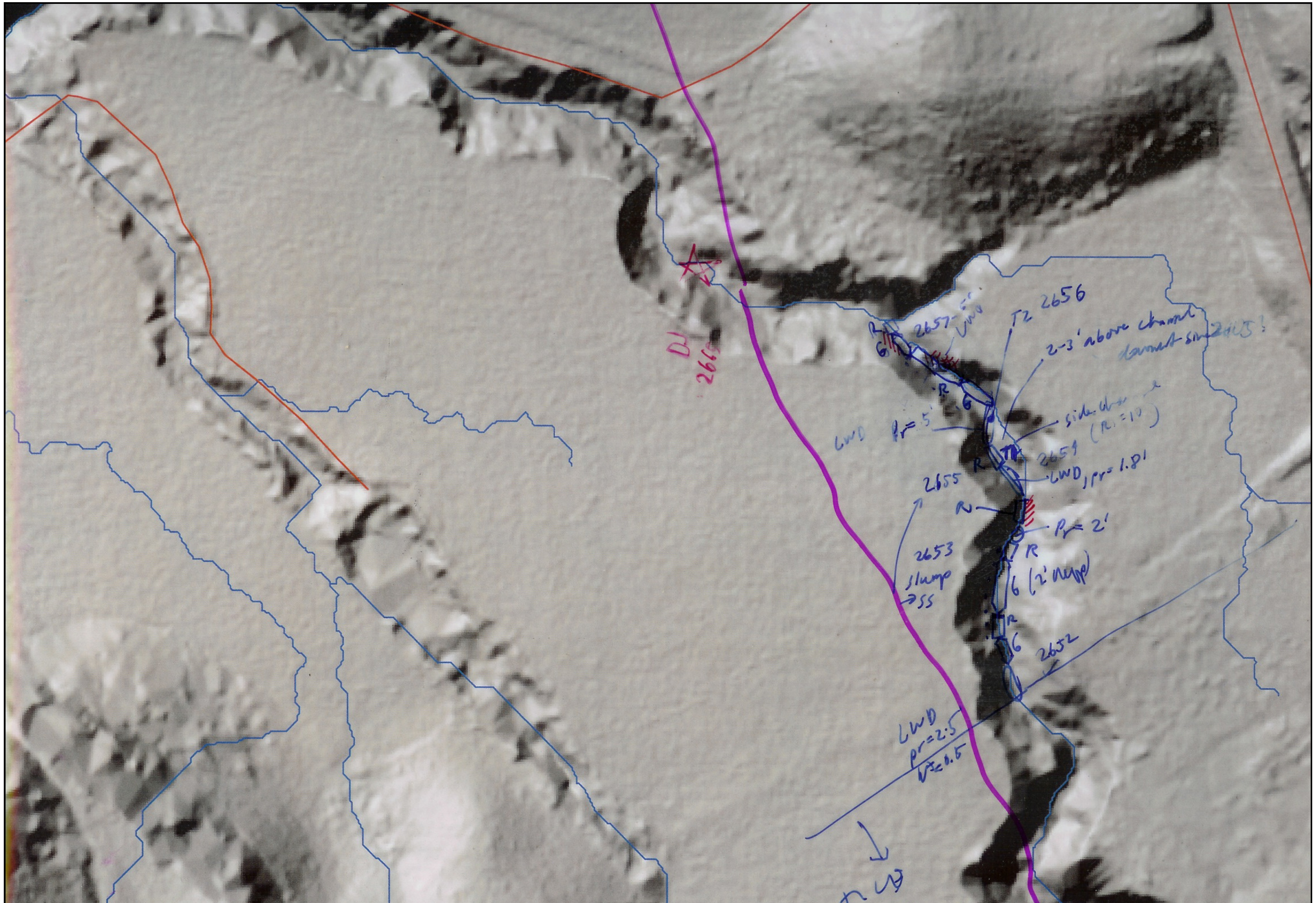
Ongoing land-use triggered active hillside gullying persistently supplies fine-textured sediment to watercourses and Pescadero Marsh/Lagoon Complex, either directly from within unique drainage area (UDA) or via overland pathways from non-UDA sources. Sediment travel distances of hundreds meters have been observed between hillside gully and sediment delivery locations.

Ongoing land-use triggered active hillside surface erosion persistently supplies fine-textured sediment to watercourses and Pescadero Marsh/Lagoon Complex. Significant stripping of soils in Pescadero-Butano Watershed began in about 1820, exposing bedrock in many locations subject to past ranching and grazing activities.

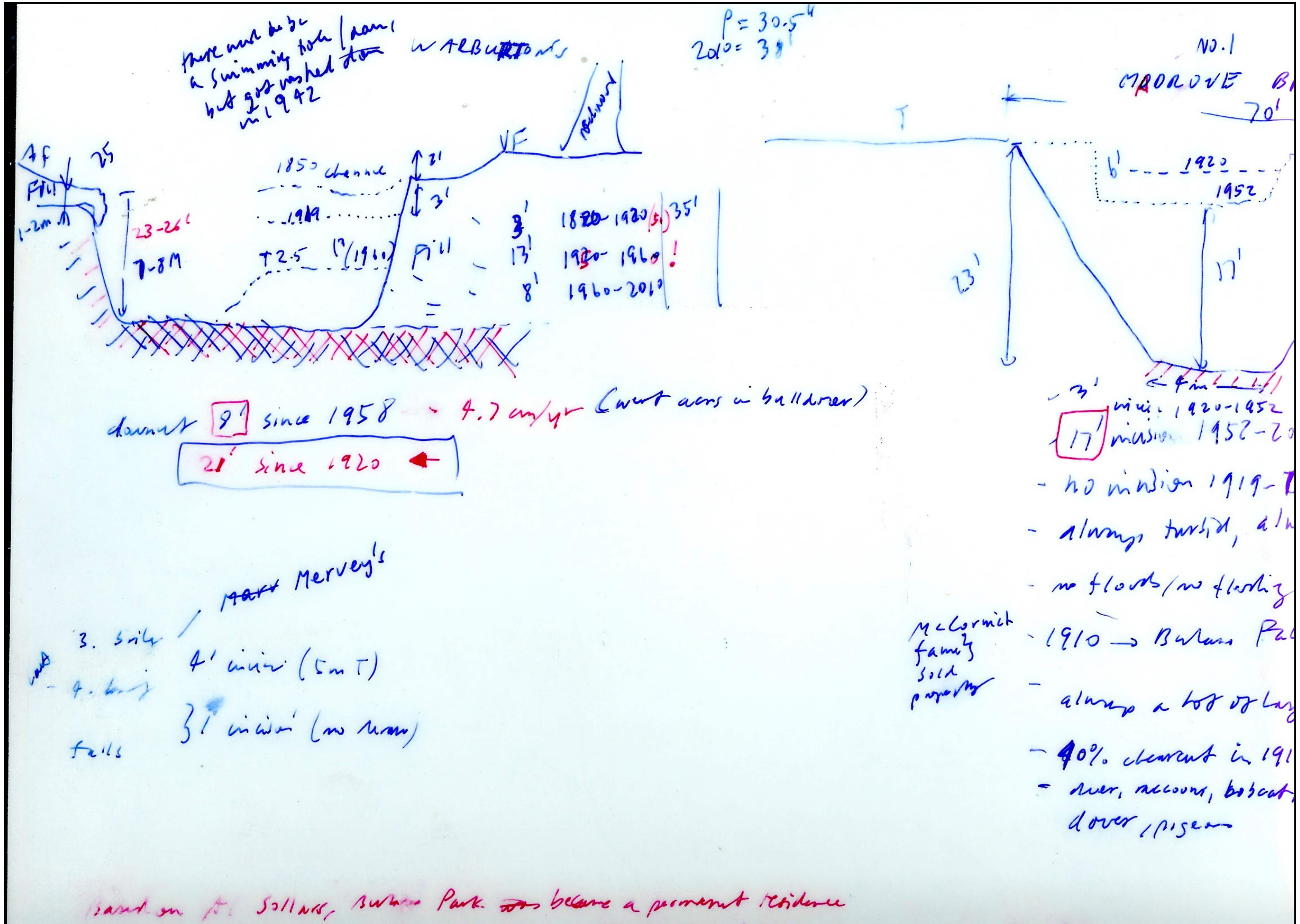
8. In lower Pescadero Creek, the channel has incised by 15 feet (5 meters) or more since 1860. In lower Butano Creek, the channel has incised by 25 feet (9 meters) or more since 1920. Along Butano Creek, incision in the canyon (i.e. alluvial-fan reach) did not begin until after the late 1940s when wood (LDW) removal began in earnest. In many reaches of lower Butano and lower Pescadero, soft bedrock is now exposed on the bed, and channels are beginning to rapidly widen as unconsolidated banks dominated by sand size material collapse. Based on interviews of local residents and field observations, it appears that soft-bedrock exposure first became widespread after 2005. Absent intervention, the amount of sand delivered to the marsh could be extreme in future decades.

Evidence:

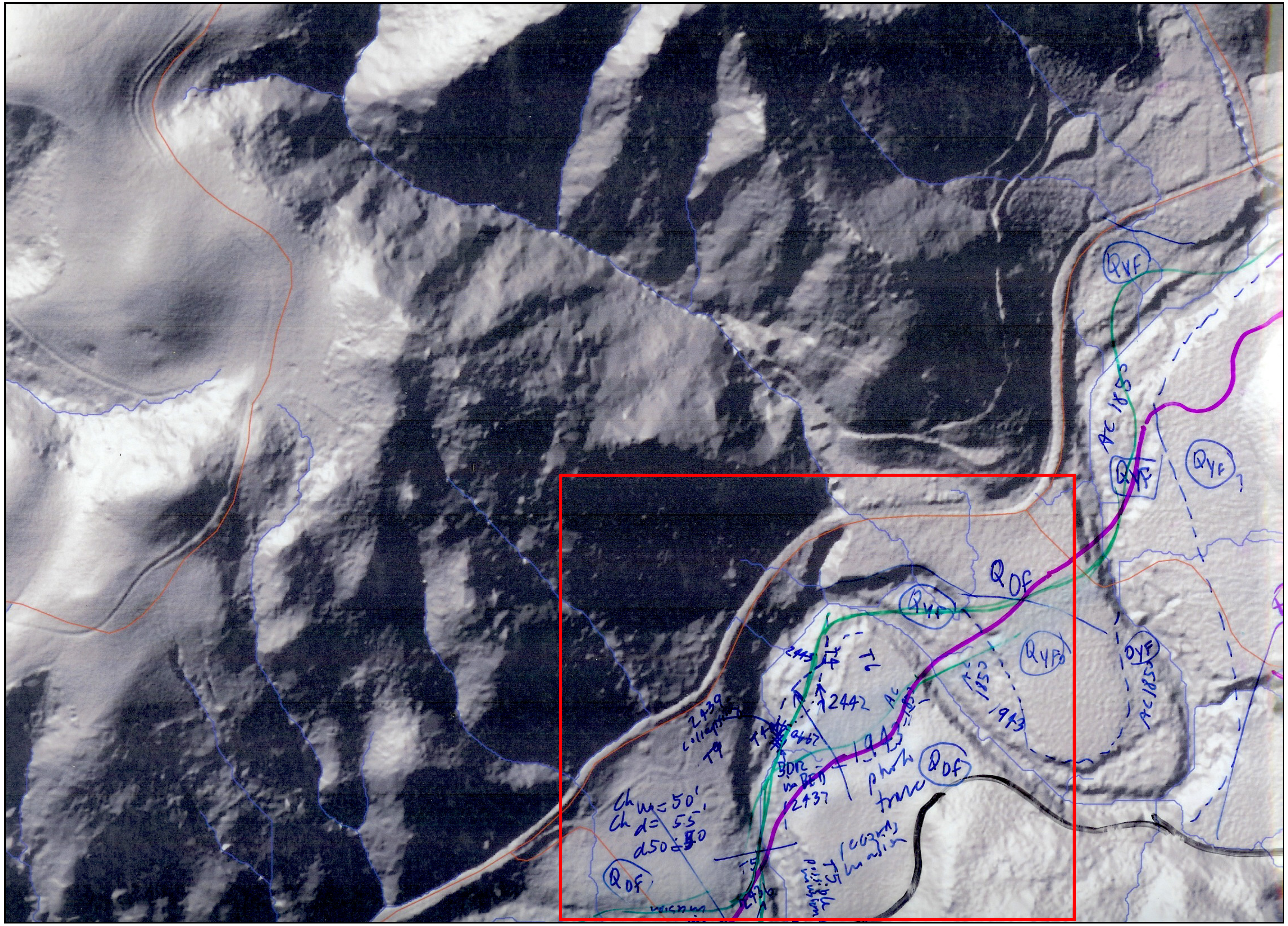
- See discussion in Conclusion (1);
- Clarification: Since 1850, the swampy-meadow reach of Pescadero Creek has experienced lateral shifting, engineered relocation (including straightening), vertical incision, and/or ditching in nearly all locations upstream of the marsh. Additionally, starting around 1920, wider degradational (abandoned) floodplains, i.e. emergent terraces, in the area of the Stage Road Bridge in the town of Pescadero, as well in other locations within the former swampy meadow area, were being buried with engineered fill, at the level of top of the alluvial valley fill, in an effort to reclaim more land by the property owners. The swampy-meadow reach of Butano Creek has also experienced lateral shifting, engineered relocation (including straightening), vertical incision of up to 10 meters (including 2.5 meters post-1960), and/or ditching in nearly all locations upstream of the marsh; however, these processes started occurring around 1900-1920. The alluvial-fan reach of Pescadero Creek has experienced, since 1850-1860, lateral shifting, and/or vertical incision (up to 5 meters), including 2.5 meters post-1940. The alluvial-fan reach of Butano Creek has also experienced lateral shifting, and/or vertical incision of up to 8 meters, including 2.5 meters post-1940; however, these processes started occurring around 1920, but dramatically accelerated in the late 1940s, following the removal of in-channel large woody debris (LWD);
- Conducted numerous visits and interviews with Al Sollars of Butano Falls ([redacted]), born in 1916, who remembers and who has walked the alluvial-fan canyon reach of Butano Creek since 1919. Al can be reached at the following email address, which he reads a few times a week: [redacted] He can also be reached on his mobile phone at ([redacted];
- *See the 1820-1970 planform changes map, which will indicate the likely constricted, engineered-fill sites*;
- See hard copies of the Laminated Field Maps for locations of the photographic sites and soft-bedrock exposures in the channel bed, and see the Field Photographs folder for the 2010 corresponding ground photographs.



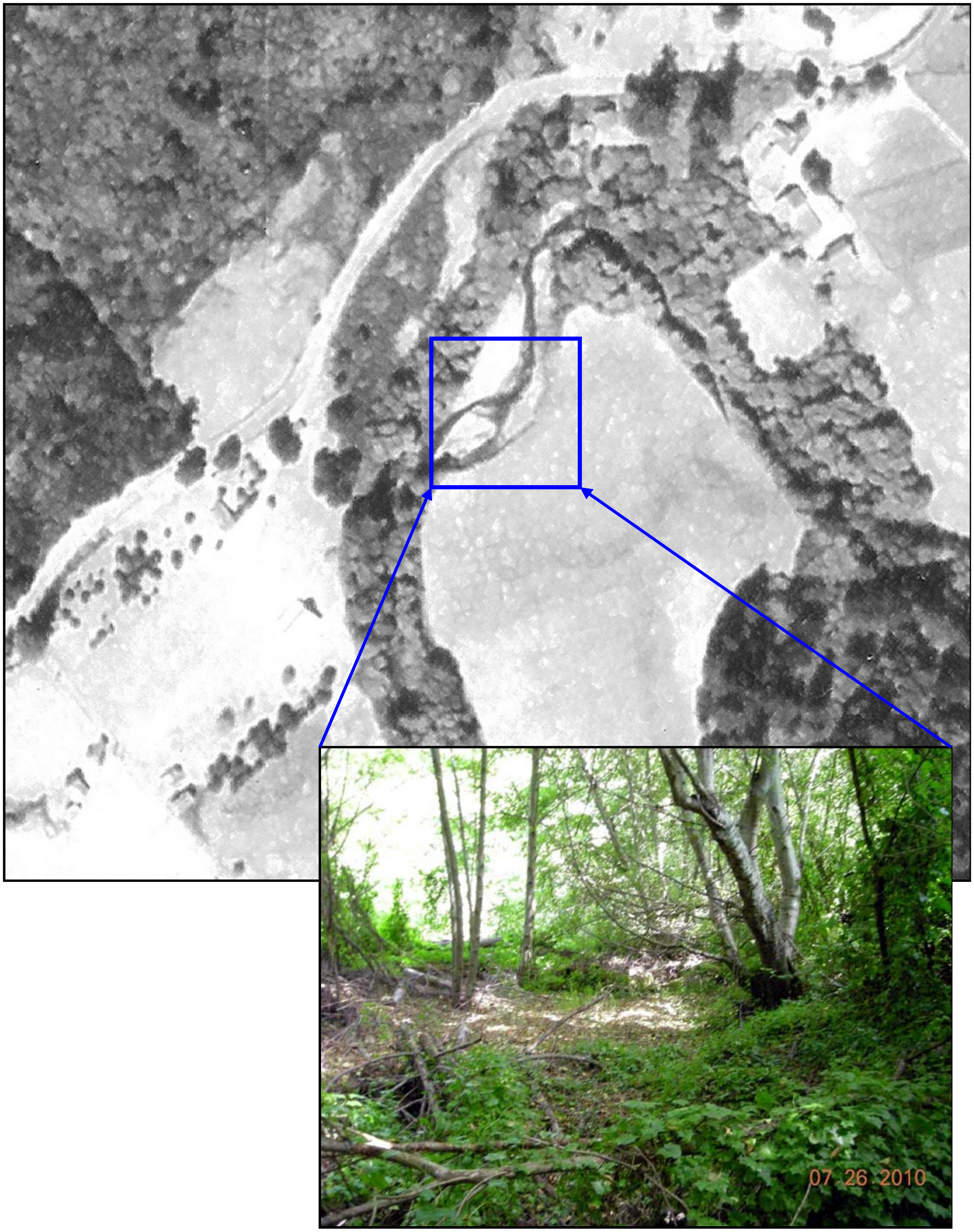
Example of field map depicting lower Butano Valley and a short sub-reach of swampy-meadow reach of Butano Creek. Note deeply entrenched channel of Butano Creek, and a 19th century trace of Butano Creek channel (purple line). Red hatched lines located in channel bed indicate exposures of bedrock underneath valley fill.



Example of field map depicting upper Butano Canyon and alluvial-fan reach of Butano Creek, near gated Butano Falls residential community. Note observations of incisional history in this reach since early 1900s.



Example of field map depicting middle Pescadero Valley and a sub-reach of alluvial-fan reach of Pescadero Creek, near (downstream) USGS gaging station. Note 19th century traces of channel of Pescadero Creek (green and purple line), and LiDAR DEM (2005) SHD imagery recording progressive channel incision. Area in red box shown in 1943 aerial photography on next page, documenting 2.5-meter incision post-1943.



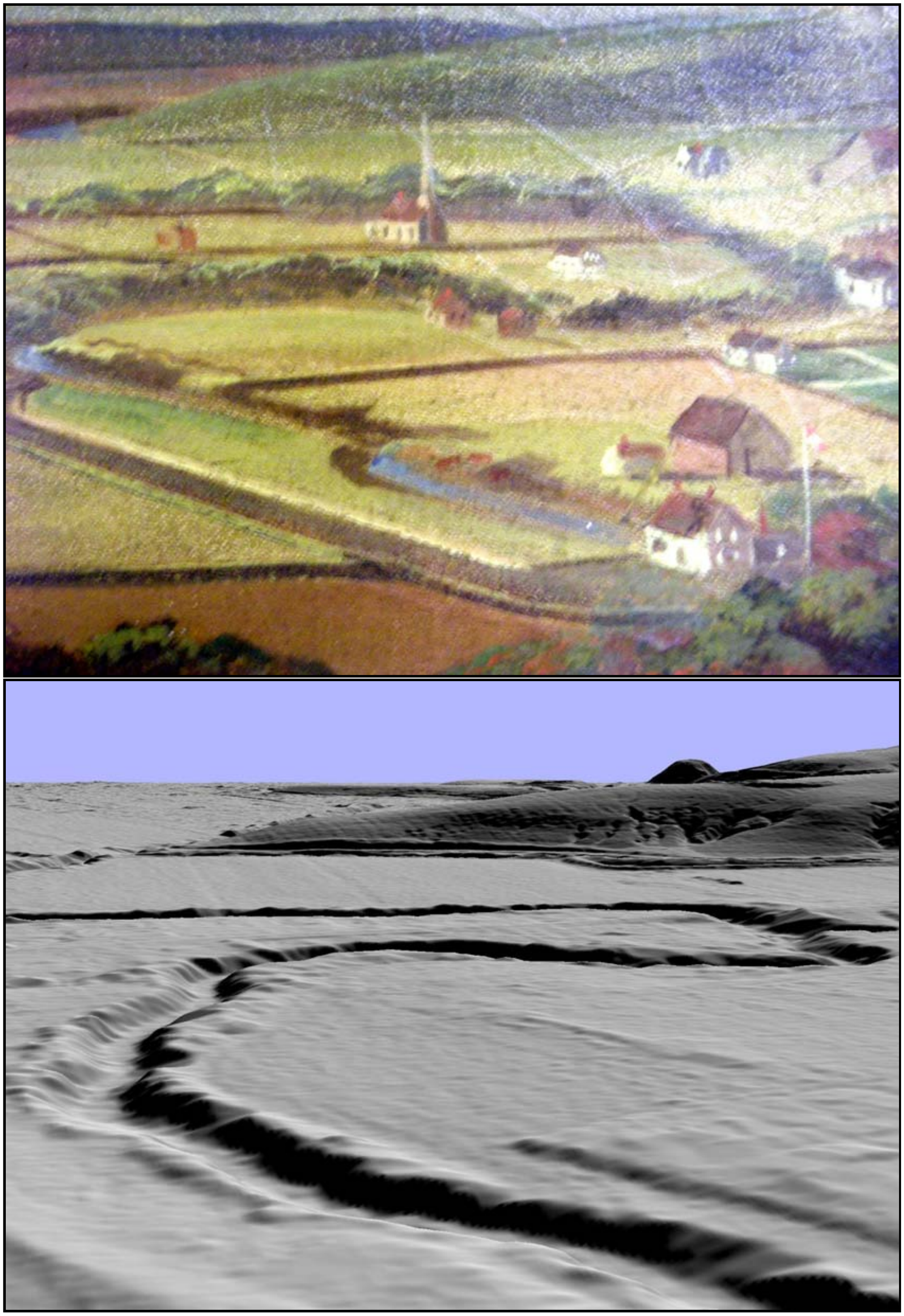
View of low-flow channel located within alluvial-fan reach of mainstem Pescadero Creek in 1943 (USDA-NRCS 1943). Trace of 1943 channel located on 2-4-meter-high alluvial terrace under present-day conditions (see inset ground photograph), providing off-channel winter rearing habitat, with mainstem channel deflected to valley wall by 30-40 meters.

Ongoing channel incision and related active terrace bank instability and fine-textured sediment supply in swampy-meadow reach of Butano Creek.

Ongoing channel incision and related active terrace bank instability and fine-textured sediment supply in alluvial-fan reach of Butano Creek. Photograph on right denotes a site on creek near Camp Butano Creek, where wood charcoal material was collected at base of valley fill for ^{14}C dating.

Ongoing channel incision and related active terrace bank instability and fine-textured sediment supply in (former) swampy-meadow reach of Butano Creek. Right photograph shows ancient trees (5-10 ka) which were recently exhumed by channel incision, within channel at base of valley fill.

Ongoing channel incision and related active terrace bank instability and fine-textured sediment supply in (former) swampy-meadow (left) and bedrock canyon reaches of Pescadero Creek.



Swampy-meadow reach of Pescadero Creek at Pescadero in 1855 (above), and rendering of same view to capture conditions in 2005 using San Mateo County LiDAR DEM (2005). Note unentrenched and shallow (about 1-meter-deep) unconfined channel in 1855, with cattle standing on streambank, and 4-5-meter-deep channel in 2005.

5 SEDIMENT BUDGET ANALYSIS

The following section is compiled from the previously disseminated technical information, science team presentations, and summary memorandum (Martin Trso, P.G. 2012c).

The Pescadero-Butano Watershed is located in the Santa Cruz Mountains, within the central California Coast Ranges physiographic province (Blake and Jones 1981, Blake et al. 1982). This region is an active zone of tectonic deformation associated with the northwest-trending San Andreas Fault, and is characterized by active seismicity (i.e. earthquakes), steep hillside terrain, deflected streams, and faulted, fractured, sheared, and weathered sand-producing bedrock (Wieczorek et al. 1988, Nolan and Marron 1988, Ellen and Wentworth 1995, Weber et al. 1999).

In addition to the topographic, lithologic, and soil properties factors, the hillslope stability in this region is strongly influenced by the highly seasonal climate, which is characterized by high-intensity and long-duration storms in the winter period, and by a summer drought with no precipitation. About 90% of the annual rainfall typically occurs between November and March. The most severe and widespread erosional and sediment delivery events in northern California were recorded in 1982-83 and 1997-98 (after Creasey 1988, Coe et al. 2000). These hillslope instability events were triggered by El Niño-driven rainstorms, which have a recurrence interval of about 15 years for large El Niño events.

As a result of the geologic setting, the sand-producing bedrock, and climate, the Pescadero-Butano Watershed has a natural propensity for deep-seated bedrock sliding, shallow-seated debris slides and debris flows, hillside gullying, and high channel sediment transport capacity. Nolan and Marron (1988) have also reported that due to the sand-producing bedrock, intermediate- and high-order streams in the Santa Cruz Mountains region, unlike those in northwestern California, lack the positive-feedback loop between hillslope and stream channel processes, including those involving the propagation of large pulses of sediment.

The geologic units underlying the Pescadero-Butano Watershed are described in the Pescadero and Butano Creeks Watershed Sediment TMDL report (Region 2 Water Board 2013a, 2013b, 2013c, 2015), and the ESA (2004) report. Similarly, the methods used on the sediment source assessment are presented in detail in the Pescadero-Butano Watershed Sediment TMDL report (Region 2 Water Board 2015).

In brief, the natural sediment sources were allocated by partitioning the total natural landscape denudation rate, applying the published rates on soil creep and shallow landsliding within undisturbed watersheds, and subtracting these from the total natural landscape denudation rate to estimate the rate of sediment delivery within the deep-seated bedrock slide terrain. The management related sediment sources include: hillside surface erosion (associated with the thinning and/or loss of soil) within the areas affected the 19th and 20th century ranching and agricultural activities; shallow-seated landslide/debris flows within the areas affected by 19th and 20th century timbering activities; channel incision along the trunk streams of Pescadero and Butano creeks; road-watercourse crossing related hillside gullying within the areas affected by all land uses in the 20th century; hillside gullying within the areas affected by the 19th and 20th century ranching and agricultural activities; and road surface erosion within the areas affected by all land uses in the 20th century.

The natural landscape denudation rate for the Pescadero-Butano Watershed was inferred from cosmogenic radionuclide surface exposure dating across numerous watersheds in the Santa Cruz Mountains by Gudmundsdottir et al. (2008, 2013) and Hilley et al. (2009). The watershed-wide rate of total denudation corresponds to 0.25 mm/year, or 650 tons/km^2-yr. Accounting for the watershed-specific chemical weathering rate of 0.03 mm/yr, or 80 tons/km^2-yr (Phillips and Rojstaczer 2001) yields a physical denudation rate of 570 tons/km^2-yr. Similar long-term natural landscape lowering rates have been estimated for the watersheds located within the northern California Coast Ranges that are underlain by similarly fractured bedrock, such as the 80-km^2 property located in the Gualala River Watershed (530 tons/km^2-yr, Martin Trso, P.G. 2008), the 1,784-km^2 South Fork Eel River Watershed (400 tons/km^2-yr, Stillwater Sciences 1999b), and the relatively undisturbed 17-km^2 Elder Creek Watershed, a tributary to South Fork Eel River near Branscomb (about 670 tons/km^2-yr, Stock et al. 2005).

The unit-area rate of shallow-seated landsliding/debris flows within undisturbed watersheds in central California Coast Ranges amounts to an average rate of 70 tons/km^2-yr. This is based on our interpretation of the sediment source analysis developed for the Pescadero-Butano Watershed by PWA (2003, 2004), and the rates reported from the neighboring La Honda Creek Watershed (after Balance Hydrologics, Inc. 2006). The shallow soil creep rate was calculated by applying the model SEDMODL2 (Boise Cascade and NCASI 2005), as part of the road erosion and sediment delivery assessment for the Pescadero-Butano Watershed, and it also equally amounts to 70 tons/km^2-yr.

According to the sediment source analysis carried out by the author of this memorandum, an estimated 21.2 million tons were naturally produced on the hillsides across the Pescadero-Butano Watershed during the period 1820-2010, and additional 25.2 million tons due to the geomorphic effects of land-use. The natural sediment sources are estimated to have provided the following loads of sediment: 16 millions tons (75%) from deep-seated bedrock slide terrain, 2.6 million tons (12%) from shallow-seated landslides/debris flows, and 2.6 million tons (12%) from shallow soil creep. The land-use related sediment sources are estimated to have provided the following loads of sediment: 11.4 million tons (45%) from surface erosion (associated with the thinning and/or loss of soil) within the areas involved with the 19th and 20th century ranching and agricultural activities, 4.3 million tons (17%) from shallow-seated landslide/debris flows within the areas affected by 19th and 20th century timbering activities, 3.5 million tons (14%) from the channel incision along the trunk streams of Pescadero and Butano creeks, 2.6 million tons (10%) from road-watercourse crossing related hillside gullying within the areas affected by all land uses in the 20th century, 2.4 million tons (10%) from hillside gullies within the areas affected by the 19th and 20th century ranching and agricultural activities, and 0.7 million tons (3%) from road surface erosion within the areas affected by all land uses in the 20th century.

Of the natural sediment production and delivery, an estimated 0.5 million tons (2%) were deposited across several dozen large-scale Quaternary/Holocene landforms, such as debris-flow fans, alluvial fans, alluvial valleys, and the (former) trunk-stream swampy meadow valleys. Of the land-use related sediment production and delivery, an estimated 9.1 million (36%) were deposited in a scattered manner at thousands of sites across the watershed and in association with various land uses: 4.6 million tons (51% of the total deposition) were deposited in small-scale shallow-seated, fine- and coarse-textured gully and landslide deposits within the areas affected by the 20th century timbering activities; 3.4 million tons (37%) in medium-scale, fine- and coarse-textured debris-flow deposits within the areas affected by the 20th century timbering activities; 0.8 million tons (9%) in medium-scale, fine-textured debris fans at the bases of hillside gullies within the areas affected by the 19th and 20th century ranching and agricultural activities; and 0.4 million tons (4%) of fine-textured sediment in the reaches of the historic tidal reaches of Pescadero and Butano creeks.

According to the sediment source analysis, the stream channels in the watershed experienced the doubling of sediment delivery due to the effects of the land-use activities: 65% over the baseline sediment loading of 111,300 tons/year (183,200 tons/year) during the period 1820-1850, 101% (224,200 tons/year) in 1850-1920, 173% (304,200 tons/year) in 1920-1970, 134% (260,900 tons/year) in 1970-1990, and 133% (259,300 tons/year) in 1990-2010. The supply of sediment from the watershed to the Pescadero Marsh/Lagoon Complex (including the historic tidal reaches) increased from an estimated 106,000 tons/year in 1820 to about 219,200 tons/year in 1920, to 193,000 tons/year under the current conditions. Due to very high attrition of the bedrock and colluvial particles, an estimated 60% of the watershed's sediment supply to the marsh/lagoon complex would be characterized as silty clays, and 24% as sand. Assuming grainsize-specific sediment settling (i.e. trapping) in the estuary and the tidal channels, the sedimentation within the Pescadero Marsh/Lagoon Complex (including the historic tidal reaches) increased from an estimated 1,200 tons/year in 1820 to about 13,700 tons/year in 1920, to 37,300 tons/year under the current conditions.

Based on the watershed sediment supply predicted by the sediment source analysis (SSA), an estimated 5.7 million tons of fine-grained sediment have been deposited within the Pescadero Marsh/Lagoon Complex (including the historic tidal reaches) since 1820. Of this, 0.3 million tons originated from natural sediment sources, and 5.4 million tons from the land-use related sediment sources. Within the period 1820-1990, an estimated 4.97 million tons of fine-grained sediment have been deposited within the marsh-lagoon complex (including in the historic tidal reaches), based on the SSA.

This predicted sediment settling is corroborated by detailed stratigraphic, palynological, and topographic investigations, which indicate that about 3.05-5.14 million tons of fine-grained sediment have been deposited within the Pescadero Marsh/Lagoon Complex (including the historic tidal reaches) during the period 1820-2010. Of this, 0.66 million tons of sediment accreted within the marsh during the period 1820-1990 (after Bergolar Geotechnical 1988), about 2.07-4.14 million tons within the lagoon during the period 1820-1990 (after Smith 1990), and about 0.22-0.30 million tons in the marsh and about 0.04 million tons within the lagoon during the period 1990-2010 (after ESA 2011). The stratigraphic-palynological investigations alone indicated that a total of 2.73-4.80 million tons accreted within the marsh and the lagoon during the period 1820-1990.

The deposition of sediment in the marsh and the lagoon in the period 1990-2010 was interpreted by the author of this memorandum, based on the topographic surveys carried out by ESA-PWA in 1987, 2002, 2003, and 2011. The associated rate of sediment deposition (i.e. "observed deposition") in the 1990-2010 period is equal to about 10,800 tons/year, and corresponds to about 30% of the value of the sedimentation predicted by the sediment source analysis, i.e. 37,300 tons/year. The 2002, 2003, and 2011 re-surveys by ESA-PWA involved occupying the semi-permanent benchmarks established in 1987, over an area of 209 acres within the marsh, and

17 acres within the lagoon. As numerous 1987 benchmarks could not be located in 2011, the surveys of topographic changes within the marsh and the lagoon captured only a portion—about half—of the entire marsh-lagoon complex, potentially explaining the discrepancy between the "observed" and SSA-predicted values of sedimentation. Equally plausible is the explanation that the SSA-predicted value of sedimentation within the estuary and the historic tidal channels had been over-predicted, by over-estimating the grainsize-specific sediment trapping efficiency factors.

The sediment budget is expected to be accurate within an error range of 50% (after Reid and Dunne 1996), though this error may be in fact larger if there is any absence of data on sediment yield. The sediment budget analysis presented above also contains considerable uncertainty, but due to the available data on the long-term sedimentation within the Pescadero Marsh/Lagoon Complex, the error margin is estimated to be 24-55%. The upper range is the sum of errors associated with individual sediment sources, while the lower range originates from the comparison between the SSA-predicted sedimentation in the marsh-lagoon complex during 1820-1990 (i.e. 4.97 million tons) and the "observed" sedimentation as inferred from the stratigraphic-palynological investigations in the marsh-lagoon complex during 1820-1990 (i.e. 2.73-4.80 million tons).

PBW Rapid Sediment Budget	Pre-1820 (tons/yr)	1820-1850 (tons/yr)	1850-1920 (tons/yr)	1920-1970 (tons/yr)	1970-1990 (tons/yr	1990-2010 (tons/yr)	1820-2010 (tons)
Watershed Sediment Delivery							
Natural Sediment Sources							
Deep-seated landslide toes							
Inner gorge landslides							
Shallow landslides/debris flows							
Soil creep							
SUBTOTAL	111,321	111,321	111,321	111,321	111,321	111,321	21,150,990
Anthropogenic Sediment Sources							
Hillside surface erosion (ranching/agriculture landuse)	0	71,874	83,285	41,661	41,661	41,661	11,735,639
Hillside gullying (ranching/agriculture landuse)	0	0	8,393	16,786	25,179	25,179	2,350,000
Shallow landslides/debris flows (timbering landuse)	0	0	8,100	53,567	26,039	26,039	4,286,903
Holocene-landform channel incision	0	0	9,333	32,200	32,200	32,200	3,457,980
Road surface erosion (all landuse)	0	0	0	10,673	6,008	4,415	742,110
Road-watercourse crossing hillside gullying (all landuse)	0	0	0	37,953	18,450	18,450	2,635,650
SUBTOTAL	0	71,874	109,111	192,839	149,536	147,943	25,208,281
TOTAL	111,321	183,195	224,165	304,160	260,857	259,264	46,359,271
Watershed Sediment Storage							
Natural/Holocene landforms (SW, VF, AF, DFD)	5,300	5,300	2,320	2,320	2,320	2,320	530,200
Hillside gully fans (ranching/agriculture landuse)	0	0	2,679	5,357	8,036	8,036	750,000
Debris-flow deposits (timbering landuse)	0	0	0	48,960	23,800	23,800	3,400,000
Shallow landslide small-scale deposits (timbering landuse)	0	0	0	65,849	32,010	32,010	4,572,834
Agricultural reservoir sedimentation	--	--	--	N/a	N/a	N/a	0
Lower channel reach levees	--	--	N/a	N/a	N/a	N/a	350,000
Pescadero Marsh/Lagoon sedimentation	***1,200***	***8,387***	***13,731***	***60,491***	***37,461***	***37,253***	***5,731,160***
TOTAL	6,500	13,687	18,094	182,977	103,626	103,419	15,316,963
Watershed Sediment Output							
TOTAL	104,821	169,508	206,071	121,183	157,231	155,845	31,042,308

Pescadero-Butano Watershed, Rapid Sediment Budget Period 1820-2010: Historical Sediment Delivery, Storage, and Yield Trends.

PBW Rapid Sediment Budget Period 1990-2010	**Pescadero Creek Sub-Watershed**				**Butano Creek Sub-Watershed**			
Sub-Watershed Sediment Delivery	**Total Sediment (T/Yr)**	**>2mm Sediment (T/Yr)**	**Sand Sediment (T/Yr)**	**Silt+Clay Sediment (T/Yr)**	**Total Sediment (T/Yr)**	**>2mm Sediment (T/Yr)**	**Sand Sediment (T/Yr)**	**Silt+Clay Sediment (T/Yr)**
Natural Sediment Sources								
Deep-seated landslide toes								
Inner gorge landslides								
Shallow landslides/debris flows								
Soil creep								
SUBTOTAL	81,419	16,105	26,624	38,690	29,902	7,177	7,476	15,250
Anthropogenic Sediment Sources								
Hillside surface erosion (ranching/agriculture landuse)	32,980	0	15,520	17,460	8,681	0	4,085	4,596
Hillside gullying (ranching/agriculture landuse)	17,709	2,656	7,083	7,969	7,470	1,121	2,988	3,362
Shallow landslides/debris flows (timbering landuse)	18,780	3,715	6,141	8,924	7,259	1,742	1,815	3,702
Holocene-landform channel incision	9,333	2,020	4,144	3,169	22,867	1,875	5,031	15,961
Road surface erosion (all landuse)	3,616	0	1,474	2,142	799	0	263	536
Rd-watercourse crossing hillside gullying (all landuse)	14,746	2,917	4,822	7,007	3,703	899	926	1,889
SUBTOTAL	97,164	11,307	39,184	46,672	50,779	5,627	15,107	30,046
TOTAL	178,583	27,412	65,808	85,362	80,681	12,804	25,583	45,296
Sub-Watershed Sediment Storage								
Natural/Holocene landforms (SW, VF, AF, DFD)	2,205				115			
Hillside gully fans (ranching/agriculture landuse)	5,652				2,384			
Debris-flow deposits (timbering landuse)	23,800				0			
Shallow ls small-scale deposits (timbering landuse)	23,086				8,924			
Agricultural reservoir sedimentation	N/a				N/a			
Lower channel reach levees	N/a				N/a			
Pescadero Marsh/Lagoon sedimentation	***25,035***				***12,218***			
TOTAL	79,778				23,641			
Sub-Watershed Sediment Output								
TOTAL	99,805				57,040			

Pescadero Creek Sub-Watershed and Butano Creek Sub-Watershed, Rapid Sediment Budget Period 1990-2010: Sediment Delivery, Storage, and Yield.

6 MANAGEMENT RECOMMENDATIONS

In this section, recommendations are made for future sediment-management and watershed rehabilitation and/or restoration in the Pescadero-Butano Watershed, based upon the results of the sediment source analysis and the understanding of the effectiveness and cost/benefit of sediment reduction treatments from the Grass Valley Creek watershed, a tributary to Trinity River. General and treatment-specific recommendations are made for cost-effective prioritization of future watershed rehabilitation in the Pescadero-Butano Watershed, primarily focusing on management of sand-producing sediment sources and reduction of fine-textured sediment supply to the alluvial-fan and swampy-meadow reaches of Pescadero and Butano creeks, and the Pescadero Marsh/Lagoon Complex.

In response to land-use history, the watershed has been experiencing the cumulative effects of multiple environmental changes associated with particular land-use practices. Many of these cumulative hydrological effects, and the effects of watershed changes on sediment sources and sediment routing along channel networks, have nearly irreversible impacts. These impacts include the following: (1) the continuing degradation of the coastal hills, involving active soil stripping due to soil erosion and hillside gullying, which annually produce about 66,800 tons of fine-textured sediment supply to the stream channels in the lower Pescadero-Butano watershed; (2) continuing channel enlargement along the alluvial reaches of Pescadero and Butano creeks, which annually produce about 32,200 tons of fine-textured sediment supply to the stream channels in the lower Pescadero-Butano watershed; (3) the loss of 99% of the natural floodplains, with detrimental impacts to the terrestrial and aquatic habitat and biota (especially the native fishery) across the watershed, and which primarily cause flooding in the town of Pescadero during moderate storms; (4) the deposition of up to 9.1 million tons of fine- and coarse-textured and unconsolidated sediment across the watershed, of which 4.2 million tons form medium-size landforms (gully debris fans and debris-flow deposits) that support intermittent watercourses within the areas affected by the 20th century timbering activities; 4.6 million tons are stored in small gully and landslide deposits along the road networks within the areas affected by the 20th century timbering activities, which support ephemeral overland flows pathways or channels; and 0.4 million tons of fine-textured sediment have infilled the historic tidal reaches of Pescadero and Butano creeks; and (5) the several-foot-deep blanketing of the Pescadero Marsh and the nearly total infilling of the Pescadero Lagoon with fine-grained sediment, with an estimated 5.7 millions of tons deposited post-1820 due to the effects of the elevated sediment supply from the watershed and the physical manipulations along the historic tidal channels by the private agricultural and ranching land owners and the government agencies, with detrimental impacts to the native fishery in the marsh/lagoon, and the exacerbation of flooding in the town of Pescadero during moderate storms.

If no sediment management and watershed rehabilitation and/or restoration actions are taken, the ongoing legacy channel incision-turned-widening and hillside gullying processes, as well as the industrialized agricultural activities, are likely to maintain this elevated sediment delivery of 100-130% over the natural background levels across the watershed, as well as sediment delivery to the Pescadero Marsh/Lagoon Complex (including the historic tidal reaches), for decades to come. Such elevated sediment supply will persist unless active watershed management is pursued, focusing on reducing sediment supply from these three land-use related sediment sources under the present conditions: (1) 41,700 tons/year (16% of the total watershed sediment delivery in the period 1990-2010, or 28% of the management-related sediment supply) of fine-textured sediment supply from hillside surface erosion within the areas affected by past (presently idle) and present-day agricultural activities; (2) 32,200 tons/years (12%, or 22%) of fine-textured sediment supply originating from the ongoing excavation, due to legacy channel incision and widening, of the Holocene valley fills (about 3.5 million tons have been excavated since about 1860, or 3.5% of the long-term sediment storage of 99 million tons); and (3) 25,200 tons/year (10%, or 17%) of fine-textured sediment supply from hillside gullying within the areas affected by past (presently idle) and present-day agricultural activities. Additional sediment delivery is expected to occur in the event of the remobilization of recent unconsolidated, land-use related sediment deposits across the watershed, such as 3.4 million tons stored in the medium-size, fine- and coarse-textured debris-flow deposits associated with the 20th century timbering activities (the majority of these deposits are located in steep valleys located between Butano Ridge and Old Haul Road, which support intermittent watercourses), and 0.8 million tons of fine-textured sediment stored in medium-size debris fans at the bases of hillside gullies within the areas affected by the 19th and 20th century ranching and agricultural activities.

Active management of these readily and potentially available sediment sources is expected to have the greatest positive medium- and long-term effect on mitigating excessive sedimentation within the lowermost reaches of Pescadero and Butano creeks and the Pescadero Marsh/Lagoon Complex, and the associated flooding within the town of Pescadero. Additional flood mitigation and aquatic habitat benefits would potentially be achieved in the short- or medium-term, with the re-establishment of floodplain functions via re-connecting downcut trunk channels to present-day alluvial terraces (i.e. the former—abandoned—floodplains), wherever it would be topographically appropriate and cost-effective.

However, caution is warranted given that active sediment management or watershed rehabilitation and/or restoration is being performed at a watershed scale, especially within such a geomorphically sensitive, responsive, and degraded area as the Pescadero-Butano Watershed. If poorly designed and/or administered by inadequately trained or experienced practitioners, such restoration activities could potentially be ineffective and perhaps as damaging as the effects of resource-extraction-focused land-use, as evidenced in the literature (Kondolf et al. 2007, Pess et al. 2003, and other). As reported by the author of this memorandum, a marked difference in the effectiveness and cost/benefit between sediment yield treatments (sediment settling ponds and reservoirs), preventive sediment delivery treatments (excavation of potential sediment from unstable roads, road-watercourse crossings, landings, and ephemeral watercourses), and active sediment source restoration activities (erosion control by means of re-vegetation) has been found in the Grass Valley Creek watershed, a 96-km^2 (37 mi^2) tributary watershed to Trinity River (Martin Trso, P.G. 2004). Starting in the 1960s, this watershed had experienced a 5-to-10 fold increase in sediment supply in response to timbering activities, which included a clearcut deforestation of nearly the entire watershed from the late 1940s to early 1990s. The sediment yield and the preventive treatments were found to be 5 times more cost-beneficial in terms of the cost of 1 ton of sediment saved: $30 vs. $150, in the medium- and long-term. While the preventive treatments on hillsides and along valley fills had at best a moderate efficiency in reducing erosion and sediment delivery (this is due to various adjustments following mitigation actions), the hillside toe erosion-control (re-vegetation) treatments reduced erosion and sediment delivery by a factor of 2-3 in the short-term. In total, the sediment yield treatments in the 96-km^2 Grass Valley Creek watershed amounted to an estimated cost of $31.5 million (2002 dollars) in the period 1984-2002. The preventive treatments amounted to $5.9 million in the period 1992-1997, and the re-vegetation treatments to $1.2 million in the period 1997-2002. These costs do not include land buy-outs to retire and restore timberlands. In response to these watershed restoration activities, the watershed's sediment supply decreased 30% in the period 1991-2002, as compared to the period 1975-1990. An additional 30% reduction in the watershed's sediment supply post-2002 has been reported by Gaeuman (2010), implying that a total 60% reduction in sediment supply was achieved in response to watershed restoration activities, within the medium-term, as compared to the period 1975-1990.

It is recommended that the results of the sediment budget be used to guide the development of the sediment management plan for the Pescadero-Butano Watershed and the related sediment source-specific treatments, and provide the framework for both plan design and monitoring in subsequent years. When coupled with the results of the salmonid population dynamics modeling study (Stillwater Sciences, Inc. 2015), it is recommended that the sediment budget be used to guide the watershed rehabilitation and/or restoration plan for the Pescadero-Butano Watershed. Furthermore, it is recommended that the lessons learned from other watershed sediment management projects in California be considered during the development of the sediment management plan for the Pescadero-Butano Watershed, particularly from the watersheds that are similar in terms of natural processes and geomorphic response to land-use.

Only the tested agricultural and engineering Best Management Practices (BMPs) and restoration measures should be pursued to mitigate all point and chronic sediment sources across the Pescadero-Butano Watershed. Within the active agricultural lands (16% of the watershed sediment delivery), the agricultural BMPs should include the development of high-density cover crop and the management of riparian buffers, to curb soil erosion and sediment delivery, as well as improve water quality from agricultural areas that supply fine-textured sediment to the lower Pescadero and Butano creeks and the Pescadero Marsh/Lagoon Complex. Within the active pasturelands in the coastal hills (10%), including the abandoned and degraded pastures turned to open space, gully debris-fan footslopes should be vegetated, to disconnect sediment transport across these unconsolidated sediment deposit features, and to prevent turning these into sources of sediment in the medium- and long-term. In the absence of vegetative mitigations, short-term sediment yield control actions such as temporary ponds should be employed downslope from large hillside gullies, in order to immediately reduce sediment delivery to the lower Pescadero and Butano creeks and the Pescadero Marsh/Lagoon Complex.

It is acknowledged that the most effective actions of mitigation of the ongoing channel incision and widening (12%) are cost prohibitive, and could amount to hundreds of millions of dollars. Additionally, these actions would require extensive and disruptive construction activities in areas occupied by hundreds of people. However, a decrease in sediment production and delivery from the cut terrace banks could be achieved by decreasing peak flows in the trunk streams, via a cost-effective reconnection of available and suitable alluvial terraces, by building flood bypass channels wherever possible, and by bank stabilizing bio-engineering actions.

Given the empirical evidence for their high long-term effectivity along the Alder Forest reach of Butano Creek, an introduction of beavers should be considered along the perennial incised alluvial-fan and swampy-meadow reaches of Pescadero and Butano creeks, as a potential low-cost and highly efficient mechanism of building up the incised trunk channels with sediment and reducing flooding in the lower Pescadero and Butano valleys. These reaches would include the following: the alluvial-fan reach of Butano Creek from Butano Canyon to Cloverdale Road Bridge; the alluvial-fan reach of Pescadero Creek from the USGS gaging station to Pescadero Cutoff Bridge; and the swampy-meadow reach of Butano Creek from Cloverdale Road Bridge to the upstream-most extent of the historic tidal reach of Butano Creek, upstream from the present-day Alder Forest reach. Based on the recent successes in the United Kingdom, where beavers were re-introduced after 400 years in the late 2000s, as well as in the United States (New York Times 2014), this would amount to a substantial benefit to the public, by greatly reducing the cost associated with the mitigation of the ongoing channel incision and widening and the related sediment delivery.

Irrespective of the mitigation measures needed to manage the ongoing channel incision and widening and the related sediment delivery along the downcut trunk streams, it is recommended that the beavers from the Alder Forest reach be relocated and their dams removed, to enable sediment flushing of the aggraded historic tidal reach. This, however, would need to be complemented by the breaching of the sand bar in the marsh, to minimize sediment deposition within the Pescadero Marsh/Lagoon Complex.

Given the sustainable forestry practices within the active timberlands post-1973, including those of Big Tree Lumber Co. and Redtree Properties, Ltd., the sediment-management treatments within the active timberlands should be limited to seasonal management of haul roads and road-watercourse crossings. Within the former timberlands, presently State and County parks, the potential for erosion and sediment excavation from within the post-1920 timbering-related debris-flow sediment deposits should be evaluated, to identify management actions needed to prevent the remobilization of the sediment storage within these medium-scale landforms in the future.

While the road-related sediment delivery amounts of a mere fraction of the total watershed sediment delivery in the period 1990-2010 (9%), the road-watercourse crossings across the entire watershed, including the agricultural lands, timberlands, ranchlands (including abandoned), timberlands-turned-parks, and residential lands, should be upgraded, in order to improve sediment passage and reduce the potential for flow diversion and the related sediment generation and/or re-entrainment. Furthermore, special focus should be paid to the repair of the road-watercourse crossings in the areas underlain by the Mindego Basalt, Vaqueros Sandstone, and Butano Sandstone geologic units, to improve the passage of the coarse, cobble-boulder streambed substrate. It is recommended that all road and road-watercourse crossing repair activities be prioritized, utilizing the spatially-explicit Sedmodl2 maps developed for the Pescadero-Butano Watershed by the author of this memorandum.

Lastly, it is recommended that the flood mitigation actions rely only on minimal dredging, unless only short-term (emergency), and instead focus on the following measures: the deployment of cost-effective, portable and adaptable interlocking mechanical barrier-type flood containment solution (such as the Muscle Wall, and other barrier types) in the short-term, and on point-source and chronic sediment control across the watershed in the medium- to long-term. In the event of emergency dredging activities within the estuary, it is recommended that the excavated sediment be placed in the hillside gully voids, in the coastal hills in close proximity to the Pescadero Marsh/Lagoon Complex.

7 LIMITATIONS

This technical memorandum describes the geomorphic, land-use, and sediment source assessments, which were carried out in a manner consistent with the level of care and skill exercised by consulting hydrologists, geologists, and fluvial geomorphologists. The information in this technical memorandum is based on the assembling, review, evaluation, and interpretation of several dozen historical, technical and research documents and reports developed by multiple agencies, inter-disciplinary programs, consultants, contractors, non-profit organizations, and private citizens, amounting to about 120 days of work; about 35 day-long field surveys, as well as 40 field and office science panel and interview meetings; and about 100 days of quantitative analysis and map development. The total effort to-date, including the preparation of numerous memoranda technical updates, is estimated at 2,750 hours.

The information presented in this memorandum should not be applied beyond the methods used and described. The limitations under which this work was carried out have been described. The findings and the recommendations are prepared and presented in accordance with the California Geological Survey's (2013) and the California Business and Professions Code's (CBPELSG 2013) guidelines for reviewing and writing geologic reports.

Due to the substantial amount of data collected and the required in-depth and extensive scope of the quantitative and qualitative analytical assessments, as well as the budgetary constraints associated with the original scope of work prepared by the San Francisco Bay Regional Water Quality Control Board staff in 2009, the results of Balance Geo's geomorphic, land-use, and sediment source assessments could not be presented in a full-fledged technical report. Instead, the results are presented in a results-summary memorandum format only, containing only a fractional subset of the information collected on the watershed geology and Quaternary/Holocene geomorphology, the land-use history, the geomorphic response to land-use, and the results of the sediment budget analysis (including historic trends).

Should more funds become available, the abbreviated-text sections would be fully and adequately expanded, so as to provide additional spatially-explicit information to inform the future sediment management and watershed rehabilitation and/or restoration actions. Specifically, the technical report would feature more historic pictorials of stream channel, valley, and hillside conditions over the past 150 years, and ground photographs capturing present-day stream channel, valley, and hillside conditions across the watershed; details on the methods employed (including confidence levels) in and the results of the quantitative assessment of the type-specific sediment sources and their deliveries to watercourses across the watershed, including hillside gully mass wasting and partial sediment delivery, channel incision/widening and complete sediment delivery, and road surface erosion and partial sediment delivery; details on the methods employed on and the results of the quantitative assessment of sedimentation within the Pescadero Marsh/Lagoon Complex; and details on topographic-geomorphic assessments documenting land-use-related small- and medium-scale sediment deposit sites across the watershed, and flood-prone areas along the alluvial reaches of Pescadero and Butano creeks, including the alluvial-terrace areas suitable for cost-effective reconnection and habitat enhancement.

This memorandum has been prepared for the exclusive use of the San Francisco Bay Regional Water Quality Control Board and their partners for purposes so stated. The results of the geomorphic, land-use, and sediment source assessments presented in this memorandum are intended for use in the Pescadero-Butano Watershed only, and to supplement technical data presented in the Pescadero-Butano Watershed Sediment TMDL (Region 2 Water Board 2013a, 2013b, 2013c, 2015) and the Pescadero and Butano Creeks salmonid population dynamics modeling study (Stillwater Sciences, Inc. 2015).

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