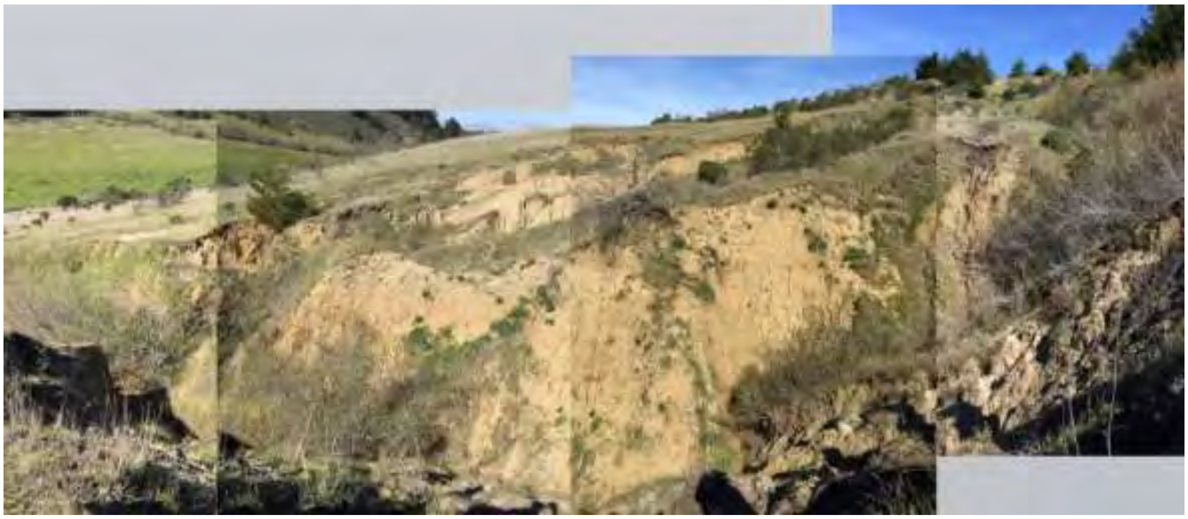
Update to the Coastal San Mateo County Gully Erosion Report



SAN MATEO RESOURCE CONSERVATION DISTRICT

June 30, 2021

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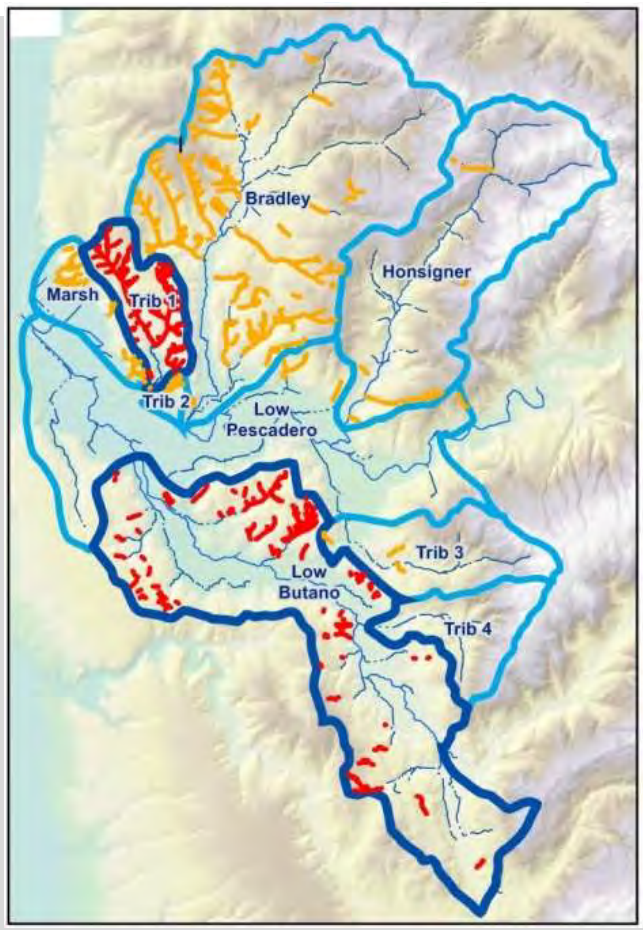
Executive Summary (Updated)

In San Mateo County in California, elevated rates of erosion have caused an unhealthy abundance of sediment in some local stream systems such as the Pescadero-Butano watershed (PBW), which is listed as impaired for sediment under the Clean Water Act. Excess sediment degrades aquatic habitat and impairs the stream's ability to carry floodwaters. Gullies are common erosional landforms and have been documented to deliver significant amounts of sediment to local aquatic habitats.

This report on gully erosion focuses on the lower PBW, and builds on previous work. Gullying was assessed to evaluate the problem, better understand causes and characteristics of gully erosion, and identify and prioritize solutions. Part I of the report contains a literature review; a gully inventory based on aerial imagery and GIS analysis; and criteria for prioritizing treatments. Part II identifies practices for gully erosion remediation and preventing gully formation.

The majority of gullies in the lower PBW are found in the Bradley Creek subwatershed, and the highest densities (linear foot per acre) exist within the adjacent unnamed subwatersheds (referred to in this report as Tributary 1 and Tributary 2). **Characterization of gullies was done for Lower Butano (1,940 acres) and Tributary 1 (342 acres). Initially (in 2017) for the period between 1928 and 2016, and for this update (2021) through 2018.**



The nine subwatersheds in the lower Pescadero-Butano watershed in coastal San Mateo County, CA. Red and yellow lines are gullies that have been mapped based on data from this study and from RWQCB (2012), respectively. Detailed characterization of gullies in Tributary 1 and Lower Butano (outlined in dark blue) was conducted for this study.

The initial analysis showed that gully expansion, activity and sediment production peaked between 1982 and 2005, and that active gullying decreased by 15-20% from 2005 to 2016. Comparatively few new gully segments were observed in 2016, with the majority of new gully length resulting from headwall expansion of existing gullies or the formation of flutes (vertical grooves) in gully sidewalls. This suggested that areas in the lower PBW that are likely to develop gully erosion due to site characteristics or past land uses, had already experienced gullying, and that many of the gullies in these areas were beginning to stabilize.

However, relatively low storm activity from 2012 to 2016 may have allowed for this gully stabilization to progress, and an uptick in storm activity could reactivate stabilized gullies and/or create new ones. The heavy precipitation winter of 2016-2017 could not be captured in the initial (2017) analysis, but informal field observations suggest expansion of existing gullies and formation of new ones in areas where gullying previously occurred. Given the episodic nature of gully erosion and these observations, the study was updated with analysis (post-2016-2017 winter) of gullies in 2018 aerial photos. **Recognizing the limitations of the updated analysis, the overall conclusion is that the trend towards gully stabilization continued despite the heavy precipitation of the 2016-2017 winter.**

Gullies within Lower Butano and Tributary 1 were also evaluated relative to rural roads and hydrologic connectivity to creeks and the marsh. In the Lower Butano, about 20% to 25% of all gullies appear to be road related. A much lower incidence of road related gullies in Tributary 1 is due to the fact that there are very few roads in that subwatershed. The Tributary 1 subwatershed has a comparatively large number of hydrologically connected, active and wide gullies. Nearly all gullies in Tributary 1 are hydrologically connected to streams, whereas a majority of gullies in Lower Butano drain to a catch basin or pond, or are otherwise disconnected from the main stem of the creek.

GIS analysis of gullies throughout the lower PBW indicates that the combination of geology, aspect, and proximity to the ocean are especially important attributes in understanding modern day gully distribution. Slope, modern land use, and vegetation were also evaluated relative to gully distribution but were not as coincident. Areas underlain by the Purisima Formation Tahana member that face south or southwest, and are close to the ocean are more gullied. These combined factors are coincident with gully distribution and may indicate a greater susceptibility of the landscape with those attributes to gullying. Impacts of past and present land use practices on erosional processes can also significant controlling factors for gully erosion. Analysis of historical land use practices in this watershed (Frucht 2015) illustrate the connections between specific land use practices and susceptibility, or, conversely, resilience to gullying.

Review of a wide range of treatment options for gullying showed that environmentally and economically, it is far better to prevent gullies from occurring than to attempt to control them after the erosion has started. Comparatively, gully treatments and sediment containment strategies are costly, require numerous permits, have construction-related impacts, and require long-term maintenance. These challenges only increase with the size of the gully. Furthermore, observations of treated gullies suggest that treatments can reduce erosion rates but are not effective at stopping sediment delivery.

Once gullies have formed, prioritizing their treatment to address sediment delivery to creeks depends on their size, activity, hydrological connectivity to streams, potential future sediment delivery to creeks, and other resource impacts such as loss of rangeland and infrastructure damage (e.g., roads, buildings) due to continued gully erosion. Development of a treatment and/or containment approach requires evaluation of the cause(s) of the gully formation and its potential for continued growth (e.g., concentrated drainage from a road or a failed culvert), and the efficacy of potential actions, including costs, impacts, and need for long-term maintenance.

A holistic approach to addressing gully erosion in the lower Pescadero-Butano watershed consists of actions to prevent gully formation combined with treatments and sediment containment of active gullies. Specific strategies include:

- Restoring and improving soil water holding capacity throughout the watershed to build broader resilience to gully erosion through practices that improve soil health and vegetation cover.
- Improving and maintaining rural road drainage to avoid road-related gullying
- Monitoring lands susceptible to gullying regularly to detect early stages of gully formation, treating initiating gullies, and addressing acute causes of gullying (e.g., improper drainage).
- Based on the gully inventory and characterization conducted for this study, prioritizing active (i.e., unvegetated and growing), bigger gullies that are hydrologically connected to creeks for further site specific evaluation and development of treatment and/or containment projects.

Options for preventing gully formation, treating existing gullies, and containing sediment discharges from gullies are also discussed in Part II of the report; and applicable Natural Resources Conservation Service (NRCS) Conservation Practice Standards are noted.

(UPDATED) PART I: Understanding Gully Erosion in the Pescadero-Butano Coastal Watershed

INTRODUCTION

Erosion is a natural occurrence in coastal San Mateo County, CA watersheds. However, elevated rates of erosion due to some land use practices and other human activities can cause unhealthy abundances of sediment in local streams. Excess sediment degrades aquatic habitat and impairs the stream's ability to carry floodwaters. Gullies are common erosional landforms in these watersheds, and have the potential to deliver significant amounts of sediment to local coastal aquatic habitats.

The San Mateo Resource Conservation District (RCD) has a Rural Roads and Gullies Program to assist landowners with erosion control projects that also benefit the watersheds. As part of this program, the RCD partnered with U.S. Fish and Wildlife Service and the Natural Resources Conservation Service to address gully erosion in the lower Pescadero-Butano watershed. (Figure 1)

This area was selected because Butano and Pescadero creeks are listed as impaired (under Section 303(d) of the Clean Water Act) by the San Francisco Bay Regional Water Quality Control Board (RWQCB) due to excessive sedimentation. Furthermore, the 2004 Pescadero-Butano Watershed Assessment calls for gully control, noting that "gullies have been shown to be the most important source of controllable sediment delivery in the western part of the Pescadero-Butano watershed" (ESA 2004: 2-20).

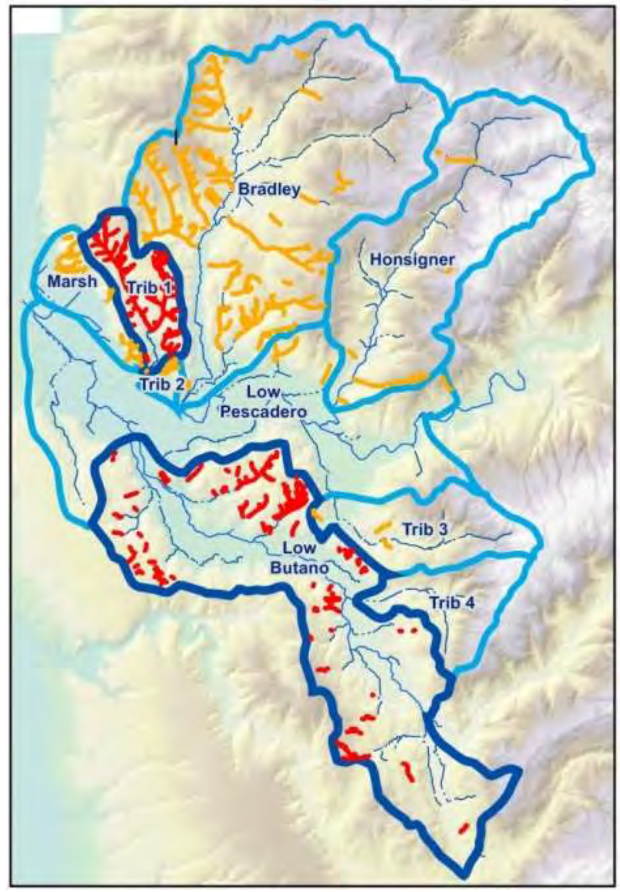


Figure 1. *Subwatersheds in the lower Pescadero-Butano watershed in coastal San Mateo County, CA. Red and yellow lines are gullies that were mapped based on data from this study and from RWQCB (2012), respectively.*

PURPOSE AND SCOPE (UPDATED)

The purpose of this study and report was to evaluate gullies in the lower Pescadero-Butano watershed (PBW) (Figure 1), prioritize them for treatment, and identify effective erosion remediation options as well as management practices that prevent gully formation. Work included:

- Literature review of gully processes
- Review of local studies of gullies and treatments in coastal San Mateo County
- Development of a gully inventory, including detailed mapping and characterization of the historic and current gully network in two subwatersheds
- Analysis of potential gully-controlling factors throughout the lower PBW
- Criteria for prioritizing gullies for treatment
- Identification of treatment options for gullies in this setting
- Development of recommendations to prevent gully formation

The specific purpose of this update (2021) to the original (2017) report was to evaluate the impact of 2016-2017 storms on renewed gully erosion and to document new gully formation. This required additional work on the gully inventory (mapping and characterization of the gully network in the two subwatersheds).

The approach taken for this study built on previous technical work, included new mapping and analysis, and used available aerial photos and GIS data layers. The RCD enlisted the help of Tim Best, Certified Engineering Geologist, for the aerial photo analysis, and professional expertise on treatment options and prioritization.

Reconnaissance-level remapping was done for the entire lower PBW, and, due to funding considerations, two (of nine) subwatersheds were selected for more detailed analysis (Figure 1). Lower Butano Creek (1,940 acres) was selected because the creek currently carries 2.5 times the amount of its historic sediment load and a large sediment accumulation at its confluence with Pescadero marsh has resulted in an almost complete passage barrier for protected fish species, and significant investments in restoration and sediment control projects are being made in this subwatershed (Frucht 2013). Tributary 1 (342 acres), a small drainage on the north side of lower Pescadero Creek, was included because previous mapping found it to have the highest rate of gully activity in the region (RWQCB 2012).

Through detailed analysis of aerial photos of the lower PBW taken over a 90 year period (1928-2018), the historic gully networks in Lower Butano and Tributary 1 were mapped and characterized with respect to location, size, activity and sediment production, and evaluated for change over time.[1] From this geomorphic characterization, gullies were identified that are most likely to contribute significant quantities of sediment to the stream network. Gully erosion control treatments and practices were identified that could be employed to prevent gully formation, stabilize existing active gullies, or contain sediment that may erode from a gully before reaching Pescadero marsh or the mainstem of Pescadero or Butano Creek.

Additionally, factors that have been reported in the literature as correlative to gully formation (i.e., geology, slope, aspect, etc) were mapped with the current gully network across all nine subwatersheds in the lower PBW. GIS analysis of available data layers was used to examine potential correlations to gullying, and identify locations where new gullies may be expected to form. It is important to note that historical land use practices (e.g. land clearing, extent of past grazing and plowing) which can have big impacts on erosional processes could not be evaluated in the GIS analysis because these data layers were not available.

Lastly, the project team and partners conducted a field visit to two gully control sites to observe and discuss treatment outcomes with the landowners and managers. Preliminary recommendations for gully treatment and prevention were refined based on the findings of this field visit.

PHYSICAL SETTING

The Pescadero-Butano watershed is located approximately 50 miles south of San Francisco along the western slope of the Santa Cruz Mountains. (Figure 1) The watershed's two primary streams, Pescadero Creek and Butano Creek, drain into Pescadero Marsh. The study area was the western portion of the PBW which is bisected by the San Gregorio Fault and underlain primarily by sedimentary rock units (Figure 18). Extensive clearing of forest cover, and conversion of scrub vegetation in lowlands and hillslopes for agriculture and ranching occurred throughout the 19th and early 20th century. Current vegetation in the lower PBW consists mainly of grasslands and shrub (Figure 21), and primary land uses are grazing and agriculture (Frucht 2015, Frucht 2013, ESA 2004).

LITERATURE REVIEW

Gully erosion is an issue globally, and is receiving additional attention in the context of climate change. Worldwide, gullies are a major cause of degradation and loss of agricultural lands, and have significant negative off-site impacts on water quality and sedimentation (Valentin et al. 2003, Poesen et al. 2003). In gullied

[1] Due to the timing of project, the effects of the exceptionally high amount of rainfall during the 2016-2017 winter could not be captured within scope of the aerial photo analysis. Given the episodic nature of gully erosion and anecdotal observations of increased gullying in the lower PBW, efforts will be made to amend this study with analysis of gullies in the 2017 aerial photos once these become available, and to update the recommendations if necessary.

watersheds, gully erosion has been reported to contribute more than half, and as much as 96%, of the total sediment loads (Poesen et al. 2003, Betts 2003, Valentin et al. 2005). Furthermore, gully expansion is positively correlated with rainfall intensity, which is expected to increase with climate change (Vanmaercke et al. 2016).

GULLY DEFINITION AND PROCESSES

Gullies are large erosional channels caused by concentrated but intermittent water flows usually during, and immediately following, heavy rains. Gullies vary in size and typically form in poorly consolidated sediment. Typically, gully channels range in depth from 0.5m to 25m, and are characterized by steep, erosional banks or slopes (Soil Science Society of America, 2017). In agricultural settings, the threshold for defining erosional channels as gullies (as opposed to rills) is when they become too deep to easily plow with standard farm equipment. Gullies can be connected to, and form part of, a drainage network, or be discontinuous and disconnected from any drainage network (Bull and Kirkby 2002).

Gully erosion processes in arid and semi-arid environments are more thoroughly reported in the literature, though gullies are also common in more humid environments (Hadley et al. 1985). Generally, factors that control gully development are soil type and profile, climate (i.e., precipitation and temperature), topography and land use (Valentin et al. 2005). A variety of natural and anthropogenic factors can increase susceptibility to gullying and/or trigger gully processes at site-specific and landscape scales. Intensive and frequent rainfall, road building, poor rangeland vegetation cover and removal of deep-rooted perennial vegetation, overgrazing, improper cultivation and irrigation designs, and improper discharge of stormwater are factors identified in studies of gully systems within the U.S. and multiple international sites (Valentin et al. 2005, Hadley et al. 1985, Swanson 1989, Spreiter 1979, Betts 2003, Nyssen et al. 2002). Of note is that factors reported to significantly contribute to gully formation in a specific area may not be important elsewhere. Gully formation processes are complex and strongly affected by the unique combination of local conditions (Le Roux et al. 2012).

Figure 2. *A large gully that opened adjacent to Butano Creek (left side of the photo) in March 2016 that initiated due to storm drainage flows redirected by a failed culvert. Concentrated subsurface flows via soil piping and subsequent tunnel formations can be seen (yellow arrows), as well as concentrated surface flows that contributed to headward expansion of this gully (red arrow). Note that this is a panoramic photo; the gully mouth (on the left side of the photo) points west, and the man in the photo is standing almost opposite this (i.e. due east).*

Gully formation and subsequent growth can result from both surface and subsurface flows. Typically, gully initiation due to surface erosion from concentrated water flows in small channels, or rills, is emphasized in the literature. However, the dominant influence of subsurface flows in gully initiation and erosion has also been reported (Hadley et al. 1985, Swanson et al. 1989, Bocco 1991). Abruptly decreasing soil profile permeability was one of the key factors documented by Bocco 1991 in gullying due to subsurface flows. Gully formation via subsurface flows follows a process of soil piping, followed by formation of open subsurface conduits (tunneling), and eventual roof collapse of tunnels (Hadley et al. 1985, Swanson et al. 1989). (Figures 2 and 3) Expansion of gullies occurs through headward erosion, or headcutting (lengthening) as well as sidewall erosion (widening), both of which can trigger branching from the mainstem gully (Crouch 1987, Bull and Kirkby 2002). Expansion and fusion of a discontinuous (i.e., discrete) gullies can also form a network of gully channels (Bocco 1991, Heede 1967, Mosely 1972).

Figure 3. *Photo on the left shows a gully that has substantially revegetated, but is experiencing headward erosion, or "headcutting" as seen in the close up shown in the middle photo. Photo on the right shows an adjacent gully as an example of active branching resulting from past mainstem gully erosion. Sidewall fluting (i.e. formation of vertical grooves) is visible in the gully branch shown in the photo on the right. Photos were taken during a heavy precipitation winter (2016-2017).*

SIGNIFICANCE OF GULLIES IN THE PBW

The relative significance of sediment delivery from gullies was addressed by the RWQCB in its assessment of sediment inputs to the PBW (Frucht 2015), and in a sediment budget for the Santa Cruz littoral cell into which the PBW drains (Best and Griggs 1991). The sediment budget for 1970 to 2010 indicated that gullying represented 1-2% (2,900 – 5,800 m^3/year) of the total annual sediment delivery from creeks (290,000 m^3/year) to the cell (Best and Griggs 1991). The RWQCB concluded that gullies are a more significant sediment input into this watershed. Between 1860 and 2010, gullying delivered approximately 2.4 million tons of sediment to the local streams and Pescadero marsh and lagoon. The assessment of sediment sources within the PBW by the RWQCB identified the following erosion inputs (in tons/year) for 1970-2010: 260,000 total (with 110,000 from natural sources, and 150,000 from anthropogenic-induced erosion); and of this total, 24,000 from gullying on rangelands and 29,000 from road-induced gullying/landslides (Frucht 2015). This analysis suggests that as gully-related erosion contributes as much as 20% of the sediment delivery in the PBW.

GULLY FORMATION AND DEVELOPMENT IN THE PBW

Spreiter (1979) and Swanson (1989) examined gully formation and distribution in detail in coastal San Mateo County, California, and the studies offer key insights into the specific factors that cause and contribute to gully development in the PBW. Field analyses of gully formation and distribution in coastal San Mateo County by Spreiter (1979) identified subsurface flows and soil piping erosion in the A horizon soils (surface soils) as the main cause of gully formation. Swanson et al. (1989) monitored gullies in watersheds just north of the PBW with very similar conditions, and also found that the predominant mechanism of gully formation and growth was subsurface flow. Monitoring of one such gully strongly suggested this subsurface control: tunnel outlets in the gully walls delivered 70% of the flows into the gully, whereas overland flows contributed just 25% (rain directly into gully made up the remainder). Furthermore, the flows from the tunnels contained 90% of the suspended sediment generated from the gully and were an order of magnitude greater than concentrations in overland flow.

Gully formation as a result of subsurface flow can initiate with soil piping and the development of subsurface open conduits that allow for rapid erosion (tunneling) until the tunnel roof collapses (Figure 4). Subsequent flows will then remove the roof sections and debris, creating on open channel, and then rapidly downcut (typically, 5-10m deep, but as much as 15m) until bedrock is reached (Spreiter 1979). Gullies continue to grow laterally by slumping, tunneling, and headward erosion. Gully headwalls are generally steep to vertical, have tunnels or caves leading uphill that (as already noted) can be significant sources of flow to the main gully channel during and after periods of heavy rain. Surface runoff over the lip of the headwall can contribute to head cutting and further gully growth (Spreiter 1979). (Figure 2)

A forthcoming assessment of sediment contributions in the PBW by the RWQCB identifies the important roles of both surface and subsurface erosion in gully formation and growth, as well as a number of interrelated factors: rainfall intensity, vegetation cover, rooting depth, microrelief, slope, position in the landscape, contributing upslope are, soil permeability, soil depth, and soil cohesion and dispersiveness (Frucht 2013).

Figure 4. *Gully development due to soil piping and tunneling, which has led to tunnel roof collapse.*

FACTORS CONTROLLING GULLY FORMATION AND EXPANSION

GEOLOGY AND SOILS

Spreiter (1979) and Swanson et al. (1989) identify the Purisima Formation-Tahana Member as especially prone to gullying. The Purisima Formation is a sedimentary rock unit consisting of siltstone, mudstone, and sandstone deposited in a marine basin during Pliocene time (5.33 mya to 2.58 mya). The Tahana is rich in sediments of volcanic origin that weather into the smectite group of clays, known for their dramatic swelling and shrinking characteristics. Hence, soils from this rock unit swell in the wet season and are prone to shrinking and cracking in the dry season. Additionally, these clays are quickly rendered dispersive in the presence of Na^+ (Sherard and Decker 1977). These factors, combined with weak bonding between layers, allow clay particles to readily mobilize in water moving through the soil. In areas of concentrated water seepage, clay particles can be selectively removed from the soil, increasing permeability locally and creating conditions that are prone to pipe formation. As a contrast, the Pomponio Mudstone formation (found adjacent to the Purisima in the lower PBW) which has much lower volcanic-derived clay content, does not produce expansive clays in abundance, and its associated soils are less prone to piping (Swanson et al. 1989).

PROXIMITY TO THE OCEAN

For soils underlain by the Purisima Formation, proximity to the ocean appears to be a controlling factor for gully formation (Spreiter 1979). Ocean aerosols (i.e., ocean spray, mist, fog) are a steady supply of Na^+ which drives the dispersive process in Purisima Formation soils with high smectite clay content. Spreiter (1979) noted that the majority of gullies in the peninsula occurred on moderately steep, south or west-facing slopes within about 3 miles of the ocean, and that gullies were generally not present further inland on sites with similar characteristics (i.e., underlain by Purisima formation, comparable slopes and vegetation).

IMPERMEABLE SOIL LAYER

Another controlling factor for soil piping identified by Spreiter (1979) and Swanson et al. (1989) is the presence of a relatively impermeable claypan layer below dispersive A horizon soils. Under these conditions, a concentrated flow of water downslope on top of the claypan contributes to formation of soil pipes in the A horizon (Swanson et al 1989). Dessication cracks, root casts, burrow holes and other voids compound the soil piping effects by permitting water to move rapidly down, accumulate on the claypan, and cause further erosion (Spreiter 1979).

SOIL EXPOSURE

Unvegetated soils are susceptible to surface erosion as well as soil pipe enlargement, particularly on hillslopes where the gradient favors more rapid drainage of soil water. Additionally, exposed dispersive soils erode more readily when exposed to surface flows (Spreiter 1979).

SLOPE AND ASPECT

Spreiter (1979) concluded that moderately steep slopes between 15 and 25 degrees[2] are conducive to soil pipe formation in combination with other factors. The soil profile is generally not deep enough support soil pipe formation on steeper slopes and subsurface flow on shallower slopes may be too slow to trigger this type of subsurface erosion (Spreiter 1979).

Spreiter (1979) identified south and west-facing slopes, characterized by grass and sparse shrub vegetation, as more prone to gully formation because they receive more direct sunlight and less-favorable moisture supply result in relatively poorly leached soil with higher concentrations of Na^+. In dispersive soils proximate to the ocean, these conditions can lead directly and indirectly (via formation of more dessication cracks) to soil piping.

HISTORIC LAND MANAGEMENT AND USES

A variety of anthropogenic activities and land uses that created conditions favorable to gully initiation and development in the lower PBW have also been identified (Spreiter 1979, Swanson 1989, Frucht 2015).

- Construction of roads that exposed highly dispersive soils formed from the Tahana.
- Poorly designed or maintained drainages along rural roads that concentrated water into highly erosive flows.
- Conversion of much of the lower PBW low coastal scrubland to agriculture for dryland cultivation of flax and grains, and introduction of annual, shallow-rooting grasses. This removal of deep-rooted native and perennial vegetation (for land clearing) allowed formation of voids where roots rot away and serve as conduits for lateral and downward water flow.
- Plowing that increased the formation and depth of dessication cracks, and increased soil permeability and downward movement of water particularly on the moderately steep hillslopes that are conducive to soil piping.
- Conversion of coastal scrub habitat to grasslands and extirpation of predators may have supported increased burrowing rodent populations, and the resulting proliferation of burrows that allow for rapid lateral and downward water flow.
- Overall, historic poor soil conservation practices (i.e., over-grazing) that increased soil erosion and degradation, and further exposed dispersive clays in the soil.

[2] This corresponds to a range of about 27-47% slope.

Historical aerial photos from 1956, 1963 and 1972 for the Tributary 1 subwatershed indicate a potential correlation between brush removal and accelerated gully formation and expansion (Jim Howard, NRCS, pers. comm.). Acreage where brush was removed increased noticeably, primarily on steeper slopes toward the bottoms of the canyons. Gullies which were apparent in earlier photos (1956 and 1963), but were primarily limited to canyon bottoms, expanded dramatically in the 1972 photos, becoming longer and deeper with lateral gullies appearing along the side slopes. These observed changes coincided with increased herbicide use, advances in heavy equipment technology that allowed for working on steeper slopes, and a large storm event in 1964 (Jim Howard, NRCS, pers. comm.).

METHODS (UPDATED)

ANALYSIS OF AERIAL PHOTOS

Historic gullies were mapped and their activity and growth characterized within a 2,282-acre area of two sub basins of the Pescadero-Butano watershed based primarily on an analysis of historic aerial photos, and review of LiDAR data. For this update to the 2017 analysis, the same methods were utilized on the new 2018 set of aerial images.

MAPPING THE HISTORIC GULLY NETWORK (UPDATED)

The extent of the gully network was mapped using seven sets of historic aerial photographs taken in 1928, 1943, 1963, 1982, 2005, 2016 and 2018. Years selected were based on air photo availability, photo resolution and quality, and time span between the photos. Mapping from the 1928 photos was completed only for Tributary 1; Lower Butano was not mapped for this year.

The 1928, 1943, 1963 and 1982 photos were scanned and digitally rectified into GIS based on spline transformation using common reference points visible in the aerial photographs and/or LiDAR. The 2005 photos are San Mateo County Half-Foot Orthophotography. The 2016 and 2018 photos are georectified Google Earth imagery. For each of the seven different photo years the location of the gully axis was mapped into GIS using the 2005 LiDAR-derived topography as the base map. The original (2017) mapping of gullies was an iterative process starting with the 2016 photos and working backward in time to 1928. After the maximum extent of gullies was mapped the gullies were sub-divided into segments based on their age (date they first appeared in the photos/images) and physical attributes (See Characterization, Table 1). The gully database was subsequently revised to ensure consistency in observations between the different photo years and to include measurements and observations from the 2018 images.

CHARACTERIZATION

Characterization of gullies was done for two subwatersheds, Lower Butano and Tributary 1 (1,940 acres and 342 acres, respectively, Figure 1). Gullies were divided into segments based on similar physical characteristics. For each gully segment, the attributes described in Table 1 and Table 2 were collected based on interpretation from the photos. These attributes were used to further characterize gully activity, road related gullying and hydrologic connectivity of gullies.

Table 1. *Attributes used for characterization of gullies.*

FIELD	DESCRIPTION
GULLY ID	Unique ID of each gully segment.
YEAR	Air photo year gully first observed: 1928,1943, 1963, 1982, 2005, 2016, 2018
WIDTH (ft)	Average gully top width of each gully segment per photo year was measured in 5 foot increments (i.e. 5, 10, 15). Measurements were made in GIS from the georectified photos and images. Accuracy of this measurement depends on how well the gully edge can be identified in the photos, which is a function of gully exposure, degree of vegetation, presence of shadows in the photos and/or photo resolution.
LENGTH (ft)	Length of each gully segment
ACTIVITY	Qualitative and relative classifications of gully activity based on the degree of gully wall vegetation and/or changes in gully morphology and width from the previous photo. (See Table 2 for detailed definitions of activity classifications.) • **A:** Active • **P:** Partially Active • **D/I:** Dormant/Indeterminate
LOCATION	Location of gully on hillslope based on the following criteria: • **Valley Bottom**: Gullies and/or incised channels following watercourses along the larger valley bottoms. Many of these are older features that predate the 1943 and 1928 photos. • **Swale:** Gullies located in topographic swales. The drainage area of the swale is generally much smaller than that of a valley and, in most cases, an incised watercourse does not appear to have existed prior to gully development. • **Hillside**: Gullies that largely developed on a mostly a planar hillside • **Flute**: Small (< 100 ft long) gullies that have incised into sidewalls of larger gullies.
ROAD ASSOCIATION	Qualitative determination if the gully is a result of road activities. This would include the gullies that formed along roads as a result of water being diverted along the road bed, formed below the road when interpreted to be the result of runoff being discharged off of the road prism, are gullied-out road prisms at stream crossings, and gullies extending upslope of a road cut and interpreted to be the result of the road cut intercepting groundwater and forming a knickpoint that erodes upslope. • **Y:** Gully most likely caused by the road, typically by concentrated road runoff • **P:** Possible road association • **N:** Not associated with a road • **U:** Unknown – not determined
HYDROLOGIC LINKED	Qualitative determination if the gully is linked to a watercourse. Any gully system that drains into a watercourse is considered to be hydrologically linked. Gullies that drain into agricultural ponds or catch basins are assumed not to be hydrologically connected. Small gullies located in upper portion of the hillside and which do not appear to extend down to a watercourse are also assumed not to be hydrologically connected. • **Y:** Hydrologically linked • **CB:** Drains into a catch basin (agricultural pond) and therefore the coarse grained sediment is not hydrologically linked. • **P:** Possibly linked • **N:** Not linked
SUBWATERSHED	Tributary 1, or Lower Butano

FIELD	DESCRIPTION
GULLY DEPTH AND SIDEWALL SLOPE LENGTH (ft)	Gully depth and gully sidewall length per segment were approximated based on measurements of gully width and assuming a pre gully (native) sideslope gradient of 30% and a post gully sideslope gradient of 80%: Depth (ft) = $W/2*(S_{pre} – S_{post})$ Sidewall Length (ft) = $W/2*\cos(\tan^{-1}(S_{post}))$ Where: D = Gully Depth (ft) SW = Gully Sidewall (ft) W = Gully width (ft) S_{pre} = Gully sideslope (pre gully) = 30% S_{post} = Gully sideslope (post gully) = 80%
UNIT EROSION RATE (cy/lf/yr) and SEDIMENT PRODUCTION (cy/yr)	Sediment production volumes (cubic yards) and erosion rates (cubic years per year) gully were calculated based on change in calculated gully cross-sectional area between sequential photos. This assumes a pre gully (native) sideslope gradient of 30% and a post gully sideslope gradient of 80%. Erosion rate is the difference in cross-sectional areas divided by the time period between photos. Gully Volume (cy): V = $(W^2*(S_{pre} – S_{post})/ 4)*L/27$ Sediment Production (cy/yr): SED = V/t Unit Erosion Rate (cy/lf/yr): ER = SED/L Where: V = Gully volume (cy) L = Gully length (ft) W = Gully width (ft) S_{pre} = Gully sideslope (pre gully) = 30% S_{post} = Gully sideslope (post gully) = 80% T = time period between photos

<u>Gully Activity</u>

It is clear from the historic aerial photographs that gully activity has varied over time with many having reached their peak size and are now starting to revegetate and stabilize. For this study gullies were classified as active, partially active, or dormant, based on the observed changes in gully morphology and/or level of revegetation (Table 2). Gullies that had observed bare sidewalls and/or change is width were classified as "active"; gullies that have revegetated and do not show signs of active erosion or widening were classified as "dormant". An example of how this classification was used to track gully growth from initiation to partial stabilization over time is depicted in Figure 5

Table 2. *Definitions of gully activity levels*.

ACTIVITY	DESCRIPTION
ACTIVE	Gullies that are actively eroding or have experienced notable erosion since the last photo. They are identified based on the following criteria: • <u>Vegetation:</u> Gullies with bare and unvegetated sidewalls, **AND/OR** • <u>Change in morphology:</u> Notable increase in gully width and/or gully morphology since the last photo. Some gullies exhibiting bare slopes are classified as active but do not show measurable changes in gully width over time. This occurs when the rate of erosion is slow but sufficient to prevent vegetation growth or because the soils are poor and cannot support heavy vegetation. Some gullies that show signs of widening are classified as active but may be partially vegetated in the photos. This occurs when the erosion that resulted in gully widening occurred earlier within the time period between photos and the gully walls had subsequently partially revegetated. This is particularly true for the 1982 – 2005 time period where the 1982 photos were taken only a few days after the large storms. It is likely that some gullies continued to erosion for a few years following the storms before starting to stabilize.
PARTIALLY ACTIVE	Gullies exhibiting signs of revegetation and gully wall stabilization **relative to** the previous photo. These features have: • <u>Vegetation:</u> Partially or mostly revegetated or grassed over sidewalls and bottoms with only local exposures of bare ground, **AND** • <u>Change in morphology:</u> Do not exhibit notable changes in gully width or morphology from the previous photos.
DORMANT	Gullies and/or swales that are well vegetated with somewhat subdued (weathered) morphology and no signs of active erosion. This may include some previously active gullies that are now obscured by vegetation. Dormant gullies can be reactivated during large storms.
INDETERMINATE	Level of gully activity could not be determined from the photos.

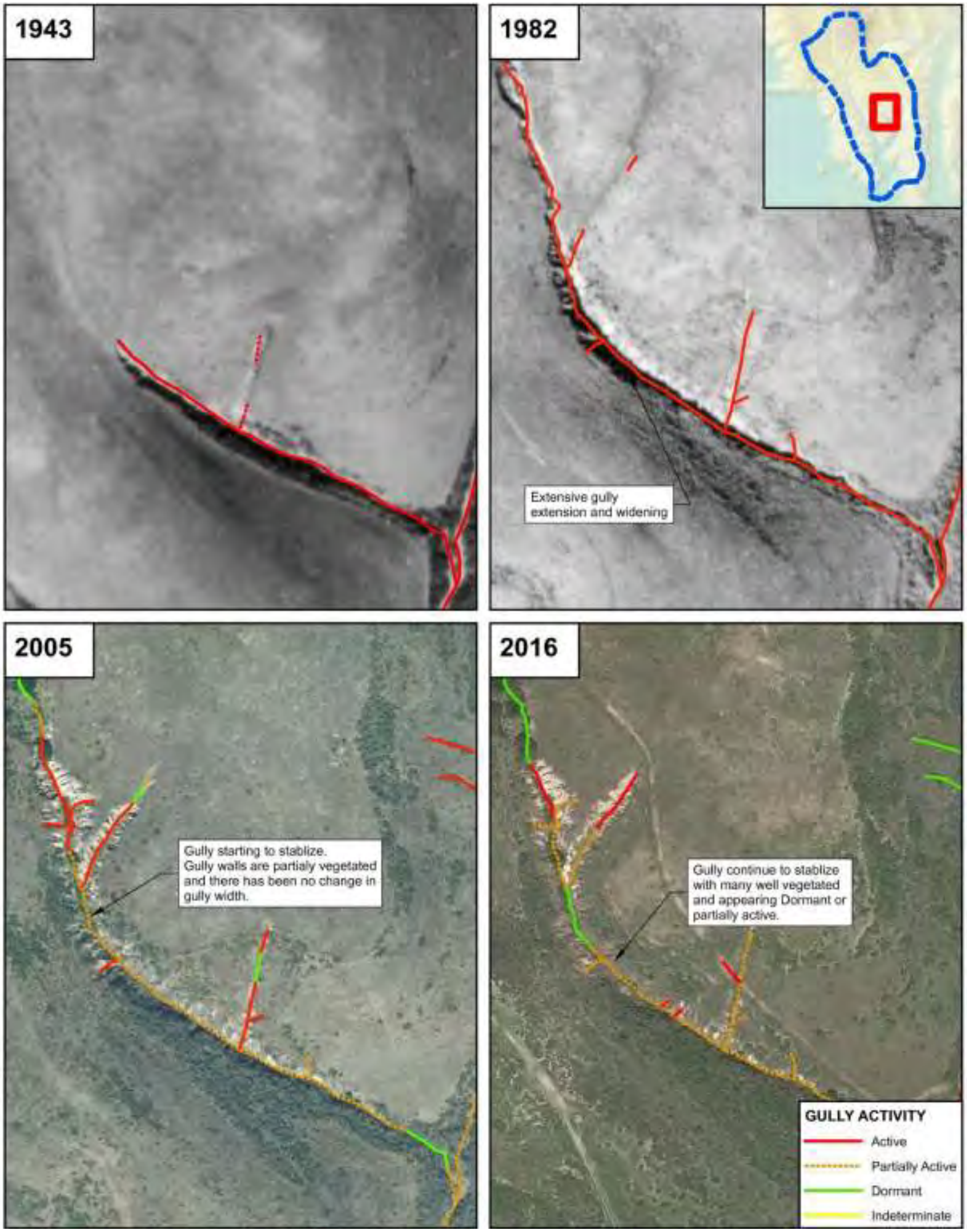


Figure 5. *Photos of a gully in Tributary (Trib) 1 illustrate gully stabilization over time. In 1943 and 1982, the entire gully length was "active" (see Table 2 for definitions of activity levels) and extensive gully growth (expansion) occurred in this period. By 2005 portions of the gully had begun to stabilize and large sections of the original gully main stem no longer shows signs of activity and thus were considered "partially active." And, as some "partially active" segments become well-vegetated and lack morphology changes in 2016, they are considered "dormant."*

Road Related Gullying

For the purpose of this study, a gully that is considered to be road related had to have been identified in the aerial photographs as being caused by that road. This would include the gullies that:

- Formed along roads as a result of water being diverted along the road bed
- Formed below the road when interpreted to be the result of runoff being discharged off of the road prism
- Are gullied-out road prisms at stream crossings
- Extending upslope of a road cut and interpreted to be the result of the road cut intercepting groundwater and forming a knickpoint that erodes upslope.

Hydro Connectivity of Gullies

Hydro connectivity is measure of whether or not a gully is hydrologically connected to the stream network, with the potential to deliver course sediment to the mainstem stream. In this analysis, any gully that is continuously incised and drains into a watercourse is considered to be hydrologically linked. Gullies that drain into agricultural ponds or catch basins are assumed not to be hydrologically connected.

GIS ANALYSIS OF GULLY-CONTROLLING FACTORS

Gully distribution relative to the distribution of gully-controlling factors that could be mapped (i.e., geology, soils, slope, aspect, and vegetation) was evaluated using ArcGIS. A composite gully distribution layer was created that includes gullies mapped in this study for Tributary 1 and Lower Butano subwatersheds and data from the RWQCB for the other seven subwatersheds of lower PBW (RWQCB 2012). The gully data layer was overlain on geology, soils, slope, aspect, and vegetation for comparison. The aforementioned factors were first identified by Spreiter (1979) and Swanson (1989). Aspect and slope layers were made from the 2005 San Mateo County wide LiDAR dataset using ArcGIS.

FIELD VISIT TO TREATED GULLY SITES

Two gully treatment sites in Pescadero, CA were selected based on opportunities to observe the long-term (>10 years) performance of a variety of gully treatments, and discuss with the landowners and managers various considerations (e.g., effectiveness, costs) associated with the treatments. The sites were located in the in the Gazos Creek watershed immediately adjacent to the project area. Although in an adjacent watershed, the site characteristics (e.g., geology, slope, aspect, proximity to the ocean, vegetation, land uses, etc.) were highly comparable to gully-prone areas in the lower PBW.

RESULTS (UPDATED)

A map of gullies in the PBW shows extensive networks of gullies concentrated in portions of the lower PBW (Figure 6). In the two subwatersheds (Lower Butano and Tributary 1) that were the focus of this study, approximately 25% to 30% more gullies (by length) were identified than were included in the data layer provided by the RWQCB (2012). Most of the newly mapped gullies were relatively small features.

Figure 6. *Locations of gullies in the lower PBW. RWQCB Gullies layer (2012) includes gullies in all subwatersheds. Detailed mapping of gully networks conducted as part of this study (yellow lines) only for the Lower Butano and Tributary 1 subwatersheds is based on 2016 aerial photo data (see Methods).*

GULLY LOCATION AND SIZE

Gully lengths and densities of all subwatersheds in the PBW were calculated using the RWQCB 2012 gully data layer (Figure 6). Bradley Creek has the largest number of gullies while Tributary 1 and nearby Tributary 2 have the highest densities (linear foot per acre).

For Tributary 1 and Lower Butano subwatersheds, the focus of this study, gully location is presented in Figure 8 and Table 3 summarizes gully length and volume. Results of the analysis of gully sizes in these two subwatersheds are shown in Figure 9. Currently (2016), all mapped gullies, regardless of activity, range in width between approximately 5 feet to 60 feet with a median width of approximately 15 feet.

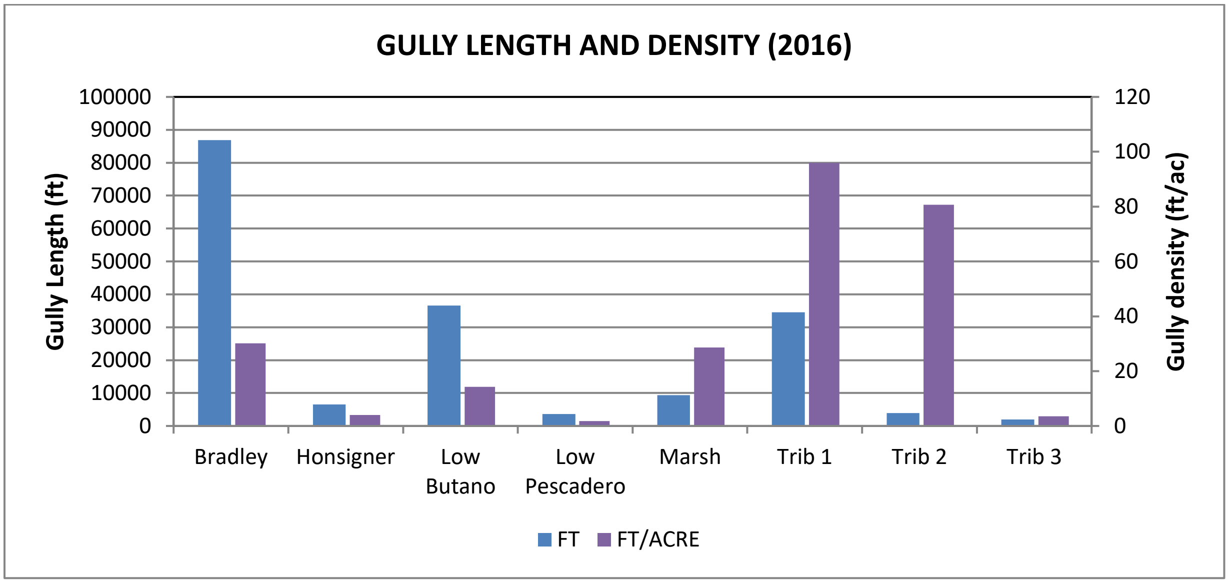


Figure 7. *Total linear feet (FT) and density, in linear feet per acre (FT/ACRE), of gullies in 2012 in each of the lower PBW subwatersheds: Bradley, Honsigner, Lower (Low) Butano, Lower (Low) Pescadero, and Tributaries (Trib) 1, 2 and 3. Note that gullies were not identified in Tributary 4.*

Table 3. *Break down of gully length and volume by landscape location within Tributary 1 and Lower Butano subwatersheds as measured from 2016 aerial photos.*

LOCATION	LOWER BUTANO					LOCATION	TRIBUTARY 1			
	LENGTH		VOLUME				LENGTH		VOLUME	
	(ft)	%	(cy)	%			(ft)	%	(cy)	%
Valley Bottom	9,228	25%	16,238	31%		**Valley Bottom**	10,084	29%	67,968	50%
Swale	14,133	39%	27,001	51%		**Swale**	10,797	31%	47,242	35%
Hillside	12,553	34%	8,062	15%		**Hillside**	10,916	32%	16,285	12%
Flute	675	2%	1,401	3%		**Flute**	2,738	8%	4,709	3%
TOTAL	**36,590**	**100%**	**52,702**	**100%**		**TOTAL**	**34,535**	**100%**	**136,205**	**100%**

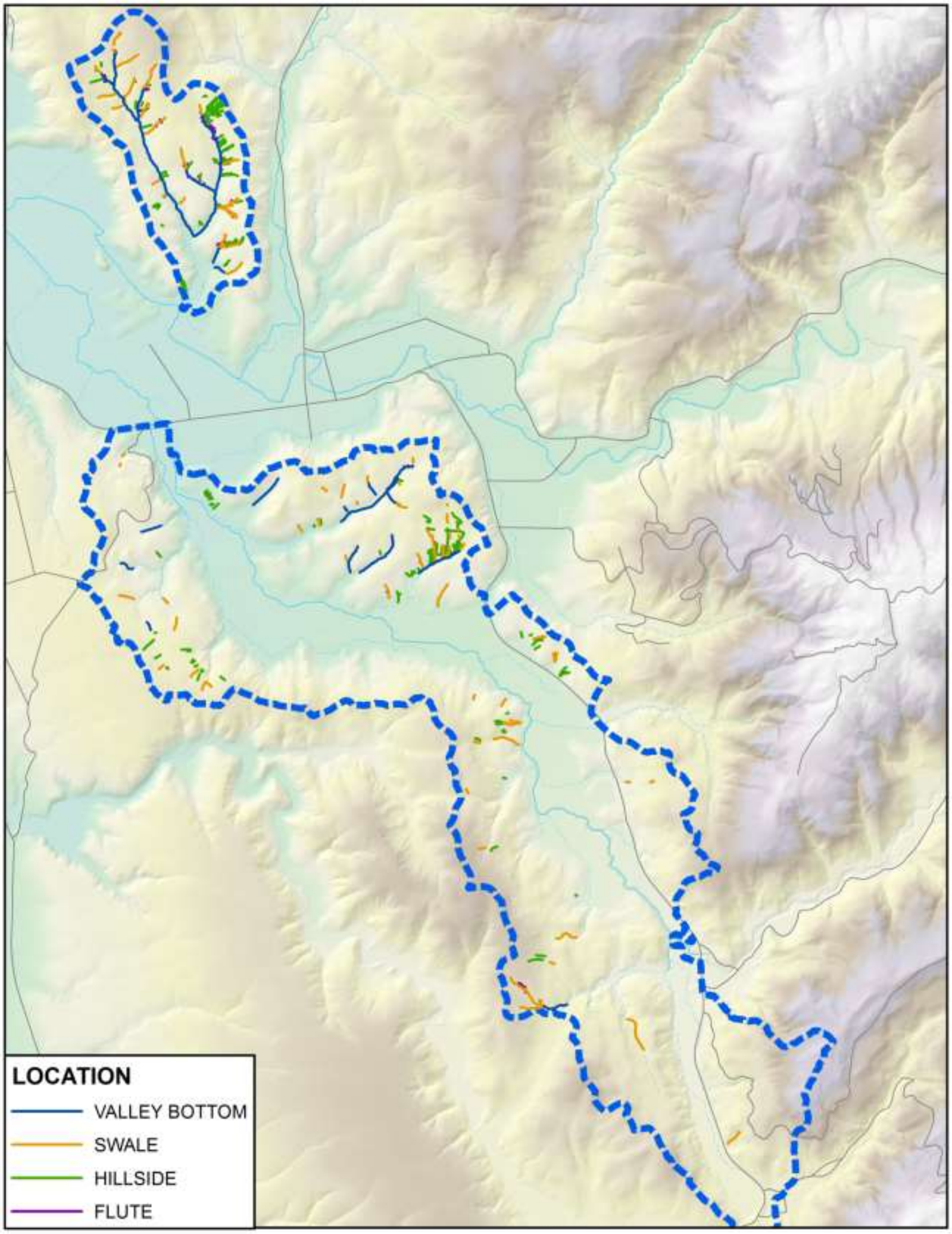


Figure 8. *Location of gullies (2016) on hillslopes based on criteria in Table 1.*

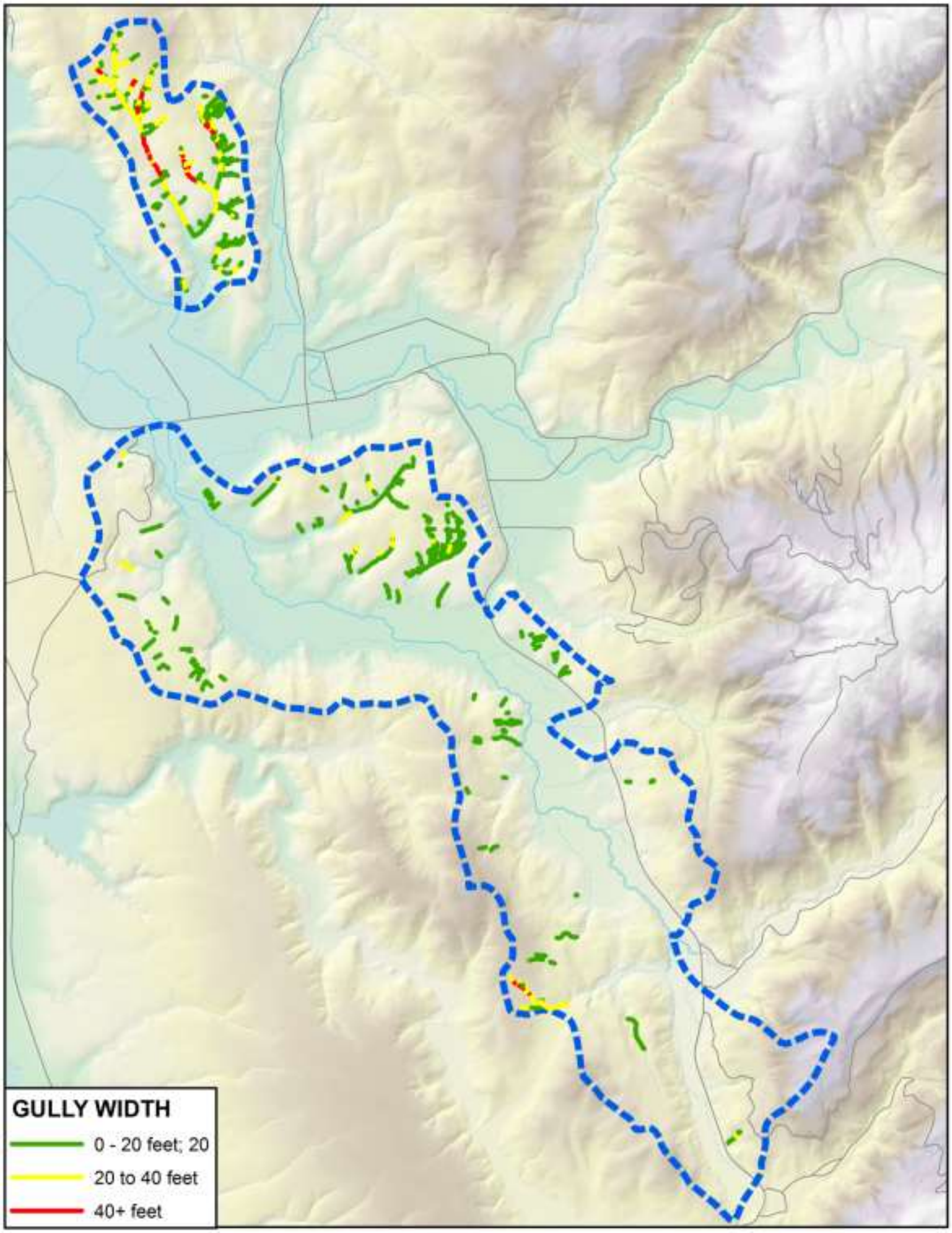


Figure 9. *Gully widths (2016) normalized by length for Tributary 1 and Lower Butano subwatersheds. Gully width is a proxy for gully size.*

GULLY EXPANSION (UPDATED)

Analysis of Lower Butano and Tributary 1 subwatersheds reveals that gully expansion (by length) peaked in 1982 (Figures 10 and 11). Note that gullies identified in the earliest analyzed photos of each subwatershed (1928 for Tributary 1, 1943 for Lower Butano) represent the starting levels of gullying for this study. The 2016-17 storms resulted in only nominal growth in gully expansion but also represent only two years between photos.

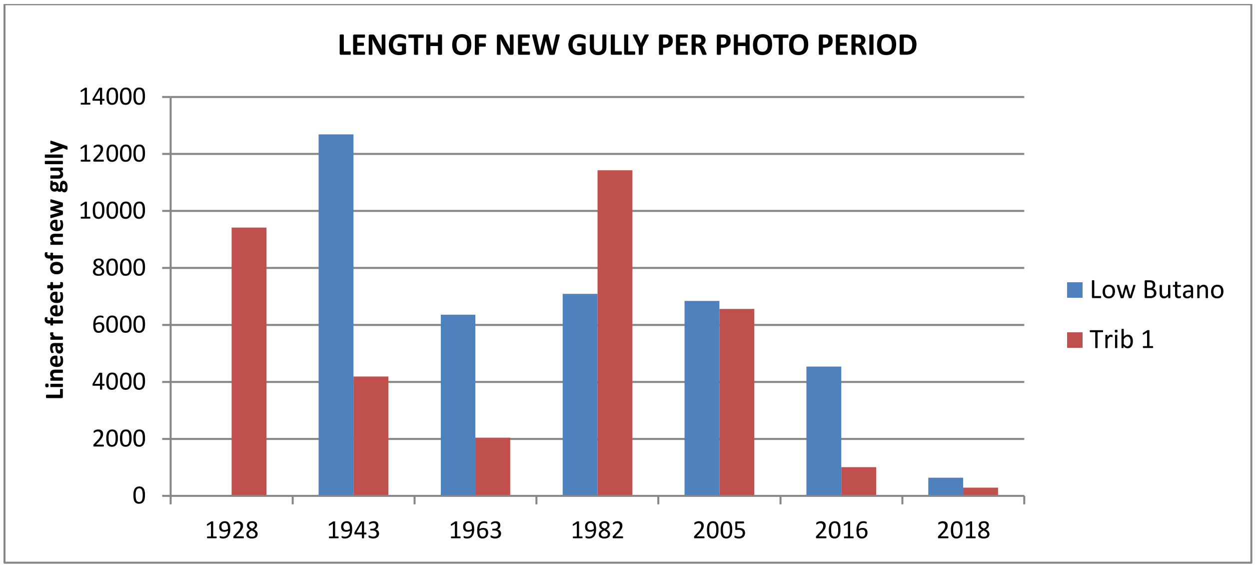


Figure 10. *Gully expansion measured as new linear feet gully observed in each aerial photo when compared with the previous photo year. Note that gullies from the 1928 photos were not mapped in the Lower Butano subwatershed.*

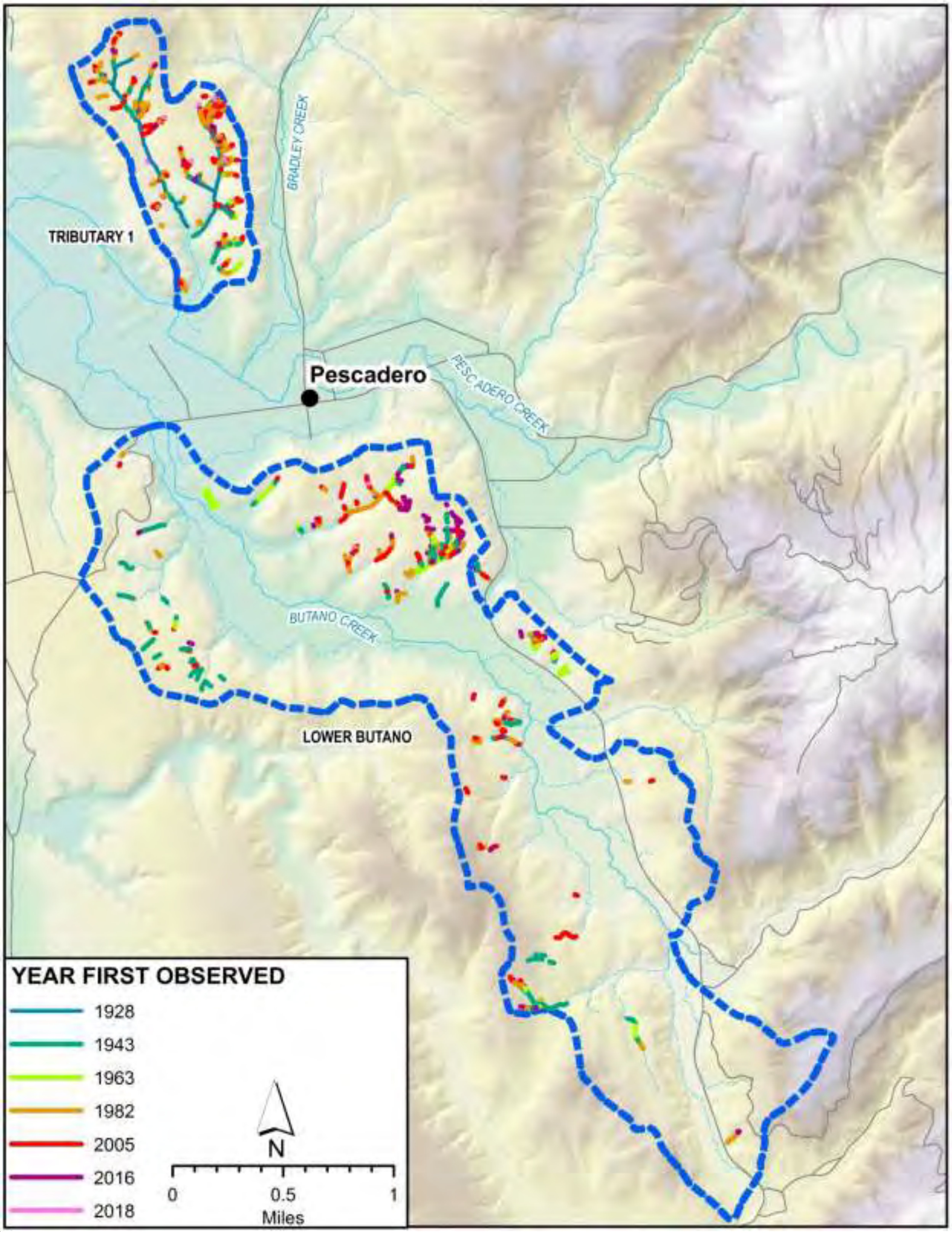


Figure 11. *Formation of new gully length by photo period. New gully formation peaked in 1982 and to a lesser extent in the 2005 photo periods. Note that 1943 is the first photo year mapped in this watershed.*

GULLY ACTIVITY OVER TIME (UPDATED)

Lengths of active gullies in both Lower Butano and Tributary 1 have decreased, with many of those segments becoming partially active (Figures 12, 13 and 14).

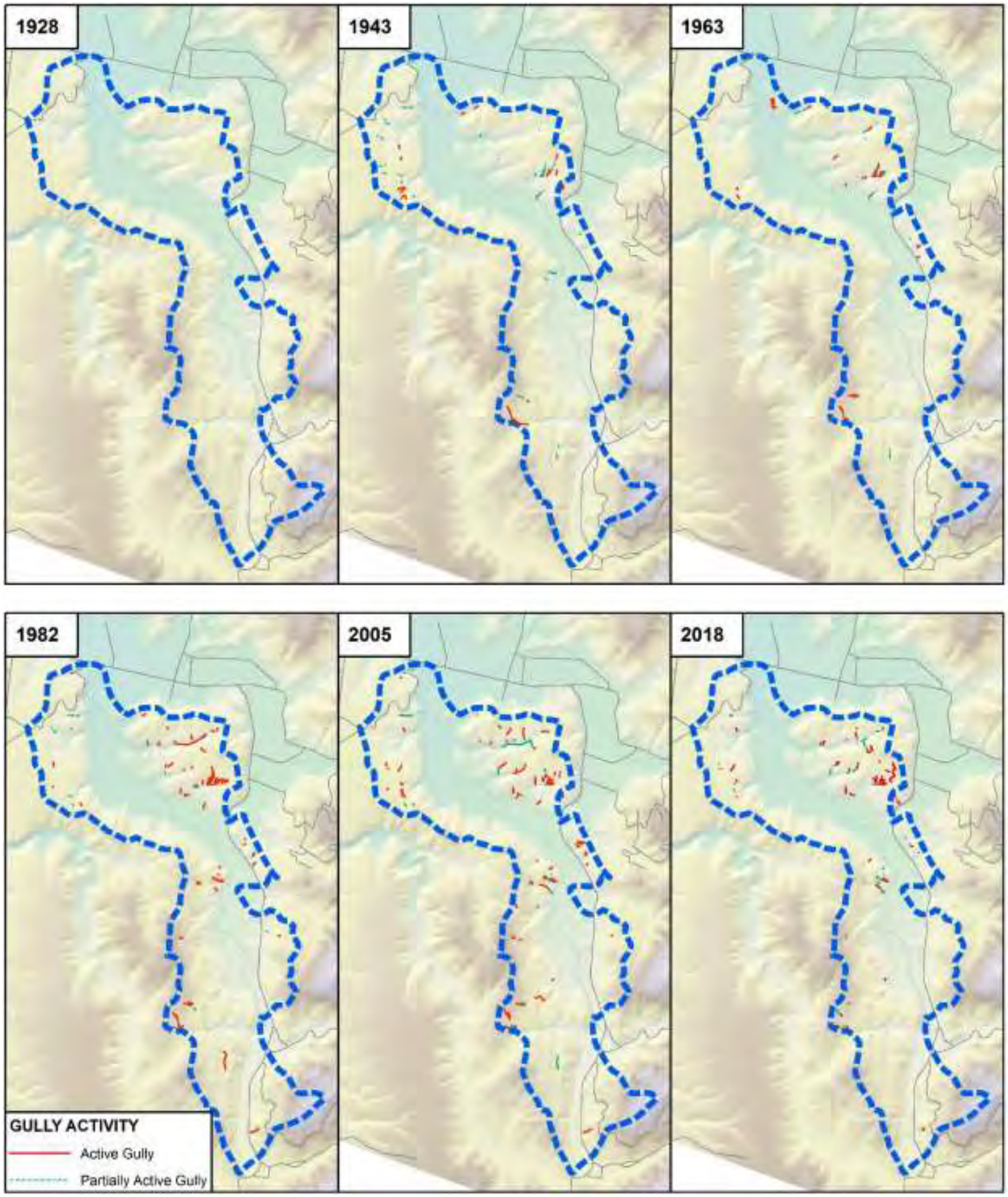


Figure 12. *Lower Butano subwatershed "active" (red) and "partially active" (turquoise) gullies over time. Since 1982, length of active gullies has decreased, with many of those segments becoming partially active.*

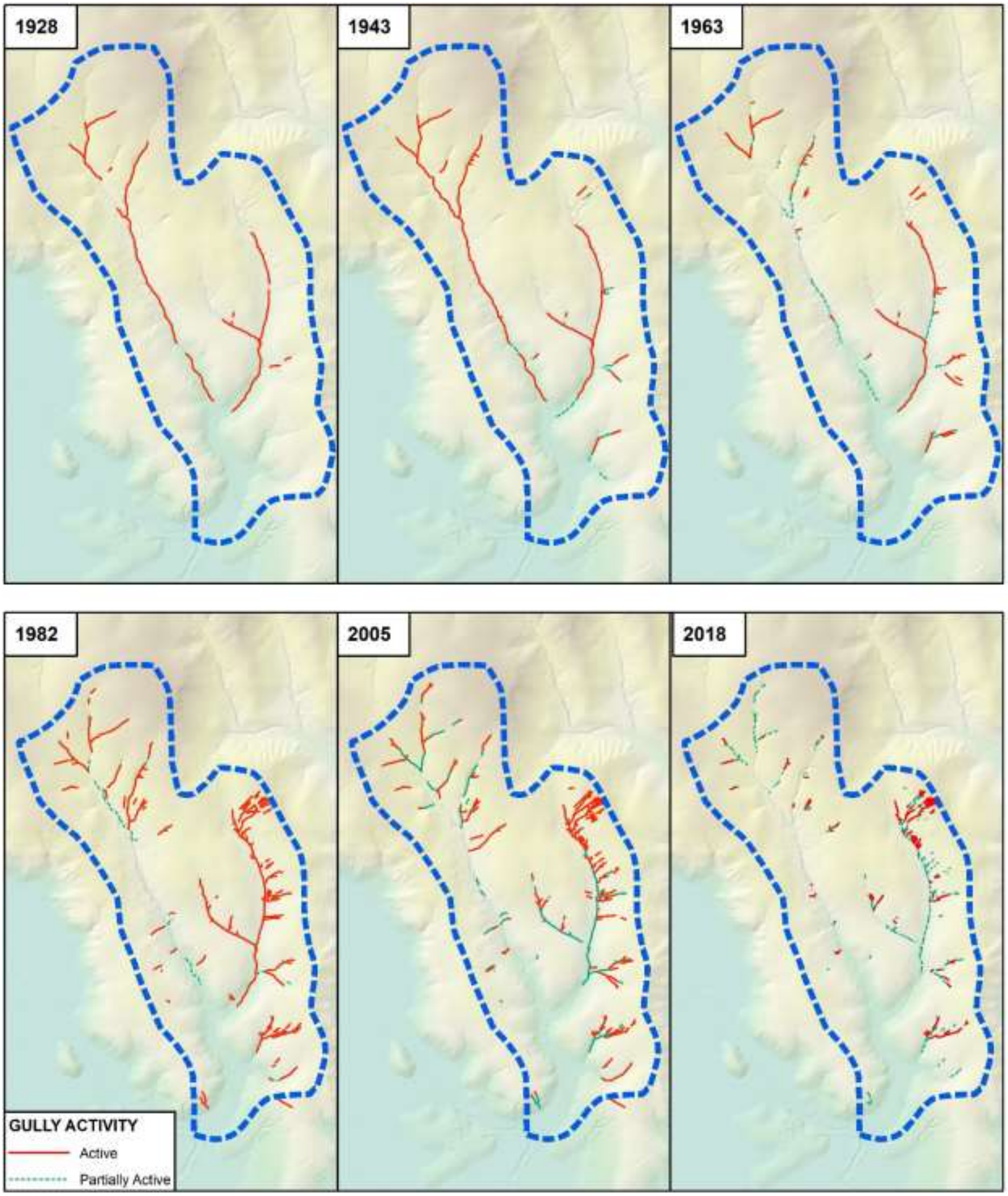


Figure 13. *Tributary 1 subwatershed "active" (red) and "partially active" (turquoise) gullies over time. Since 1982, length of active gullies has decreased, with many of those segments becoming partially active.*

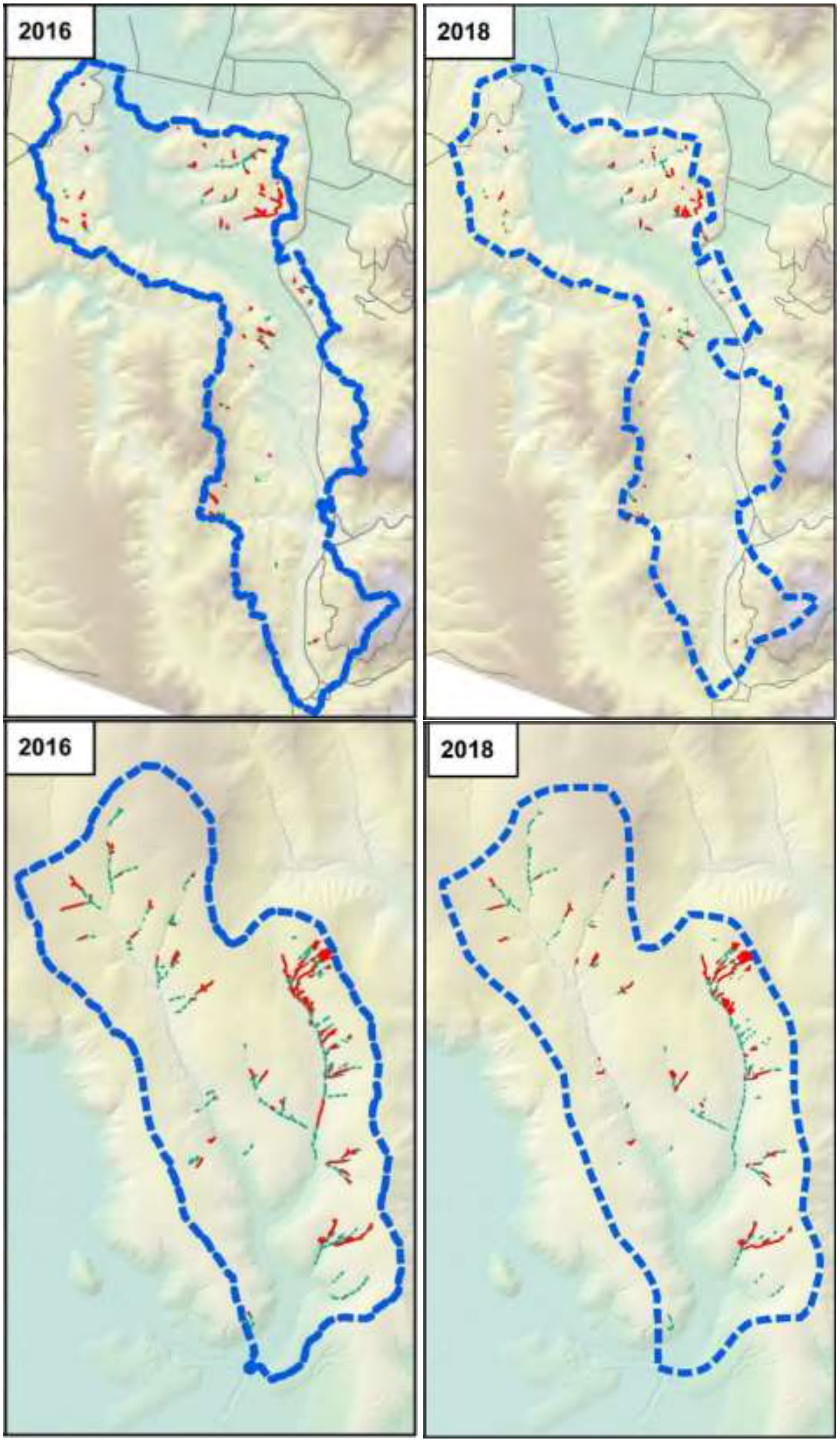
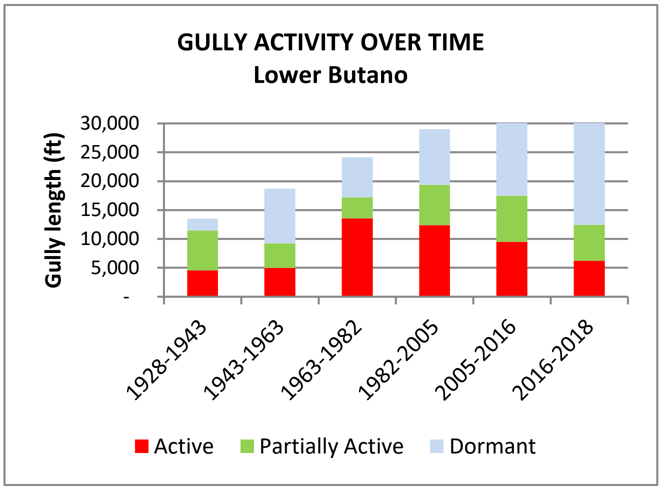


Figure 14. *Comparison of pre-2016-2017 winter (2016 photos) and post-2016-2017 winter (2018 photos) gully activity for Butano (top) and Tributary 1 (bottom) subwatersheds "active" (red) and "partially active" (turquoise) gullies.*



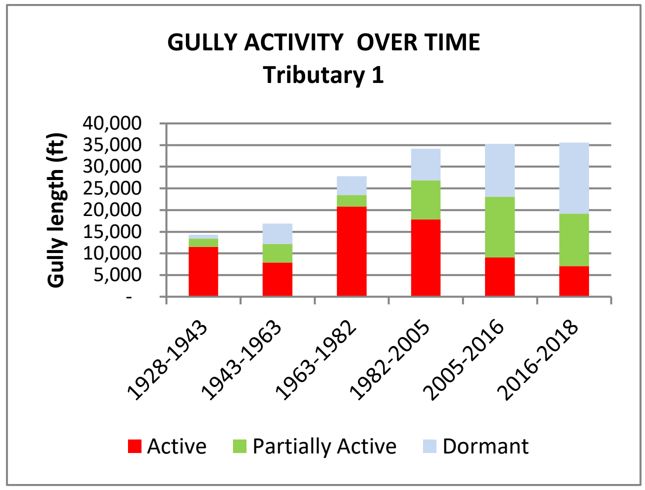


Figure 15. *Charts showing change in gully activity between photo years relative to total gully length. Total gully length peaked between the 1982-2005 photo years. After 2005, both total gully length and the proportion of gullies identified as "active" relative to "partially active" decrease. These results indicate that gullies are stabilizing.*

SEDIMENT PRODUCTION (UPDATED)

Gully sediment production volumes and rates in Lower Butano and Tributary 1 are summarized in Table 4 and Figure 15. Excluding the pre-1943 data, the highest erosion rates and sediment production volumes occurred in 1963-1982 time period with a significant reduction in the erosion rate occurring since then. Table 4 shows that 32% to 44% of total sediment volume produced from gullies in Lower Butano and Tributary 1 respectively, occurred prior to 1943. This is likely an overestimate because some of the gullies identified in the 1928 and 1943 aerial photos may have been preexisting incised streams (i.e. main stem of Tributary 1).

Table 4. *Total sediment production and rates for Lower Butano and Tributary 1 subwatersheds.*

TIME PERIOD	Years	Lower Butano		Tributary 1	
		Cy	*Cy/yr*	Cy	*Cy/yr*
Pre 1943	-	15,531	-	61,025	-
1943-1963	20	5,551	278	12,530	627
1963-1982	19	14,722	775	31,275	1,646
1982-2005	23	9,795	426	29,264	1,272
2005-2018	13	3,407	262	5,579	429
2016-2018	*2*	*38*	*19*	*1,555*	*777*

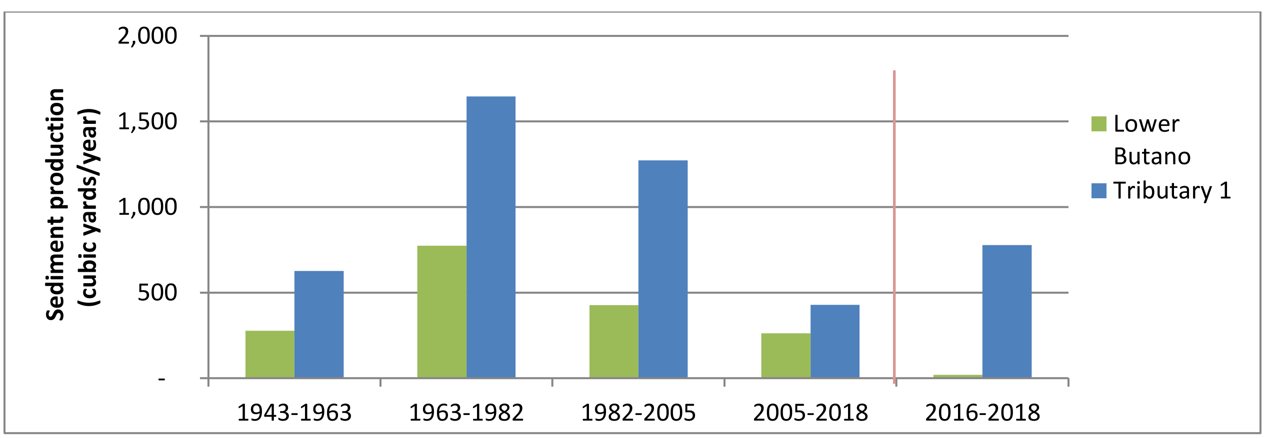


Figure 16. *Sediment production rates for Lower Butano and Tributary 1 subwatersheds.*

HYDROLOGIC CONNECTIVITY

Analyses of hydrologic connectivity (Figure 17) indicate that nearly all of the gullies in the Tributary 1 subwatershed are hydrologically connected to streams, whereas a majority of gullies in the Lower Butano subwatershed drain to a catch basin or pond or are otherwise disconnected from the mainstem of the creek.

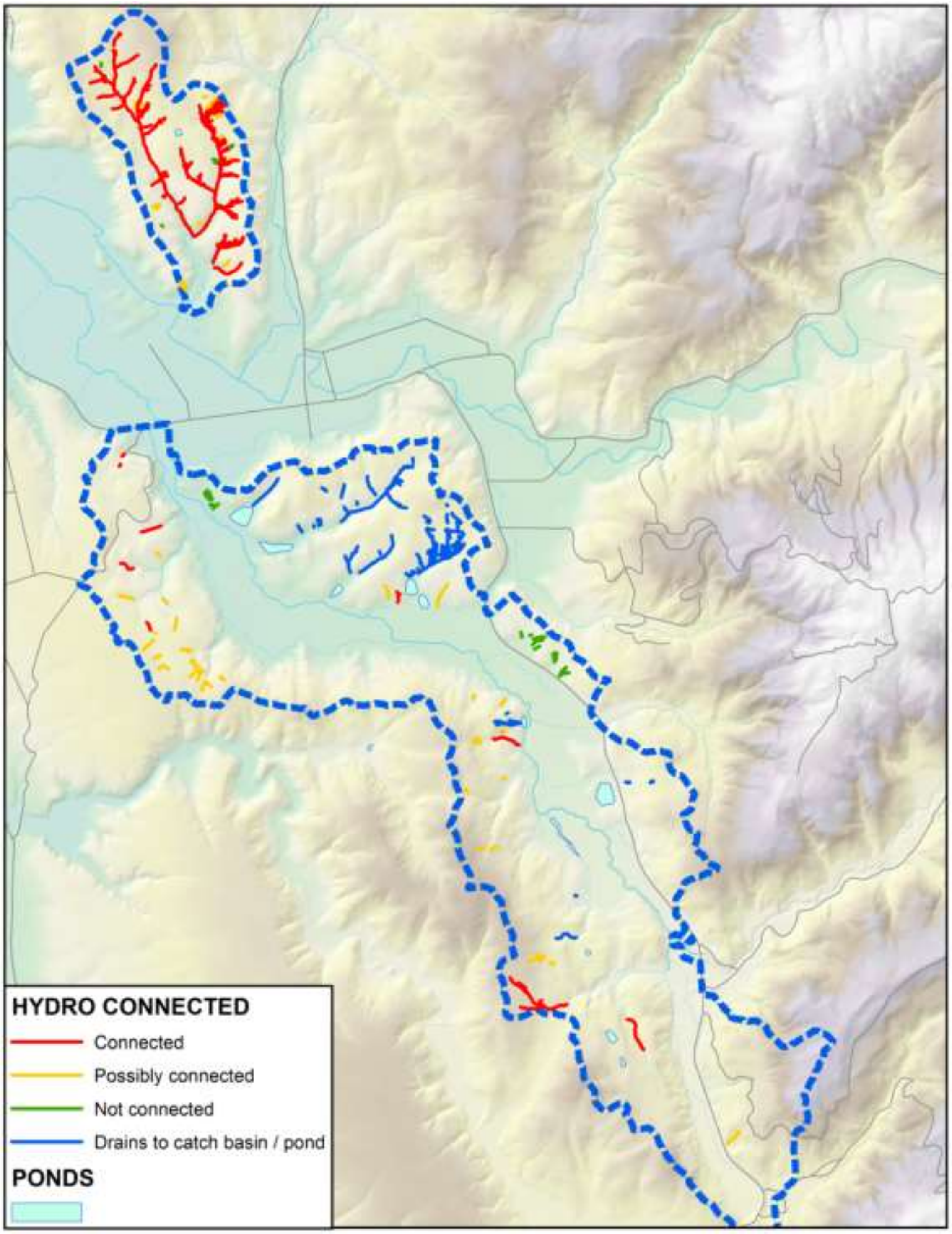


Figure 17. *Hydrologic connectivity of gullies in the Lower Butano and Tributary 1 subwatersheds.*

ROAD RELATED

A map of road related gullies is presented in Figure 18. In the Butano Creek watershed about 20% to 25% of all gullies appear to be road related. Nearly all of these features are located within Lower Butano Creek with very few in Tributary 1. The low incidence of road related gullies in Tributary 1 is likely due to the fact that there are very few roads in that watershed.

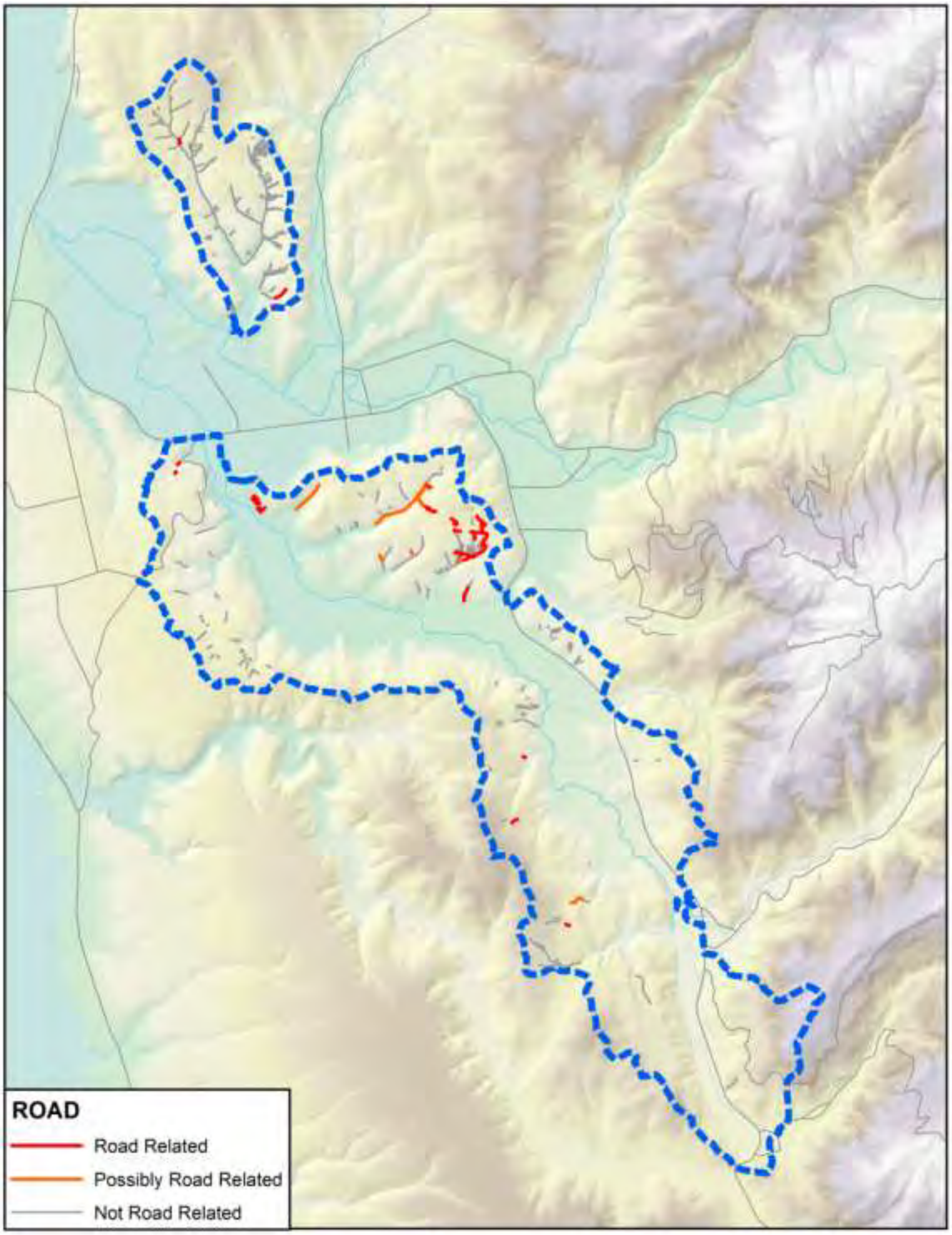


Figure 18. *Road-related gullies in the Lower Butano and Tributary 1 subwatersheds.*

GIS ANALYSIS OF GULLY-CONTROLLING FACTORS

Figures 19-23 show results of GIS analysis of gully-controlling factors identified in the literature.

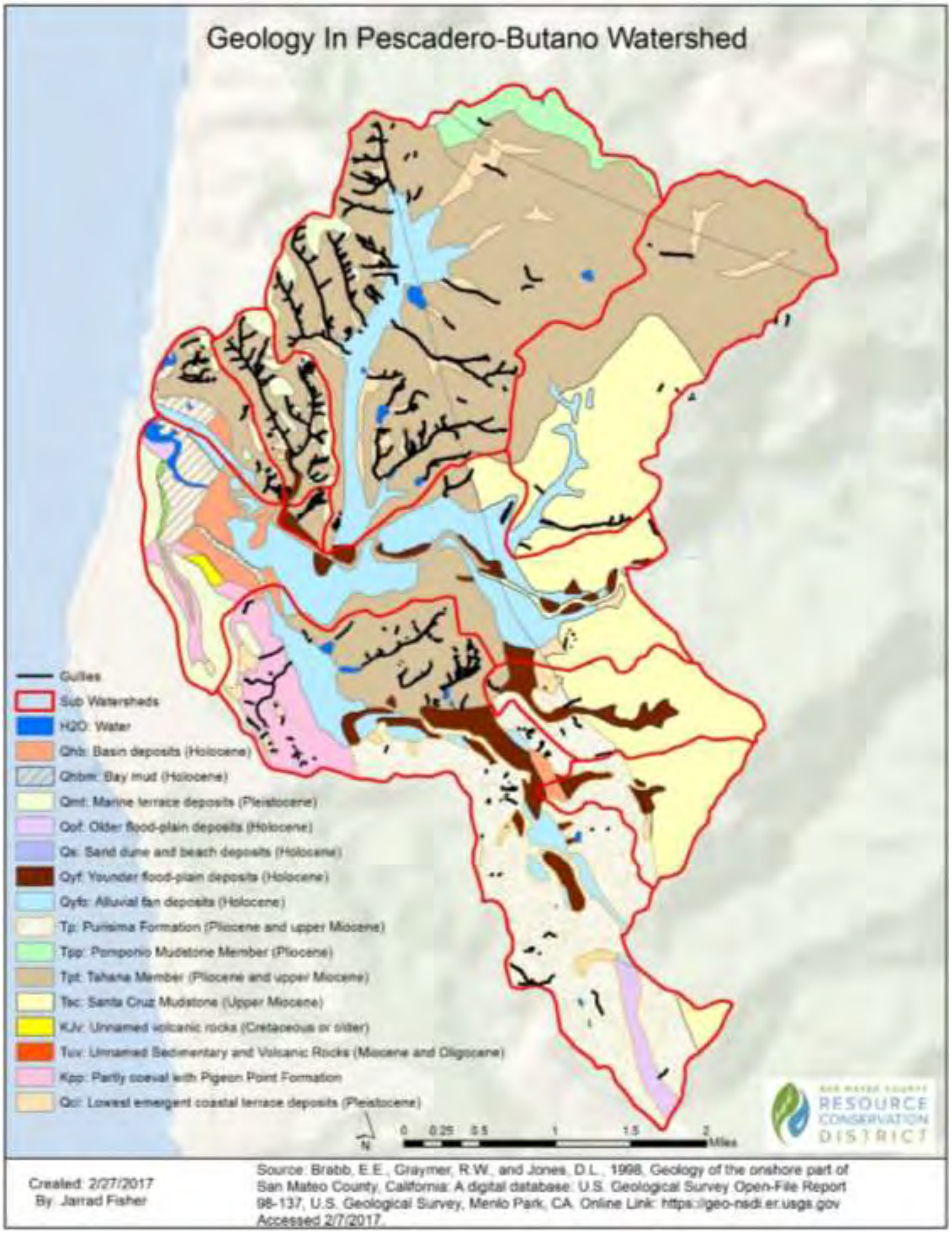


Figure 19. *Locations of gullies (RWQCB 2012) in the lower PBW relative to geologic unit. Gully networks are common over the Purisima Formation Tahana Member (Tpt). Shorter, less developed networks are present on the undifferentiated Purisima formation (Tp) and Pigeon Point Formation (Kpp). One notable large gully is seen in the Santa Cruz mudstone (Tsc). Gullying over the Tahana appears concentrated in the coastal portion of this formation within the study area, and decreases further inland.*

Figure 20. *Locations of gullies (RWQCB 2012) in the lower PBW with respect to soil type. Gullies in the northwest subwatersheds (i.e., Tributaries 1 and 2, and Bradley) are primarily found in the Tierra and Colma soil types. In the Lower Butano subwatershed, gullies occur on Tierra, Colma, Lobitos and Gazos soil types.*

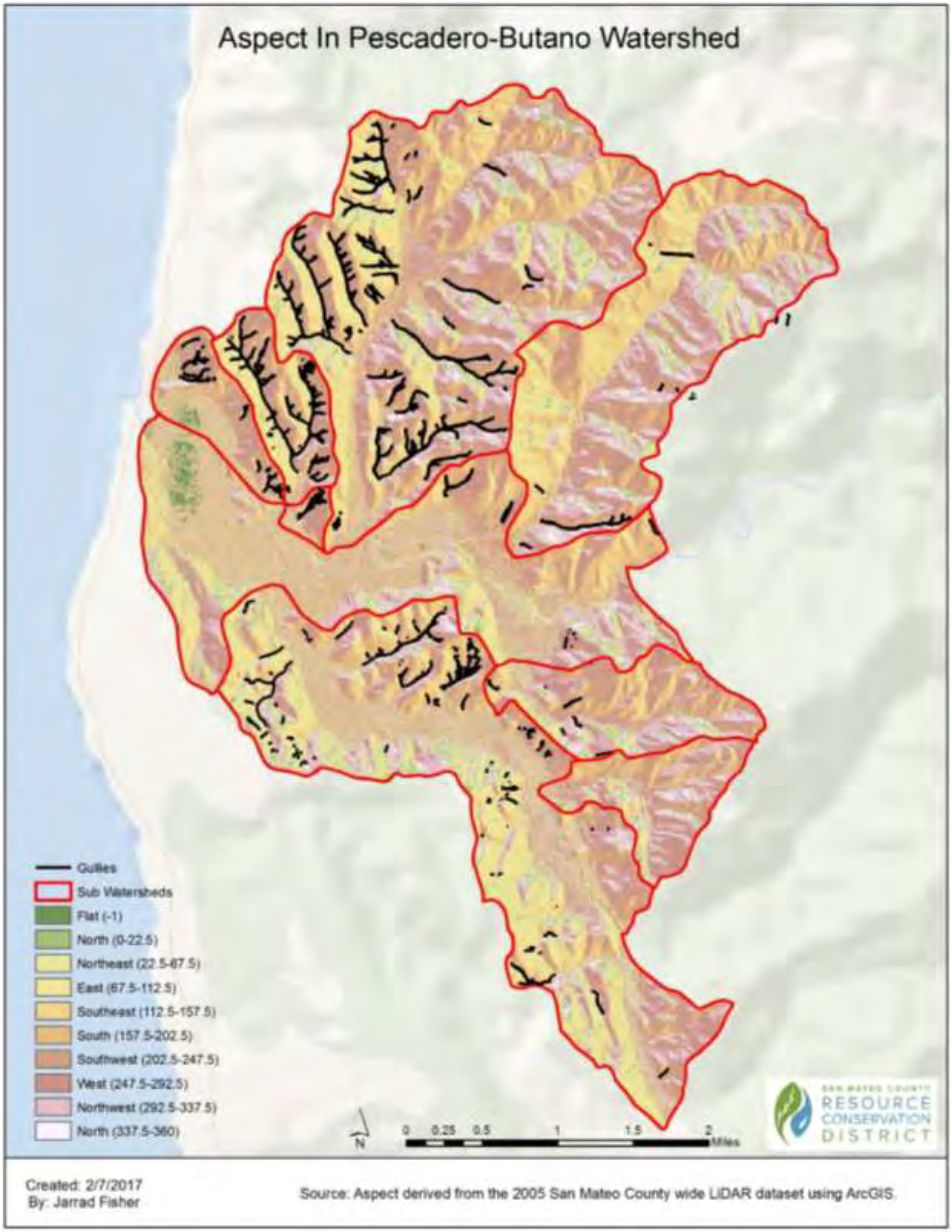


Figure 21. *Locations of gullies (RWQCB 2012) in the lower PBW with respect to topographic aspect. Gullying is predominant on southwest, south and west facing slopes. This is especially evident in the branches extending off of gully network mainstems.*

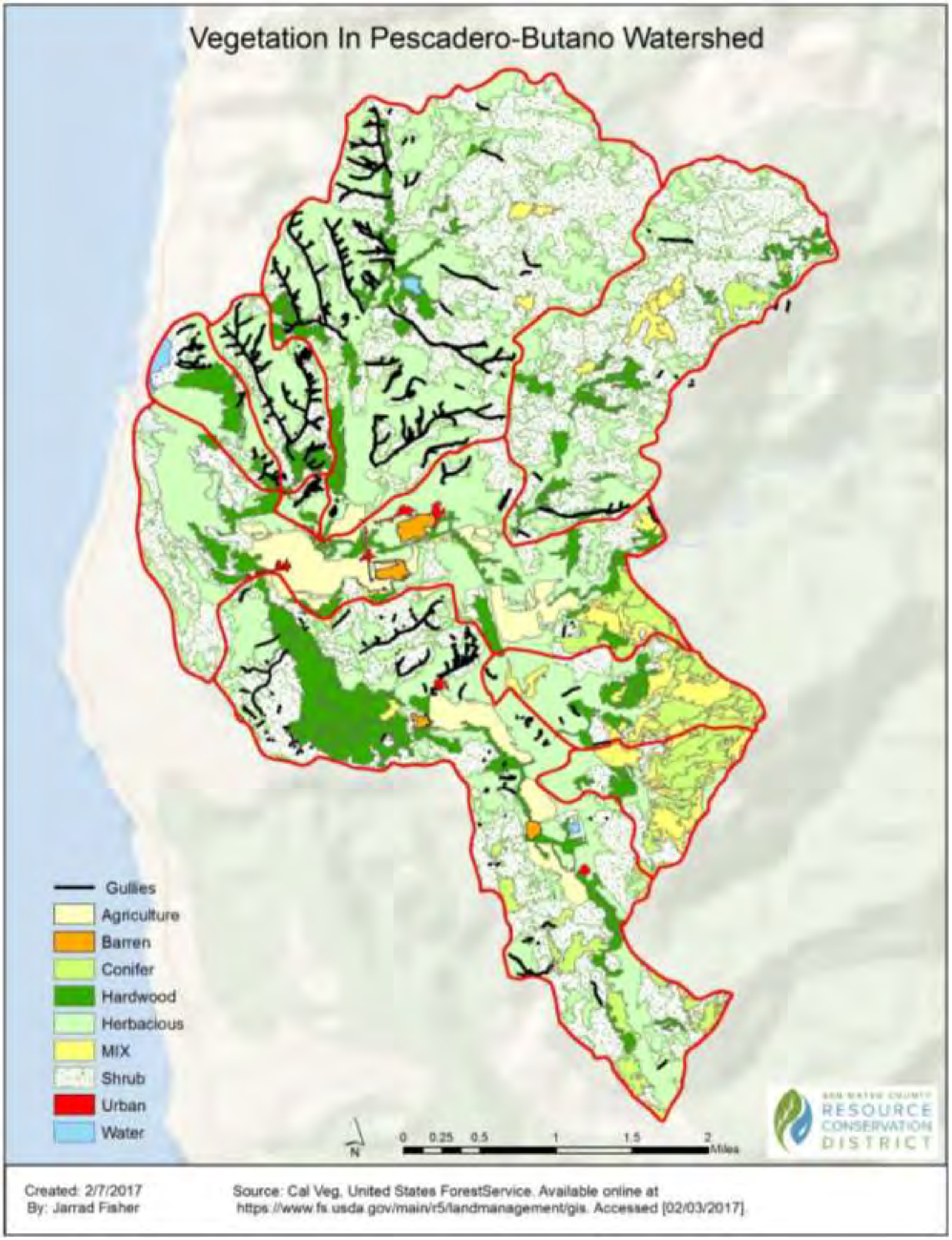


Figure 22. *Locations of gullies (RWQCB 2012) in the lower PBW with respect to vegetation type. Gullies are primarily present in areas characterized by herbaceous and shrub vegetation.*

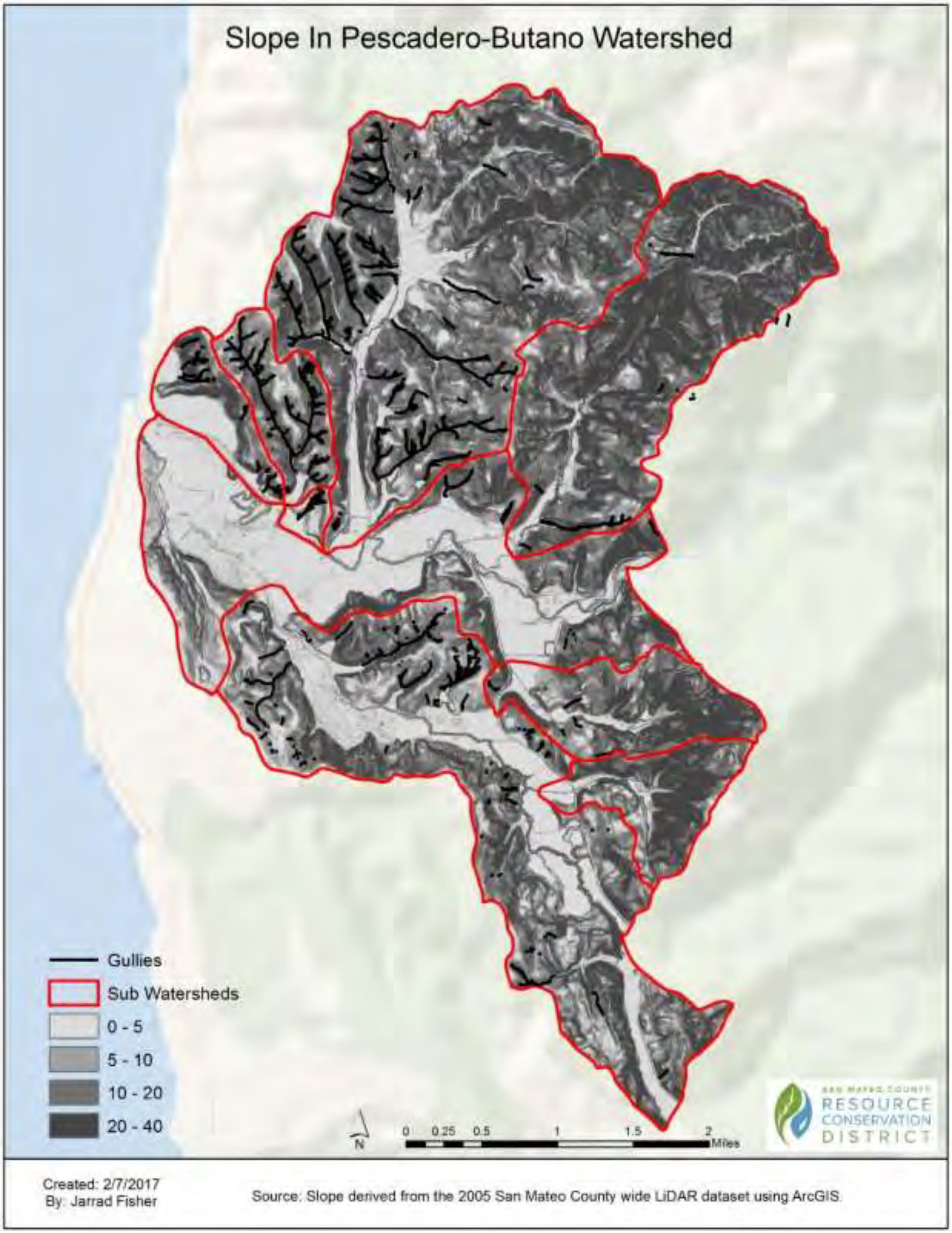


Figure 23. *Locations of gullies (RWQCB 2012) in the lower PBW with respect to degree slope do not show gullying preferentially coinciding with any specific hillslope ranges.*

FIELD OBSERVATIONS OF GULLY CONTROL SITES

March 9, 2017 site visits to two gully treatment sites in the Gazos Creek watershed in Pescadero, CA occurred at the end of a heavy precipitation winter (2016-2017). The two sites were on opposite hillslopes, one southwest-facing and the other northeast-facing, but were otherwise very similar in terms of relevant conditions. Both were approximately two miles from the ocean and underlain by Purisima formation, and had similar slopes with grasses, shrub (coyote brush) and some conifer vegetation.

At the southwest-facing site, multiple small gullies and one larger (approximately 200 feet long, 20 feet wide) gully had been treated in 2006 with low-cost and low-impact bioengineering techniques: willow stakes plantings and erosion control wattles. No post-installation maintenance (e.g., watering or replanting) was done. The treated gullies had largely revegetated, though most of the willow plantings had not survived and expansion by headcutting was occurring. For the individual gullies, these treatments appeared to have provided a marginal benefit for preventing gully expansion and sediment discharge.

At the northeast-facing site large, active gullies (1-6 feet wide) were treated in 2001 and 2002 with a mix of hardscaping (e.g., check dams, subdrain network, culvert bypass) and bioengineering (e.g., willow stakes) measures. Incipient gullies were treated with erosion control measures (e.g., wattles) and planted with conifer (pine) seedlings. No post-installation maintenance was done, but controlled cattle grazing was implemented at the site in 2010. Very little expansion of existing gullies was observed, and no new ones had formed on this hillslope. The only issues observed were a sidewall cut caused by a leak in the bypass culvert, and possibly some undercutting of one of the check dams.

DISCUSSION (UPDATED)

GULLY INVENTORY AND CHARACTERIZATION (UPDATED)

Extensive networks of gullies are concentrated in portions of the lower PBW (Figure 6), with the majority found in Bradley Creek, and the highest densities within Tributary 1 and nearby Tributary 2. The characterization of gullies in Lower Butano and Tributary 1 subwatersheds reveals that approximately 60% of these gullies by length and more than 80% by volume occurred within valley bottoms of the larger drainages or in topographic swales. This result is not surprising since these are areas where surface and groundwater tend to concentrate and where colluvial sediments tend to deposit.

In Lower Butano and Tributary 1 subwatersheds, gully expansion, activity and sediment production appear to have peaked between 1982 and 2005. The relatively high incidence of new gully segments and active gullying in 1982 could be due to the El Niño storms of 1982 (which occurred shortly before the photos were taken). Furthermore, the somewhat high incidence of new gully segments and the peak in total gully activity in 2005 could reflect residual effects of these 1982 storms, as well as (weaker) El Niño storm seasons in 1997 and 2005.

Prior to this update (i.e. without the 2018 imagery) this study concluded that active gullying in these two subwatersheds had decreased by 15-20% since 2005. Comparatively few new gullies segments were observed in 2016, with the majority of new gully length resulting from headwall expansion of existing gullies or fluting which is the production of vertically-elongated grooves in the gully sidewalls caused by running water. While some gullies were active in 2016, many of the gully segments found to be active in 1982 were classified in 2016 as partially active (i.e., showing no signs of widening or changes in morphology). Sediment production had thus also dropped over time. These decreases in gully activity were attributed to two factors. First, many of the gullies may have reached their peak size and are beginning to stabilize, and comparatively, these partially active gullies are not large sources of sediment. Secondly, it was noted that the relatively low storm activity between 2012 and 2016 may have allowed for this gully stabilization to progress, and that an uptick in storm activity could have an impact on this process and reactivate stabilized gullies. The 2016-2017 winter

included bigger precipitation events (compared with the previous years) and to understand the impacts on gully stabilization, this update evaluated the 2018 imagery. The updated analysis showed minor changes in gully activity both subwatersheds resulting from the 2016-2017 storms but impacts on sediment production (cubic yards per year) appeared mixed; between 2016 and 2018, sediment production in Lower Butano and Tributary 1 significantly decreased and increased, respectively (Table 4). These results –particularly the sediment production rates – should be cautiously interpreted for several reasons. First, the resolution of the imagery is such that measurement of changes in gully size < 5 feet is difficult and, as a result, small changes in gully size between the 2016 and 2018 imagery may not have been accurately captured. Also, based on anecdotal evidence from field observations during the 2016-2017 winter renewed erosion occurred in some existing gullies but without significant measurable changes in width or length. This erosion would have been missed in the analysis of the 2018 imagery. Second, the time frame over which the latest measurements were made was short (2 years) and included the effects of a large storm. As such, the reported sediment production rates between **2016 and 2018 probably do not reflect long term averages. Despite the limitations of the updated analysis, it supports a few general findings. Minimal reactivation of dormant gullies resulted from the 2016-2017 winter storms and, overall, gully activity declined, with existing active gullies continuing to stabilize (Figure 14).**

Nearly all of the gullies in the Tributary 1 subwatershed are hydrologically connected to streams, whereas a majority of gullies in the Lower Butano subwatershed drain to a catch basin or pond, or are otherwise disconnected from the mainstem of the creek. This has implications for prioritizing gullies for treatment based on potential future sediment delivery to local creeks and the marsh. (Figure 17)

Overall, the study showed that gullies that are “active” (i.e. unvegetated) are more likely to be expanding because they have exposed gully sidewalls that are potentially subject to erosion. However, it is important to note that the designation of active is not necessarily indicative of high sediment production. Many gullies classified as active did not exhibit significant change in their width or morphology with time suggesting that they may not be producing much sediment, particularly in comparison to previous years. Hence direct measurements of sediment production are important.

Gully width appears to have a stronger correlation to sediment production compared to gully length. In the Lower Butano and Tributary 1 subwatersheds, 50% of the gullies by length have widths less than or equal to 15 feet, and these gullies account for a comparatively small portion (8%) of the total sediment derived from gully erosion. Gullies with widths greater than 40 feet account for 9% of all gullies by length but appear to have generated nearly 45% of all sediment. Historically, wider gullies, which are comparatively few (by length), may have been responsible for a large portion of sediment production.

GULLY-CONTROLLING FACTORS

GIS analysis indicates that the combination of geology, aspect, and proximity to the ocean (of less than 3 miles) may be especially important attributes in understanding modern day gully distribution as mapped by this study and the RWQCB. Areas underlain by the Purisima Formation Tahana member, that face south or southwest, and are close to the ocean are more gullied. Although these factors are coincident with the locations of gullies and may indicate a greater susceptibility of the landscape to gullying (suggesting the strong influence of dispersive clays when exposed to higher Na^+ concentrations from salt spray closer to the ocean), they may not be the main causes of gullying.

Anthropogenic factors also affect gullying in the PWB watershed. This study indicated that in the Lower Butano subwatershed where roads are prevalent, 20-25% of the gullies appear to be road related. Data layers were unavailable to map historic land uses with gullying, but analysis by the San Francisco Regional Water Quality Control Board of land use trends in the PBW over the past 200 years, showed a strong connection between erosion (including gullying) and clearing of the land and transition to agricultural uses.

Gullying appears to be more predominant in herbaceous (grasses) and shrub vegetation, however due to the dominance of these vegetation types over the entire study area, it cannot be concluded that these vegetation types are controlling factors for gully formation. Further analysis of current vegetation cover and newly active (as of 2016) gully segments could indicate if vegetation cover is a useful factor in determining where future gullying is likely to occur.

Slope may also have controlling effect on gullying in this watershed, but this could not be clearly discerned because the presence of gullies themselves affects the slope in the mapping analysis. Site specific field analysis of gullies may be necessary to understand potential controlling effects of slope on gully formation.

TREATMENT OBSERVATIONS

Overall, observations from the field visit to gully treatment sites in the adjacent Gazos Creek watershed suggest that although treatments can be effective at reducing and slowing gully erosion, they cannot fully stop these processes in gully-prone areas. Significantly better outcomes were observed at the site where measures combined treatment of existing gullies and causative drainage issues. Conservation grazing may have also benefitted gully control this site by providing site-wide improvements to soil water holding capacity and vegetative cover. Admittedly, this site was potentially less prone to gullying because of its northeast aspect, but the overall, site-wide resilience to the heavy precipitation of 2016-2017 winter was notable. The opposite, southwest-facing hillslope – treated only with revegetation measures – was not nearly as resilient to gully erosion, yet construction of a comprehensive engineered solution for drainage would have dramatically affected site conditions (e.g., topography and habitats). This illustrates the significant trade-offs and site-specific constraints that must be considered in developing and implementing holistic solutions to gully erosion. Outcomes at both sites might have benefited from post-installation maintenance of treatments.

PRIORITIZATION FOR TREATMENT

This study shows that in the lower PBW site and gully characteristics need to be considered together in prioritizing where and how to focus treatment and containment efforts in order to reduce sediment delivery to the creeks and marsh. For existing gullies, hydrological connectivity, gully activity (i.e. active, partially active, or dormant), and sediment production potential are important characteristics. Overall, a proportionally high contribution of sediment comes from active (i.e., unvegetated), wider (i.e., bigger) that are hydrologically connect to the creeks. Effective treatment of the hydrologically connected, active, and wide gullies will achieve the greatest reductions in sediment delivery to creeks. Locations of these gullies in the Tributary 1 and Lower Butano subwatersheds are shown in Figure 24.

It is important to recognize that measures necessary to control large gullies can be very costly (e.g., treatment, design, and permitting of the large gully shown in Figure 2 cost almost a half million dollars), and have environmental impacts due to construction on gully-prone sites. In light of these challenges, areas prone to gullying (i.e. underlain by the Purisima Tahana Formation geology, with a south/west aspect and in close proximity to the ocean) should be monitored closely for signs of gully erosion. Initiating gullies should be treated as soon as possible to prevent them from becoming large gullies. Meanwhile, efforts to treat the causes of gullying (e.g. building soil health, properly designing and maintaining rural roads) across a broader geography that extends beyond existing gullied areas, should be prioritized to build landscape resilience to gully erosion.

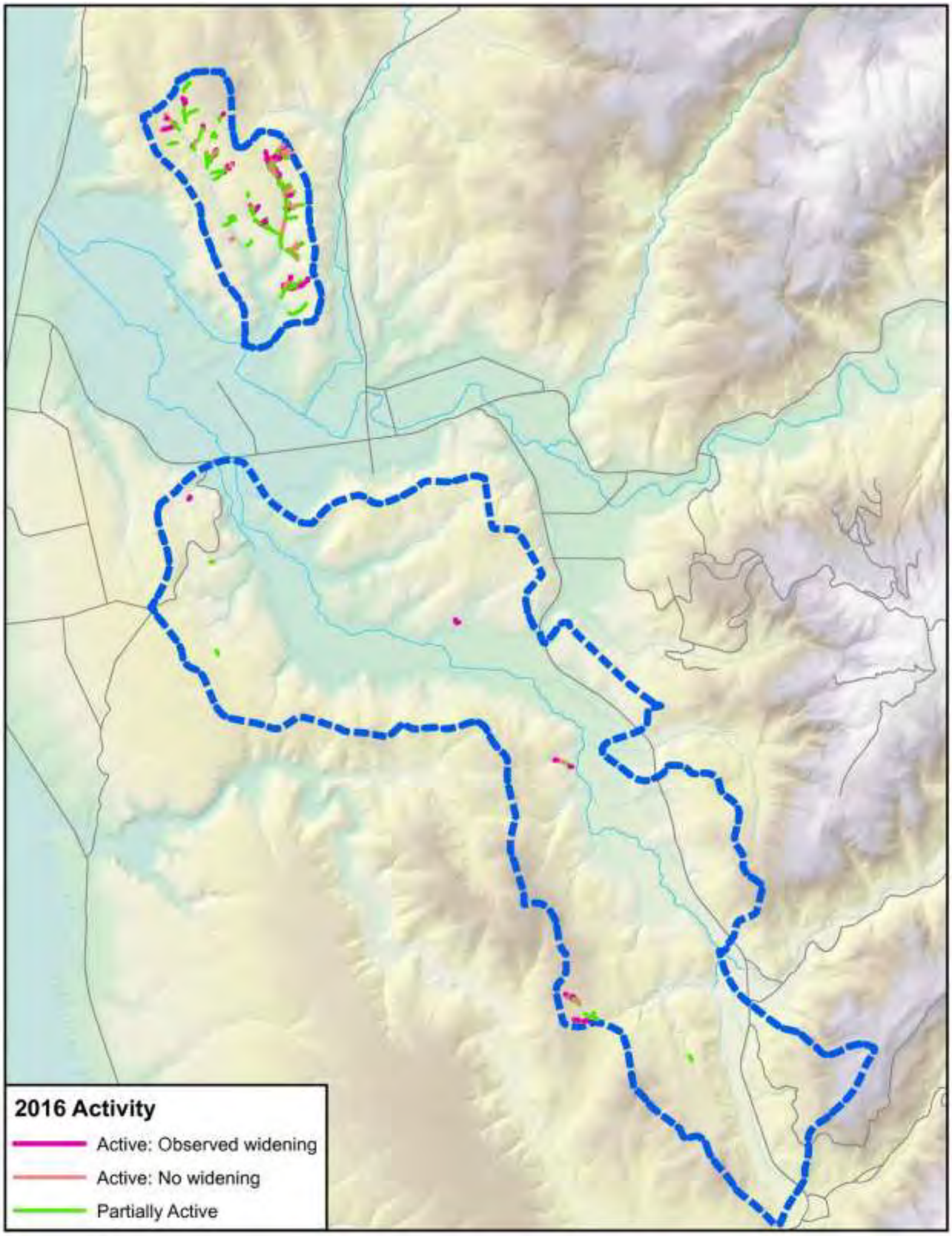


Figure 24. *Gullies with the highest potential for sediment production in the Lower Butano and Tributary 1 subwatersheds. Gullies shown are those that 1) show some activity, 2) are hydrologically connected and 3) wider than 15 feet.*

CONCLUSIONS (UPDATED) AND RECOMMENDATIONS

This evaluation of gullies suggests that areas in the lower PBW that are likely to develop gully erosion due to site characteristics and/or past land uses already experience gullying, and that many of the gullies in these areas may have reached their peak size and are beginning to stabilize.

The heavy precipitation winter of 2016-2017 could not be captured in the original study, but observations had suggested that active gullying increased, in both expansion of existing gullies and formation of new ones in areas where gullying has occurred in the past. Given the episodic nature of gully erosion and these observations, the study was updated with analysis of post-2016-2017 winter imagery to understand if relatively low storm activity leading up to the original study allowed for the gully stabilization to progress, and if an uptick in storm activity could reactivate stabilized gullies or create new ones. Recognizing the limitations of the updated analysis, the overall conclusion is that the trend towards gully stabilization continued despite the heavy precipitation of the 2016-2017 winter. The impacts of a much larger storm season (e.g., El Nino driven) on gully reactivation and stabilization remain to be seen.

Specific decisions about whether to address any particular gully will involve further assessment, including site visits and evaluation of the full project to understand potential effectiveness and impacts of treatments as well as costs for implementation and ongoing maintenance. Where possible, treating, or containing sediment delivery from the active, large gullies that are hydrologically connected will achieve important reductions in sediment delivery to creeks in the lower PBW.

However, the significant challenges of treating these large gullies point to the need for additional, preventative measures to effectively address gully erosion in the lower PBW. Sites with current and past gully activity, and/or with highly susceptible to gully expansion (i.e., with the Purisima Formation Tahana geology, located close of ocean, and with a south/west aspect) should be closely monitored. Treatment of small, initiating gullies on these sites should be prioritized to stop these from developing into large gullies.

A key recommendation is addressing the sources of gully formation: concentrated surface and subsurface water flows. As such, fixing stormwater and road drainage issues should be prioritized throughout the watershed, and practices that improve soil stability, water holding capacity, and vegetation cover should be broadly implemented.

The following section is a review of these prevention practices and treatment and sediment containment practices that can be applied to solutions for gully erosion in the lower PBW.

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PART II: Gully Erosion Control Practices and Treatments

OVERVIEW

Addressing gullies and their negative effects requires action to prevent future gullies (i.e., addressing the source of the problem) as well as addressing existing gullies (i.e., dealing with the symptoms). A comprehensive plan of action includes the following elements to be implemented individually or in combination, as appropriate:

- **Gully Prevention:** Prevent new gullies from forming
- **Gully Treatment:** Stabilize existing gullies to minimize the amount of expansion and new sediment production
- **Sediment Containment:** Retain eroded sediment onsite to prevent delivery to a watercourse

The Natural Resource Conservation Service (NRCS) recommends certain Conservation Practice Standards[3] for various land uses to address soil erosion that contributes to gullying. Recommended practices for range, pasture, crop and forest lands to address soil erosion[4] are listed in Appendix A. The following sections identify where these practices could be applicable to gully prevention, treatment and/or sediment containment.

GULLY PREVENTION

It is far better to prevent gullies from occurring than to attempt to control them once the erosion has started. Gullies can be very costly to fix, repairs can result in unanticipated environmental impacts especially in areas with protected plant and animal species, and the success of such repairs are by no means certain. On the other hand, conservation practices that are implemented before gullies become established can significantly reduce the potential for gully formation and growth. Conservation practices that build soil health and improve vegetation cover enhance soil stability and water holding capacity, which in turn increase the ability of the landscape to withstand the effects of heavy precipitation, thereby reducing the potential for erosion.

Gully prevention includes the following elements:

- Monitoring and Rapid Response
- Improving Soil Health and Vegetative Cover
- Improving Site Drainage

MONITORING AND RAPID RESPONSE

Lands that are susceptible to gullying should be monitored regularly to detect early stages of gully formation because it is much easier and cheaper to treat a small gully than a large/deep gully that is well established. Therefore, initiating or small gullies, as well as acute causes of gullying (e.g., improper drainage) should be treated promptly, especially on lands known to be susceptible to gully erosion.

IMPROVING SOIL HEALTH AND VEGETATION COVER

Improving soil health and associated vegetative cover is the most cost effective way to control erosion and prevent gullying. These practices are implemented to increase soil water holding capacity and stability, primarily

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[3] These recommendations are based on the NRCS' Conservation Practice Physical Effects (CPPE) matrix which summarizes the relative effectiveness of conservation practices in solving natural resource problems. The CPPE is currently used by all states in the EQIP ranking tool and should be used as a first level diagnostic when considering environmental effects.

[4] Soil erosion definitions (NRCS): Sheet, rill, & wind erosion: detachment and transportation of soil particles caused by rainfall runoff/splash, irrigation runoff or wind that degrades soil quality. Concentrated flow erosion: untreated classic gullies that may enlarge progressively by head cutting and/or lateral widening; and ephemeral gullies which occur in the same flow area and are obscured by tillage. This includes concentrated flow erosion caused by runoff from rainfall, snowmelt or irrigation water.

by maintain a deep rooting and stable vegetative cover. Developing and maintained a deeper rooting, perennial native vegetation cover can provide significant root reinforcement as well as prevent or disperse concentrated water flows which can lead to gully formation.

A wide variety of NRCS Conservation Practices that enhance soil health and vegetation cover can be implemented to address hillslope erosion (sheet and rill erosion) and gullying associated with range, pasture and forest land uses. These practices are summarized below. A more comprehensive list of practices that can apply to these land uses as well as crop lands is provided in Appendix A.

- Prescribed Grazing (528): Managing harvest of vegetation with grazing and/or browsing animals.
- Mulching (484): Apply plant residues or other suitable materials produced offsite, to land surface
- Critical Area Planting (340): Establishing permanent vegetation on sites that have, or are expected to have, high erosion rates, and on sites that have physical, chemical or biological conditions that prevent the establishment of vegetation with normal practices.
- Range Planting (550): Establishment of adapted perennial or self-sustaining vegetation such as grasses, forbs, legumes, shrubs, trees.
- Conservation Cover (327): Establishing and maintaining permanent vegetative cover
- Tree/Shrub Establishment (612): Establishing woody plants by planting seedlings or cuttings, direct seeding, or natural regeneration.
- Silvopasture Establishment (381): An application establishing a combination of trees or shrubs and compatible forages on the same acreage.
- Cover Crop (340): Crops including grasses, legumes, and forbs for seasonal cover and other conservation purposes.
- Herbaceous Weed Control (315): The removal or control of herbaceous weeds including invasive, noxious and prohibited plants.
- Vegetative Barrier (601): Permanent strips of stiff, dense vegetation established along the general contour of slopes or across concentrated flow areas.

IMPROVED DRAINAGE TO PREVENT GULLY FORMATION

Many gullies are associated with concentrated surface runoff, often associated with roads, tractor trails or other grading activities. Grading has the potential to concentrate runoff leading to increased flows and erosion. Addressing improper drainage – usually associated with roads – is high priority for reducing and preventing sediment delivery.

The central coast RCDs have developed the “Central Coast Private Road Maintenance Guide.” This guide provides an introduction to basic road drainage and maintenance concepts and practices, and recommended practices and guidelines for maintaining mostly unpaved ranch, forest and residential roads. (Please note that the practices outlined in the Road Maintenance Guide are described in considerably more detail in the more authoritative roads manuals that are referenced as sources for the Guide.) The Guide is available at: http://sanmateorcd.org/RuralRoads/Roads_Guide_Final_2013_10_29_low.pdf

GULLY TREATMENTS

Once a gully has become established, treatment or repairs to the gully may be required to stabilize the feature. For gully treatments to be effective, the underlying causes of erosion must be addressed.

Subsurface flow is an important mechanism for gully formation in the lower PBW, therefore any gully treatment must address the effects both groundwater seepage (which can lead to soil piping) and the surface water contribution. For this reason, gully repair in this watershed is often very difficult and has met with mixed results.

Controlling a gully once it has started generally requires a combination of engineering structures, earthworks and revegetation to control and reduce the source of water flowing through the gully, and to stabilize the gully bottom, banks and head. Because these engineering measures are often expensive, can have construction-related impacts, and can carry a significant risk of failure, it is important to carry out a full assessment of the site prior to undertaking any repairs to evaluate: causes of gully erosion; treatment alternatives; feasibility of repair; and monitoring and maintenance needs.

The following practices are designed to stabilize existing gullies, and to prevent or significantly decrease future sediment production. Classic gully treatment alternatives include a *combination* of:

- **Revegetation**: Establishment of a self-maintaining vegetative cover
- **Grade Stabilization Structures**: Check dams; rock chutes; other
- **Gully Reshaping and Infilling**: Gully sidewall sloping; backfilling
- **Surface Water Control**: Dispersing runoff from draining into gullied areas
- **Groundwater Control**: Subdrains

REVEGETATION

The objectives of revegetation are to establish a self-maintaining vegetative cover which protects the soil surface from rainfall, slows down runoff, allows for greater water infiltration, and increases soil strength through root reinforcement. Revegetation includes revegetation of denuded areas, modification of vegetation to achieve deep rooting perennial native flora, and maintenance of existing vegetation cover. Vegetation is the primary, long-term mechanism for preventing or reducing gully erosion, however, it alone may not be able to fully stabilize an actively eroding gully. Nonetheless, revegetation needs to be a component of any restoration effort.

Methods

NATURAL REVEGETATION: Allow gullies to naturally revegetate. This is most appropriate on those gullies which currently show signs of stabilization.

REPLANTING: Can be done via broadcast seeding or individual plantings, on gully sidewalls or bottom. Plant species should be native, perennial, deep rooting species (e.g., native bunchgrasses and native bunch grasses; willows).

Relevant NRCS Conservation Practices that could be applicable to revegetation treatments:

- Critical Area Planting (340): Establishing permanent vegetation on sites that have, or are expected to have, high erosion rates, and on sites that have physical, chemical or biological conditions that prevent the establishment of vegetation with normal practices.
- Tree/Shrub Establishment (612): Establishing woody plants by planting seedlings or cuttings, direct seeding, or natural regeneration.
- Range Planting (550): Establishment of adapted perennial or self-sustaining vegetation such as grasses, forbs, legumes, shrubs, trees.
- Conservation Cover (327): Establishing and maintaining permanent vegetative cover
- Grassed Waterway (412): A shaped or graded channel that is established with suitable vegetation to carry surface water at a non-erosive velocity to a stable outlet.

Effectiveness and Limitations

- Areas with less severe erosion and gully activity are more apt to successfully respond to revegetation as the primary treatment. Severely eroded sites that are depleted of topsoil and nutrients produce only anemic vegetation conditions.

- Early failures may result from poor planting practices, initial seedling health, lack of follow-up checks and maintenance. For example, for most revegetation projects watering will be required for the first several years until vegetation becomes established. Analysis is needed to determine the most appropriate planting species and design.
- Results from the gully inventory and the field visit demonstrate that older, untreated gullies show signs of revegetation on their own. For deeper gullies, the relative stability appears to be greater when that revegetation includes deeper rooting species, such as coyote brush, that become established within the gully (i.e. at the bottom or in the sidewalls).

Relative Cost

Revegetation may be the most cost effective method of reducing sediment yield, though follow-up work and monitoring will be required.

GRADE STABILIZATION STRUCTURES

Grade stabilization structures are used to control the channel gradient, and reduce the erosive forces of concentrated surface runoff with the goal of preventing erosion from occurring along the channel bottom, banks and head until stabilization by vegetation occurs. These are engineered structures that need to be properly designed to be effective. Overdesign results in unjustifiable expenditures; under design can cause damage to all other installations upstream (i.e. failure of a downstream structure can propagate into the failure of upstream structures and allow for accelerated erosion often greater than in an untreated gully).

Methods

Types of grade stabilization structures include check dams, armored chutes and rock-lined channels. The following provides a summary of two of the more common grade stabilization structures.[5] Two NRCS Conservation Practices that are recommended for addressing soil erosion from ephemeral gullies may also be applicable to a grade stabilization treatment:

- Lined Waterway or Outlet (468): A waterway or outlet having an erosion-resistant lining of concrete, stone, synthetic turf reinforcement fabrics, or other permanent material.
- Rock Barrier (555): A rock retaining wall constructed across the slope to form and support a bench terrace that will control the flow of water and check erosion on sloping land.

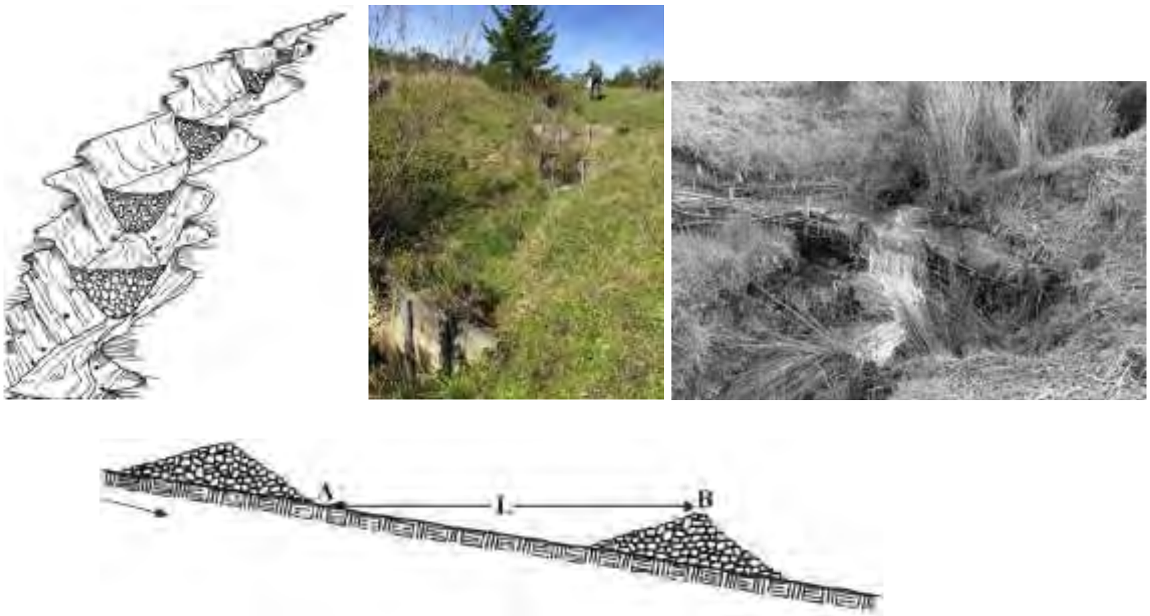
CHECK DAMS: Check dams are one of the most common grade stabilization structures. The intent of using this treatment is to stabilize the channel bottom and allow for sediment to back up behind (i.e. upstream) the structure. Backed up sediment then facilitates the growth of permanent vegetative cover. Check dams are constructed from wood, rock or vegetative material across the gully bottom to prevent gully downcutting, reduce flow velocities and trap sediment. Although they can decrease downcutting within the

[5] Guidance for grade control structures is provided in the Stream Restoration Guide (National Engineering Handbook 654): Grade Stabilization Techniques (NEH654 TS14G)
https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17816.wba

Link to the Stream Restoration Guide (National Engineering Handbook 654):

https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/water/manage/restoration/?cid=stelprdb1044707 gully, by themselves they are not likely to prevent a gully head from advancing up its catchment. Further, they provide little stability to overly steep gully sidewalls. Examples of rock and log check dams are shown in the figures below.

Check dams need to be installed at regular spacing. The spillway of the downstream check dam must be at an equal elevation to the bottom of the upstream check dam. On steep gradient gullies, which typify many of the gullies in the lower PBW, structures will need to be installed at frequent spacings (e.g., for a gully with an average channel grade of 30%, 3-foot high check dams would need to be installed at a 7’-10’ spacing).



Check dams. *Top row: Small rock check dams (from Keller and Sherar, 2003) (left), wood board check dams in a revegetated gully (middle) and a vegetative check dam (from Marin RCD 1987) (right) . Bottom: Diagram showing how the required spacing between check dams is calculated.*

<u>Effectiveness and Limitations:</u>

- Check dams are most effective on low gradient shallow gullies. They are less effective on steep gullies (i.e. >30% slope) where a large number of closely spaced structures are required, and on deep gullies (i.e. >10 feet) where check dam would provide little stability to the gully sidewalls.
- Long term success of check dams is dependent on revegetation of the gully bottom and banks.
- Stability of upstream check dams is dependent upon the stability of the downstream structures. Failure of one of the structures could result in subsequent failure of upstream structures.
- The effectiveness of check dams on gullies formed in dispersive soils from subsurface piping may be limited because of the potential for soil piping to occur within the native soils bounding the sides of the structures. Piping in these areas could to lead to failure of the gully bank and the structure being out flanked. This is particularly a problem on deeper gullies. Additional review of this potential problem is required on a site specific basis.
- Check dams have been used to stabilize some gullies in the PBW watershed but have been met with mixed results. Discussions with Dave Sands (Go Native) who has reviewed several of these structures found that once sediment backed up behind the check dam bank, erosion was able to occur on the channel sidewalls, which eventually led to the failure of the check dam structures. This tends to be a common mode of failure with check dams. To be successful, check dams need to be well-keyed into the

channel bank and bed, and have a well-defined spillway.

- For larger gullies, installation of check dams typically requires an excavator working on the side slopes of the gully. On steeper side slopes and in deeper gullies it may be logistically impractical to install the structures without substantial grading, which presents its own erosion risk.
- Check dams often do little to prevent secondary gullies from eroding back from incised edges of the main gully, or from erosion along upper gully sidewalls above the height of the structure.

<u>*Relative Cost*</u>

Due to the steepness of many gullied sites in the lower PBW, treatment of gullies with check dams could be very expensive. For example, to achieve proper function, treatment of a single gully could require more than 100 structures. The number of structures could be reduced if higher check dams were installed, but there are additional costs associated with these larger structures.

ROCK CHUTES: These are engineered structures constructed within the gully to armor and stabilize the gully bed and banks from erosion. It is most commonly used at gully heads or other knickpoints to allow for the safe passage of water to a lower level. The rock allows water to disperse and lose energy as it moves past knickpoints, controlling erosion.

Typically rock chutes are constructed by laying back the gully heads or knickpoints to an acceptable slope to create a well-defined spillway (chute). The chute is then armored with properly sized rock rip rap. In dispersive soils, filter fabric is necessary to prevent or at least minimize subsurface soil piping.

Rock chutes. *Treatment of gully with rock chutes. During installation (left) and after (right) (from Marin RCD). In this treatment only the steep scarps of the gully were treated. In some areas the entire gully may need to be armored, requiring substantial quantities of rock*

<u>*Effectiveness and Limitations:*</u>

- Rock chutes are most commonly used to armor gully headwalls for gullies with small drainage areas. If properly designed and constructed, they can be very effective in protecting the headwall or knickpoint. Unless the entire gully is rock, however, they do not provide stability to the remaining portion of the gully.
- Rock chutes need to be designed to carry the expected flow within the gully bottom. The rock must be sized to withstand displacement in the largest flows.
- Installation of rock chutes typically requires excavator access to the gully.
- They can be subject to failure by erosion along the edges of the structure and from subsurface erosion and piping. Furthermore, erosion at the toe of the structure could lead to undermining.

Relative Cost:
Material and construction costs for rock chutes can be very high.

RESHAPING AND INFILLING GULLIES

The goal of these measures is to reduce the gradient of the gully sidewalls such that they are at a stable angle, and can be revegetated – an essential component of this gully erosion control approach. It is important to note that these measures alone are unlikely to fix the causes of erosion (i.e., concentrated subsurface and/or surface water flows), and that site-wide solutions for erosion will usually require integration of additional measures that address these issues.

Methods

GULLY RESHAPING: Gully sidewalls are graded back to gentler slope.

INFILLING: A combination of reshaping and back-filling a gully as needed with compacted earth materials to help achieve a gentler slope. For sites where the causes of erosion problems can be identified and fixed, fully infilling (if practical) the eroded areas to restore the natural morphology of the site would be beneficial. Where this is not possible, partial infilling can reduce the steepness of the gully walls to a stable angle onto which erosion control measures can be effectively implemented while revegetation is underway.

All reshaping and infill projects require aggressive surface erosion control measures and revegetation, as well as continued maintenance to prevent future erosion and gully formation. Furthermore, in areas that are at risk for subsurface piping, the repairs need to include subdrains along the bottom of the backfilled gully and/or across the head of the gully to intercept groundwater and to convey the water to a stable location.

Gully reshaping and infilling. *A very large gully in the lower PBW that is being treated with extensive reshaping and infilling. Subdrains (indicated by white cleanout pipes) and a large culvert (not pictured) were installed to manage subsurface and surface water flows at this site.*

Note that the portions of the gully sidewalls that have been reshaped (on the left side of the photo) are treated with erosion control blankets and wattles and will be reseeded with perennial grasses.

None of the NRCS Conservation Practices recommended for addressing soil erosion from gullies appear to be directly applicable to reshaping and infilling, but practices are recommended for Revegetation (see previous section) and for Control of Groundwater (see section below).

Effectiveness and Limitations:

- Gully reshaping and infilling can be applied to a range of gully sizes, but they are most effective on small, shallow gullies (i.e. <3' deep), and less effective for deep gullies that intercept shallow groundwater.
- These approaches are also more effective on lower gradient terrain where the slopes are flattened to less than 25% grade, and where revegetation is viable. On steep ground, greater than 25%, it can be very difficult to stabilize using standard erosion control practices. For this reason, many of the gullies in the PWB are likely not suitable for a reshaping and infilling treatment approach.
- These practices can be a wasteful and ineffective if they are not designed and implemented properly, and if they are not regularly maintained until they are stable and revegetated.

- Infilling, in particular, requires proper design to source appropriate soils, and ensure that they are keyed-in and sufficiently compacted for stability. Costs, risks of failure and environmental impacts increase significantly with the amount of imported fill required for a project. This approach will likely require the services of a geotechnical consultant to ensure fill stability.

Relative Cost:

Compared to installation of grade stabilization structures, costs of reshaping a small gully, installing erosion control measures and revegetating the reshaped gully are low. However, infilling with imported material can be very expensive depending on the amounts and source material requirements. Costs also increase substantially with the need for subsurface groundwater controls.

SURFACE WATER CONTROL

Treatment of gullies that are the result of concentrated surface runoff may require diverting runoff away from gully heads, and discharging the waters in stable areas which are not susceptible to erosion. The basic aim is to disperse runoff to prevent concentrated flow from entering gully heads and along gully edges. Surface water must not be diverted over unprotected areas or it will cause new gullies. Further, if runoff is diverted out of its natural catchment into another drainage line, the additional runoff may increase the risk of gullying to that area.

Methods

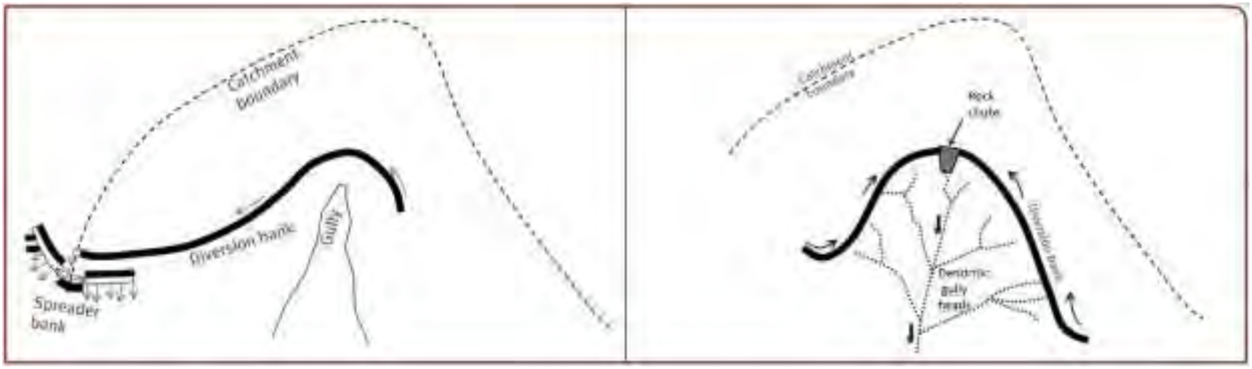
Surface water diversions are used to address road related gullies as well as hillslope gullies that are not road related. In either situation, secondary treatment of established gullies may still be required to effectively control further erosion and expansion.

CROSS DRAINS (ROAD RELATED GULLIES): Some roads within the watershed are poorly drained allowing water to concentrate for long distances resulting in gullying at their discharge points. Installing cross drains (dips or ditch relief culverts) to disperse runoff can be very effective in minimizing gully erosion. However, it is critical that drain dips are installed at frequent spacings to minimize the potential for gullying at discharge points. Ongoing maintenance of the drain dips is essential for long term success.

Methods to control surface runoff on roads are summarized in “Central Coast Private Road Maintenance Guide” (http://sanmateorcd.org/RuralRoads/Roads_Guide_Final_2013_10_29_low.pdf)

DIVERSION DITCHES (HILLSLOPE GULLIES): On hillslope gullies (not road related) control of surface water often involves small diversion ditches constructed along the head and sides of the gullies to collect surface water and discharge it either in a stable location away from the gully or convey the flow via ditches or pipes to a stable channel bottom.

Inspecting the site during large runoff events is highly recommended to determine the surface water contribution to the gully, and allow for designing the diversions to have the sufficient capacities.



Diversion ditches. *Examples of surface diversions for a hillslope gully (from Carey BW, Stone B, Norman PL, Shilton P 2015).*

The design and determination of effectives of diversion gullies is based local site characteristics and professional experience. Therefore there is no established conservation method. However, the following NRCS Conservation Practices could be applicable as site conditions dictate:

- Rock Barrier (555): A rock retaining wall constructed across the slope to form and support a bench terrace that will control the flow of water and check erosion on sloping land.
- Vegetative Barrier (601): Permanent strips of stiff, dense vegetation established along the general contour of slopes or across concentrated flow areas.

Effectiveness and Limitations:

- The dispersion of runoff by surface water will have limited effectiveness for established gullies where the majority of water appears to come from subsurface seepage.
- Redirecting water from gully head could initiate new gullies at discharge points and therefore ongoing monitoring and maintenance will be required indefinitely to make sure that this does not happen.
- If runoff is diverted out of its natural catchment into another drainage line, the additional runoff may increase the risk of gullying to that area.

Relative Cost:

Initial construction costs to control surface water can be relatively low, but the need for ongoing monitoring and maintenance to avoid high risk failures (e.g., triggering gullying elsewhere) must be factored into cost calculations.

CONTROL OF GROUNDWATER

In areas of dispersive soils and prone to soil piping, intercepting the shallow groundwater in subdrains may provide a level of stability by preventing groundwater from draining out of the gully walls.

Methods

SUBDRAINS: A subdrain (also called a French drain) is an underground drain with a perforated pipe that redirects groundwater. The perforated subdrain collector pipes should be equipped with cleanout risers, so long term operability of the subdrain system can be verified and maintained in perpetuity. Interconnected trench subdrains can be used in stabilization of larger, branched gullies.

One NRCS Conservation Practice recommended for addressing soil erosion from gullies is potentially applicable to control of groundwater:

- Subsurface Drain (606): A conduit installed beneath the ground surface to collect and/or convey excess water.

Effectiveness and Limitations:

If properly designed, constructed and maintained, subdrains can be very effective in control groundwater and therefore minimizing the potential for groundwater induced erosion. This method is generally not viable on its own and should be implemented with previously discuss conservation practices as site conditions dictate.

Proper design and construction of subdrains requires an understanding groundwater flow, including source of groundwater, depth and flow path, and soil grainsize distribution. Subdrains are most effective in granular soils and less effective in clays.

Installation of subdrains may be difficult in some areas, especially on steep slopes and may require extensive grading to install. Because the subdrains are designed to dewater the slope, they may reduce water availability to vegetation.

Relative Cost:

Subdrains are usually implemented in conjunction with other gully treatments (e.g. reshaping and infilling) and, as such, it is difficult to estimate their relative costs. In general, subdrains are relatively expensive, however when excavation is already required for other treatments, the incremental cost of installing a subdrain may be low.

SEDIMENT CONTAINMENT

Sediment containment methods include catch basins or ponds designed to intercept eroded sediment before reaching the watercourse of concern. In this alternative the gully is not repaired but rather a retention basin structure is installed at the bottom of the gully to retain the sediment and prevent it from reaching critical watercourses.

Catch basins and ponds are used when treatment of upland gullies is not possible, or to contain eroded sediment as the upland gullies heal. Furthermore, in some of the subwatersheds of PBW this may be the most cost effective and environmentally beneficial method of stopping sediment delivery, given the inherent difficulty, cost and construction impacts involved in stabilizing the large number of gullies located on steep ground. Several the agricultural ponds in Butano Creek currently serve this purpose, though not intentionally.

Sediment catch basin. *Examples of sediment catch basins. The site drains to pond so that sediment can settle before water is allowed to discharge into nearby creeks.*

Effectiveness and Limitations:

- This approach requires sufficient low gradient ground to build a basin which will need to be engineered to prevent subsurface seepage.
- A catch basin would be effective in preventing course fraction of sediment from reaching streams but may not be effective for fine grain sediment.
- Periodic maintenance will be required to clean the structure. In drainages with high sediment loads this may need to occur frequently. Therefore this practice can have a high cost of maintenance.
- Installation of catch basins on streams may have environmental impacts that need to be addressed
- Requires vacant ground for construction, which may not be usable for other purposes. In other words, it may take some land out of production.

Relative Cost:

The cost of the structure is dependent upon its size (e.g., height of the containment berm), sediment load of the source area, site geology, availability of land for basin construction, and existence of potential adjacent constraints (such as streams, buildings, roads, etc). Small structures in remote areas can be inexpensive, larger structures with potential off property impacts can expensive to design, construct and permit. Nonetheless, on some ranch lands where expensive gullying on steep slopes is present, a catch basin may be the most cost effective method of containing sediment.

APPENDIX A: NRCS CONSERVATION PRACTICES

The Natural Resource Conservation Service (NRCS) recommends certain Conservation Practice Standards[6] for agricultural land uses to address soil erosion that contributes to gullying.[7] The following four tables list the specific, California-approved practices that the NRCS has identified as providing "moderate to substantial improvement" for addressing ephemeral and classic gullies and sheet and rill erosion for range, pasture, crop and forest land uses.[8] The last table provides a brief description of the identified practices.

Land Use: RANGE		
Sheet & Rill Surface Erosion	**Ephemeral Gully Erosion**	**Classic Gully Erosion**
Conservation Cover 327	Access Control 472	Access Control 472
Cover Crop 340	Critical Area Planting 342	Critical Area Planting 342
Critical Area Planting 342	Lined Waterway or Outlet 468	Road/Trail/Landing Closure & Trtmt 654
Herbaceous Weed Control 315	Range Planting 550	Trails and Walkways 575
Mulching 484	Residue and Tillage Mgmt, No Till 329	Underground Outlet 620
Prescribed Grazing 528	Road/Trail/Landing Closure & Trtmt 654	
Range Planting 550	Rock Barrier 555	
Residue and Tillage Mgmt, No Till 329	Subsurface Drain 606	
Road/Trail/Landing Closure & Trtmt 654	Tree/Shrub Establishment 612	
Rock Barrier 555	Underground Outlet 620	
Subsurface Drain 606	Vegetative Barrier 601	
Tree/Shrub Establishment 612		
Vegetative Barrier 601		

Land Use: PASTURE		
Sheet & Rill Surface Erosion	**Ephemeral Gully Erosion**	**Classic Gully Erosion**
Cover Crop 340	Access Control 472	Access Control 472
Critical Area Planting 342	Critical Area Planting 342	Critical Area Planting 342
Field Border 386	Grassed Waterway 412	Grassed Waterway 412
Herbaceous Weed Control 315	Lined Waterway or Outlet 468	Precision Land Forming 462
Mulching 484	Range Planting 550	Trails and Walkways 575
Prescribed Grazing 528	Rock Barrier 555	Underground Outlet 620
Range Planting 550	Subsurface Drain 606	
Residue & Tillage Mgmt, Reduced Till 345	Tree/Shrub Establishment 612	
Rock Barrier 555	Underground Outlet 620	
Silvopasture Establishment 381	Vegetative Barrier 601	
Subsurface Drain 606		
Tree/Shrub Establishment 612		
Vegetated Treatment Area 635		
Vegetative Barrier 601		

Land Use: CROP		
Sheet & Rill Surface Erosion	**Ephemeral Gully Erosion**	**Classic Gully Erosion**
Alley Cropping 311	Access Control 472	Access Control 472

[6] These recommendations are based on the NRCS' Conservation Practice Physical Effects (CPPE) matrix which summarizes the relative effectiveness of conservation practices in solving natural resource problems. The CPPE is currently used by all states in the EQIP ranking tool and should be used as a first level diagnostic when considering environmental effects.

[7] Soil erosion definitions (NRCS): Sheet, rill, & wind erosion: detachment and transportation of soil particles caused by rainfall runoff/splash, irrigation runoff or wind that degrades soil quality. Concentrated flow erosion: untreated classic gullies that may enlarge progressively by head cutting and/or lateral widening; and ephemeral gullies which occur in the same flow area and are obscured by tillage. This includes concentrated flow erosion caused by runoff from rainfall, snowmelt or irrigation water.

[8] The RMS Planning Tool available at the NRCS website was used to identify the Conservation Practices shown in the table: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/econ/tools/?cid=nrcs143_009740

Conservation Cover 327	Alley Cropping 311	Critical Area Planting 342
Conservation Crop Rotation 328	Critical Area Planting 342	Grassed Waterway 412
Contour Buffer Strips 332	Grassed Waterway 412	Precision Land Forming 462
Contour Orchard and Other Perennial Crops 331	Lined Waterway or Outlet 468	Trails and Walkways 575
Cover Crop 340	Rock Barrier 555	Underground Outlet 620
Critical Area Planting 342	Stripcropping 585	
Field Border 386	Subsurface Drain 606	
Mulching 484	Terrace 600	
Prescribed Grazing 528	Tree/Shrub Establishment 612	
Residue & Tillage Mgmt, Reduced Till 345	Underground Outlet 620	
Rock Barrier 555	Vegetative Barrier 601	
Stripcropping 585		
Subsurface Drain 606		
Terrace 600		
Tree/Shrub Establishment 612		
Vegetated Treatment Area 635		
Vegetative Barrier 601		

Land Use: FOREST		
Conservation Cover 327	Access Control 472	Access Control 472
Cover Crop 340	Critical Area Planting 342	Critical Area Planting 342
Critical Area Planting 342	Lined Waterway or Outlet 468	Road/Trail/Landing Closure & Trtmt 654
Herbaceous Weed Control 315	Range Planting 550	Trails and Walkways 575
Mulching 484	Residue and Tillage Mgmt, No Till 329	Underground Outlet 620
Prescribed Grazing 528	Road/Trail/Landing Closure & Trtmt 654	
Range Planting 550	Subsurface Drain 606	
Residue and Tillage Mgmt, No Till 329	Tree/Shrub Establishment 612	
Road/Trail/Landing Closure & Trtmt 654	Underground Outlet 620	
Silvopasture Establishment 381	Vegetative Barrier 601	
Subsurface Drain 606		
Tree/Shrub Establishment 612		
Vegetative Barrier 601		

Practice Name (Code)	**Practice Description**
Access Control (472)	Temporary or permanent exclusion of animals, people, vehicles, and/or equipment from area.
Alley Cropping (311)	Trees or shrubs planted in a set or series of single or multiple rows with agronomic, horticultural crops or forages produced in the alleys between the rows of woody plants.
Conservation Cover (327)	Establishing and maintaining permanent vegetative cover
Conservation Crop Rot. (328)	Growing crops in a planned sequence on the same field.
Contour Buffer Strips (332)	Narrow strips of permanent, herbaceous vegetative cover established around the hill slope, and alternated down the slope with wider cropped strips that are farmed on the contour.
Contour Orchard & Other Perennial Area (331)	Planting orchards, vineyards, or other perennial crops so that all cultural operations are done on or near the contour.
Cover Crop (340)	Crops including grasses, legumes, & forbs for seasonal cover, other conservation purposes.
Critical Area Planting (342)	Establishing permanent vegetation on sites that have, or are expected to have, high erosion rates, and on sites that have physical, chemical or biological conditions that prevent the establishment of vegetation with normal practices.
Field Border (386)	A stripe of permanent vegetation established at the edge or around the perimeter or a field.

Grassed Waterway (412)	A shaped or graded channel that is established with suitable vegetation to carry surface water at a non-erosive velocity to a stable outlet.
Herbaceous Weed Ctrl (315)	Removal or control of herbaceous weeds including invasive, noxious and prohibited plants.
Lined Waterway or Outlet (468)	A waterway or outlet having an erosion-resistant lining of concrete, stone, synthetic turf reinforcement fabrics, or other permanent material.
Mulching (484)	Applying plant residues or other suitable materials produced off site, to the land surface
Precision Land Forming (462)	Reshaping the surface of land to planned grades.
Prescribed Grazing (528)	Managing the harvest of vegetation with grazing and/or browsing animals.
Range Planting (550)	Establishment of adapted perennial or self-sustaining vegetation such as grasses, forbs, legumes, shrubs and trees.
Residue and Tillage Management, Mulch Till (345)	Managing the amount, orientation and distribution of crop and other plant residue on the soil surface year round while limiting the soil-disturbing activities used to grow and harvest crops in systems where the field surface is tilled prior to planting.
Residue and Tillage Management, No-Till/Strip Till/ Direct Seed (329)	Managing the amount, orientation and distribution of crop and other plant residue on the soil surface year round, limiting soil-disturbing activities to those necessary to place nutrients, condition residue and plant crops.
Riparian Forest Buffer (391)	An area predominantly trees and/or shrubs located adjacent to and up-gradient from watercourses or water bodies.
Road/Trail/Landing Closure and Treatment (654)	The closure, decommissioning, or abandonment of roads, trails, and/or landings and associated treatment to achieve conservation objectives.
Rock Barrier (555)	A rock retaining wall constructed across the slope to form and support a bench terrace that will control the flow of water and check erosion on sloping land.
Silvopasture Establishment (381)	An application establishing a combination of trees or shrubs and compatible forages on the same acreage.
Stripcropping (586)	Growing planned rotations of row crops, forages, small grains, or fallow in a systematic arrangement of equal width strips across a field.
Subsurface Drain (606)	A conduit installed beneath the ground surface to collect and/or convey excess water.
Terrace (600)	An earth embankment, or a combination ridge and channel, constructed across the field slope.
Trails and Walkways (568)	A pathway for pedestrian, equestrian, bicycle, other off-road modes of recreation travel, farm-workers, construction/maintenance access and small walk behind equipment.
Tree/Shrub Establishment (612)	Establishing woody plants by planting seedlings or cuttings, direct seeding, or natural regeneration.
Underground Outlet (620)	A conduit or system of conduits installed beneath the surface of the ground to convey surface water to a suitable outlet.
Upland Wildlife Habitat Management (645)	Provide and manage upland habitats and connectivity within the landscape for wildlife.
Vegetative Barrier (601)	Permanent strips of stiff, dense vegetation established along the general contour of slopes or across concentrated flow areas.
Vegetated Treatmt Area (635)	An area of permanent vegetation used for agricultural wastewater treatment.