THE CONTRIBUTION OF INFLOW TRIBUTARIES TO SURFACE WATER, METAL CONCENTRATION, AND TOTAL SUSPENDED SEDIMENT LOAD AT HILLER TUNNEL, MALAKOFF DIGGINS

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by

Peter van Daalen Wetters

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LIST OF ABBREVIATIONS AND DEFINITIONS

Bioaccumulation of Mercury Process by which methylmercury is transported up the food chain through living organisms such as bacteria and fish.

BRL Brooks Rand Labs

CDPR California Department of Parks and Recreation

CDPH California Department of Public Health

cfs cubic feet per second or ft^3/s

CTR California Toxics Rule

CVRWQCB Central Valley Regional Water Quality Control Board

DHg Dissolved mercury

DO Dissolved oxygen

DWR California Department of Water Resources

EC Electrical conductivity

EPA United States Environment Protection Agency

MCL Maximum Contaminant Level

MDL Method Detection Limit

MeHg methylmercury

mg/L milligram per liter

NCDWQ North Carolina Division of Water Quality

ng/L nanogram per liter

Q Surface water discharge measured in cubic feet per second (ft^3/ s)

SHP State Historic Park

Subwatershed Catchment area of a stream tributary located within a larger watershed

TSS Total suspended sediment

USGS United States Geological Survey

WY 2014 Water Year 2014; time duration from October 1, 2013 to September 30, 2014

WY 2015 Water Year 2015; time duration from October 1, 2014 to September 30, 2015

ABSTRACT

THE CONTRIBUTION OF INFLOW TRIBUTARIES TO SURFACE WATER, METAL CONCENTRATION, AND TOTAL SUSPENDED SEDIMENT LOAD AT HILLER TUNNEL, MALAKOFF DIGGINS

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This thesis reports on the Malakoff Diggins Rim Trail tributary streams and their contribution to Hiller Tunnel, the main surface water outlet of the Malakoff Diggins mine pit. The study utilized field measurements, hydrologic box modeling, and the ArcGIS software. Malakoff Diggins State Historic Park was one of California's largest hydraulic gold mines. Since the California Gold Rush, discharge containing metals and sediment has continued to be released from the mine, contaminating the Humbug Creek Watershed. Research on the contribution of inflow Rim Trail streams that are located along the north rim of the mine pit, is an important step towards mitigating discharge as a part of mine site remediation. Study objectives included a) locate Rim Trail tributaries and quantify surface water discharge from these inputs and at the Hiller Tunnel output; b) determine Rim Trail discharge metal concentrations for mercury, copper, nickel, and

zinc; c) determine total suspended sediment (TSS) loads from the Rim Trail tributaries and Hiller Tunnel, and d) estimate water budgets for the Rim Trail subwatersheds and Hiller Tunnel during storm events. Quantification of surface water discharge and assessment of water quality were conducted during five storm events in Water Years 2014 and 2015. Storm runoff was sampled at the Rim Trail tributary streams and Hiller Tunnel and analyzed for TSS and metal concentrations (notably total and dissolved mercury, copper, nickel, and zinc). LiDAR (Light Detection and Ranging) datasets and ArcGIS software (Spatial Analyst Tools: Hydrology) were used to delineate the Rim Trail subwatersheds and the Hiller Tunnel watershed. A hydrologic box model was used to quantify fluxes and volumes of water within the Rim Trail subwatersheds and the Hiller Tunnel watershed. The cumulative instantaneous discharge from seven Rim Trail tributaries ranged from 0.4 to 3.8 ft^3/s (± 10%), while the Hiller Tunnel instantaneous discharge ranged from 2.5 ft^3/s (± 10%) to 47 ft^3/s (± 25%). The Rim Trail tributaries contributed approximately 6.5-26% towards Hiller Tunnel outflow discharge. Surface water entering the Malakoff Diggins Pit from the Rim Trail tributaries met the regulatory water quality standards for mercury (50 ng/L), copper (9.0 µg/L), nickel (52.0 µg/L), and zinc (120.0 µg/L). However, during a storm event on 2/9/2014, measured concentrations of mercury (500 ng/L), copper (136 µg/L), nickel (109 µg/L), and zinc (158 µg/L) in the surface water exiting the pit (Hiller Tunnel outlet) exceeded the water quality standards for these metals. The Rim Trail tributary TSS load was 508 mg/s, which contributed less than 1% towards the Hiller Tunnel TSS load of 3.4 kg/s on 2/9/2014. This indicates that surface water originating from the north rim of the pit primarily picks up metals and sediment after it enters the pit and transports sediment within the Malakoff Diggins Pit downstream towards Hiller Tunnel.

CHAPTER I

INTRODUCTION

An estimated 47,000 abandoned mines exist in California, many of which are directly related to the California Gold Rush of 1849 (California Department of Conservation [CDOC], 2000). Miners utilized a variety of gold-extracting methods across California, including hydraulic mining in the Sierra Nevada mountain range (Jackson, 1967). Within the Sierra Nevada lies Malakoff Diggins State Historic Park (SHP), currently owned by the California Department of Parks and Recreation (CDPR) (California Department of Water Resources [DWR], 1987). The park is a relic of the Gold Rush era and the site of one of California's largest hydraulic mines (DWR, 1987). Hydraulic mining consists of eroding hillsides with pressurized water cannons or "monitors" in order to break down placer ores (Alpers et al., 2005). Today, the site continues to impact downstream watersheds as surface water mobilizes sediment and sediment-bound metals such as mercury, copper, nickel, and zinc (California Regional Water Quality Control Board-Central Valley Region [CRWQCB-CVR], 2004; Nepal, 2013). The exposed sediment from hydraulic mining is visible at the ground surface and not deep in a mine shaft such as in hard rock mining. The primary source of mercury at hydraulic mines in the Sierra Nevada is from the addition of liquid mercury during hydraulic placer gold mining processes (Alpers et al., 2005). Other heavy metals are from mineralized deposits that have been exposed by the excavation process (Yeend, 1974).

As a result of the metals and sediment transported from hydraulic mine sites in the South Yuba River watershed, toxic methylmercury can bioaccumulate within the food chain and be harmful when fish is consumed by humans in sufficient amounts (Shilling et al., 2010; Grandjean and Landrigan, 2014). Consumption of mercury-contaminated fish can be toxic to aquatic and terrestrial organisms within food chains (Wolfe et al., 1998). Degraded water quality from abandoned mines is a potentially significant source of contaminates such as mercury, copper, nickel, and zinc, thus targeting abandoned mine sites as areas for remediation may have watershed-wide benefits. The overall purpose of this study at Malakoff Diggins was to 1) identify and quantify surface water inputs and total suspended sediment (TSS) loads to determine whether the water entering the hydraulic mine pit from an elevated rim is free of major metals such as mercury, and 2) approximate storm event water budgets of defined subwatersheds, in order to inform remediation activities. Site-specific thesis research questions are stated in the "Purpose of the Study" section.

Project Location

Malakoff Diggins State Historic Park is located in the Gold Country, a historic gold mining region within the Sierra Nevada mountain range. In relation to nearby cities, the park's location is 14 miles (23 km) northeast of Nevada City, CA and 63 miles (101 km) north of Sacramento, CA (Figure 1). With an elevation that ranges from 2,500 to 4,000 feet (762 to 1219 m) above sea level this historic mine lies within the upper watershed of Humbug Creek, a tributary of the South Yuba River (California State Parks [CSP], 2015). The California State Park System Statistical Report states that the park is

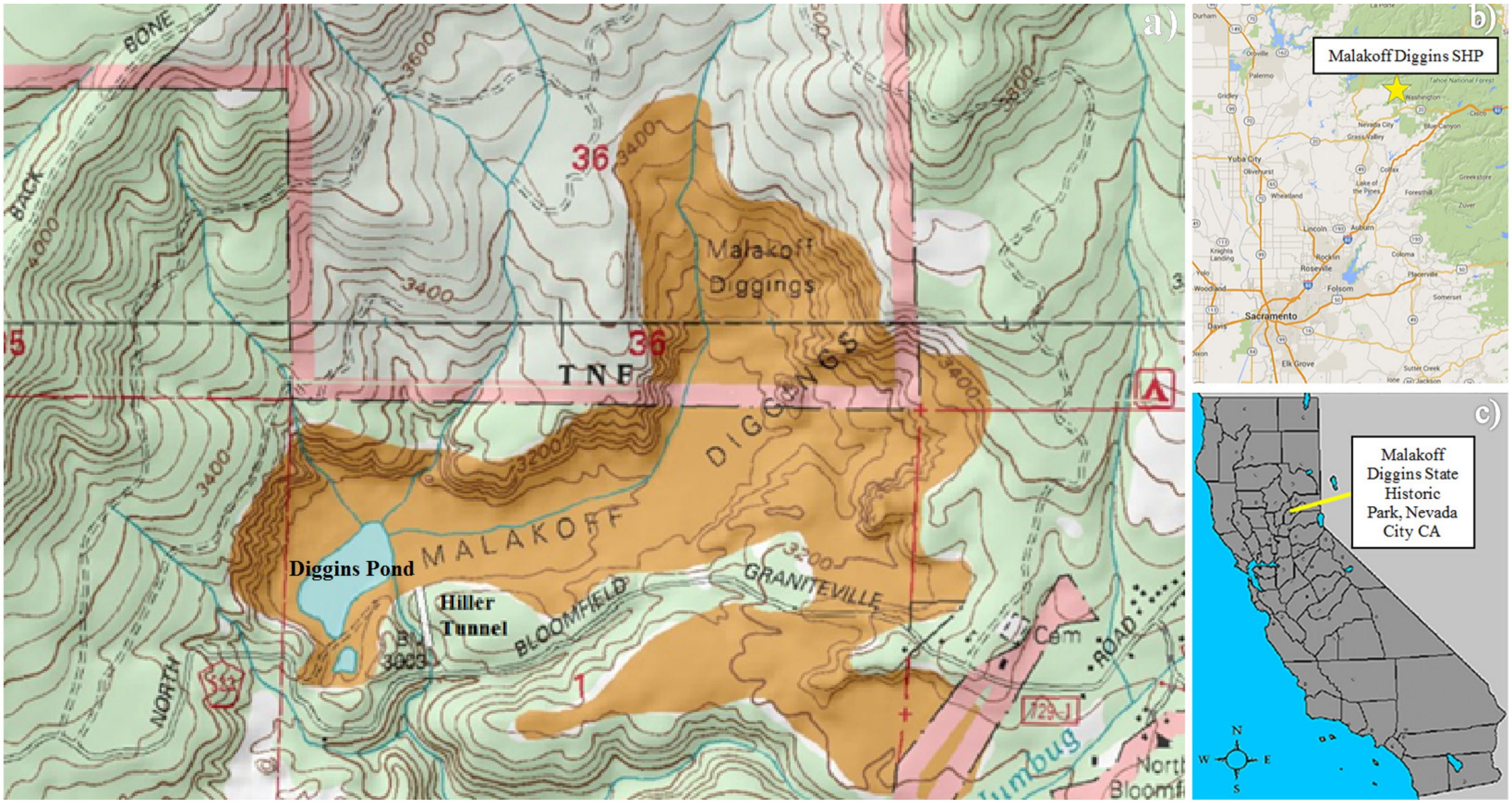

Figure 1. Topographic map of Malakoff Diggins State Historic Park, map of regional park location, and map of California with park location.

Clockwise from left: a) Topographic map showing the major Rim Trail surface water input flow paths into Malakoff Diggins Pit and Diggins Pond, as well as export of surface water through Hiller Tunnel (MyTopo USGS Enhanced Quad Map 7.5' Map Series); b) Regional map of Park with Nevada City and Sacramento locations (Google Maps, 2015); c) Map of California with Park location (Luventicus Academy of Sciences, 2013).

approximately 4.911 mi^2 (12.7 km^2) (CSP, 2009/10). The Hiller Tunnel watershed area, as delineated from the park's main output discharge point (Hiller Tunnel outlet), is within the Humbug Creek watershed and covers approximately 3.35 mi^2 (8.68 km^2) (calculated using ArcGIS and LiDAR, see Methods).

The Western Regional Climate Center (WRCC) describes the Nevada City regional climate as Mediterranean, having moderate to heavy rainfall for California with an average precipitation of 54.3 inches (138 cm) per year over the years 1893-2013 (WRCC, 2014). The greatest average monthly precipitation occurs in January at 10.2 inches (26.0 cm) while July and August see the lowest average monthly precipitation at a mean of 0.1 inches (0.3 cm) (WRCC, 2014). Nevada City's average maximum temperature of 88°F (31°C) occurs in July and August whereas the average minimum temperature of 31° F (−0.56 °C) occurs in December and January (WRCC, 2014). Total snowfall in the region occurs mainly in January with an average of 7.9 inches (20 cm) and a snow depth of 1 inch (2.5 cm) (WRCC, 2014).

The forested region of Malakoff Diggins is representative of a Ponderosa pine forest, including ponderosa pine (*Pinus ponderosa*), sugar pine (*Pinus lambertiana*), white fir (*Abies concolor*), incense cedar (*Calocedrus*), big leaf maple (*Acer macrophyllum*), black oak (*Quercus kelloggii*), and live oak (*Quercus virginiana*) (Johnson et al., 1979). Smaller bushes and shrubs consist mainly of buck brush (*Phyllanthopsis phyllanthoides*) and manzanita (*Arctostaphylos manzanita*) (Johnson et al., 1979). The hydraulic mine pit, Malakoff Diggins Pit, is a major geographical component of the Park (Figure 1). The pit floor is vegetated mainly by willows and the surrounding cliffs range in height from 100 to 500 feet (30 to 152 m) (Peterson, 1980).

During storm events, seven major tributary streams, defined as Rim Trail tributaries, flow into the pit from elevated subwatersheds (Figure 2). Each Rim Trail subwatershed is located within the Hiller Tunnel watershed. However, depending on the context, the term subwatershed or watershed will be used to describe each Rim Trail catchment area. The surface water from each tributary watershed flows into the pit, where it coalesces with additional surface water within the pit and then eventually flows out of the pit. The main surface water outlet of the Malakoff Diggins Pit, Hiller Tunnel, is a tunnel that facilitates the transport of suspended sediment and water into Diggins Creek and eventually downstream to Humbug Creek.

Miners at Malakoff Diggins Pit used hydraulic monitors to erode the soil overburden of the pit walls, creating a badlands-type of topography (Isenberg, 2005). The exposed walls allowed access to gold embedded in the placer gravels. The pit area has continued to increase over time due to ongoing pit erosion well after mining activities stopped (Yuan, 1979; Peterson, 1980; Landrum, 2014). In 2013, the pit area was approximately 1.5 miles (2.4 km) long and 0.5 miles (0.8 km) wide (Demaree, 2013). The major rock types visible at the mine site are a combination of auriferous Eocene to Oligocene gravels and Quaternary colluvium (Cassel et al. 2012; Yeend, 1974). The composition of exposed rock varies; the rocks within the steep slopes show stratification but they are not complexly faulted and folded (Peterson, 1980).

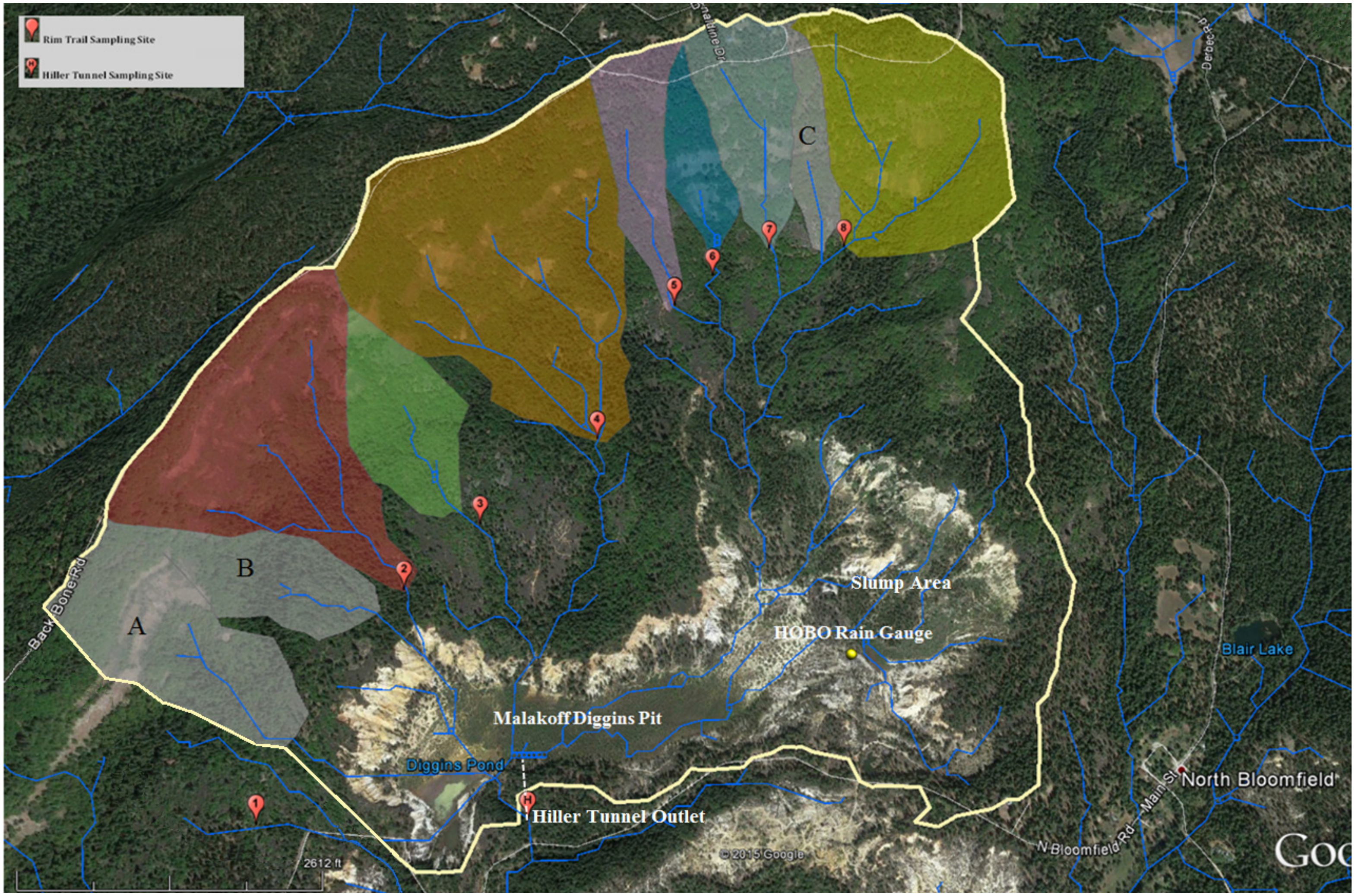

Figure 2. Detailed map of study site, Rim Trail subwatersheds and drainages, Malakoff Diggins Pit, Diggins Pond, and Hiller Tunnel (Google Earth, 2015). Measured Rim Trail tributaries 2-8 and non-measured subwatersheds A, B, and C are indicated.

The Malakoff Diggins Pit has a number of components that facilitate the transport of sediment and surface water towards Hiller Tunnel. The far eastern end of the pit, a slump area where sediment has moved down cliff walls, is sparsely vegetated andhas shown the highest overall erosion and deposition over time (Demaree, 2013). Extraction of USGS LiDAR elevation data (12/2/2014) in ArcGIS (Spatial Analyst: Extract Values to Points tool) shows that from the base of the slump area (~3,100 ft), elevation steadily decreases westward towards Diggins Pond (3,052 ft) and the Hiller Tunnel outlet (3,024 ft) (Figure 2). The Malakoff Diggins Pit northern cliffs are greatest in height and gradually descend towards the western rim of the pit. Alluvial fans, comprised of cobble-, pebble-, and sand-sized clasts, exist on the north and western rims of the pit (DWR, 1987). The alluvial fans within the pit are shaped by the movement of surface water and sediment from elevated gullies on cliffs (Peterson, 1980). The gullies were likely formed by erosional processes from hydraulic monitors and in many cases have been accentuated with the drainage of surface water (Peterson, 1980).

In addition to the sediment from erosion of the pit cliff faces, seemingly reworked gravels are indicative of bucket-line dredging, the result of the Sawyer Decision that regulated the discharge of processed mining material downstream (Gilbert and Savitski, 1991). Dredge operations disturbed fine-grained, mercury-bound sediment, which is problematic because this fine-grained sediment mobilizes during storm events and can increase mercury concentrations downstream (Gilbert and Savitski, 1991; Fleck et. al, 2010).

Hiller Tunnel has greater discharge during storm events than non-storm conditions and readily transports sediment to downstream watersheds (Nepal, 2013). During the study's storm events, a reddish-brown discharge was seen flowing within and out of Malakoff Diggins at the Hiller Tunnel outlet. The source of the distinct color of storm water runoff is likely iron oxides in exposed sediment (Yeend, 1974; Jones-Lee and Lee, 2005). Storm event runoff transports sediment and contaminants downstream of Hiller Tunnel towards Humbug Creek (DWR, 1987). This transport contributes to elevated concentrations of mercury, copper, zinc, and sediment in surface waters (DWR, 1987; The Sierra Fund [TSF], 2015). The transport of mobilized sediment through Humbug Creek subsequently impacts the South Yuba River watershed (DWR, 1987).

Humbug Creek is under violation of Section 303(d) of the 1972 Clean Water Act (CWA) for mercury, copper, zinc, and sediment, and has a Waste Discharge Requirement (WDR) issued in 1976 that is regulated by a Central Valley Regional Water Quality Control Board (CVRWQCB) Waste Discharge Permit (Order No. 76-258) (California Regional Water Quality Control Board [CRWQCB], 1976; CVRWQCB, 2010). Federal law protects "waters of the United States" to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters" (United States Environmental Protection Agency [USEPA], 1972). The CWA (33 CFR §328.3) states that ephemeral or intermittent streams shall be regulated if they are tributaries of waters of the United States (USEPA, 1972). Consequently, the violation of environmental and water quality regulations from Malakoff Diggins requires the CDPR to pay an annual discharger fee to the State Water Resources Control Board (CRWQCB, 1976). In 2000, under the EPA Clean Water Act, standardized water quality criteria for priority toxic pollutants were established in California for inland surface waters, enclosed bays, and estuaries (USEPA, 2000). These regulations, known as the California Toxics Rule (CTR), defined Maximum Contaminant Levels (MCLs) for a number of metals, notably mercury in water (50 ng/L) (USEPA, 2000). Due to the bioaccumulation factor used to establish a human health criterion, inorganic and organic (methylmercury) forms of mercury differ in toxicity; ingestion of soil or water containing inorganic mercury is not as concerning as the consumption of fish containing the organic form. Consequently the regulatory framework is more commonly guided by the organic concentrations in fish (Office of Environmental Health Hazard Assessment [OEHHA], 1999; USEPA, 2001; DWR, 2007) rather than CTR MCLs for mercury in water (USEPA, 2000). The copper, nickel, and zinc MCLs, respectively 9.0, 52.0, and 120.0 µg/L, are based on the concentrations to which aquatic life can be exposed (in dissolved form) for four days without harmful effects (USEPA, 2000). The presence of these metals downstream of hydraulic mine sites such as Malakoff Diggins can signify mobilization of metals and sediment. Thus, established water quality objectives are important to protect beneficial uses (drinking water sources, fisheries, and recreational uses) and facilitate management strategies.

History

As early as 1848, gold seekers or “forty-niners” flocked to California during the California Gold Rush in search of prosperity and opportunity (Paul, 1947). In 1851, Nevada County prospectors mined for gold at Humbug Creek, downstream of Malakoff Diggins (Jackson, 1967). Large amounts of gold-bearing Paleogene gravel were found, yet at low concentrations in the form of dust or flakes (Yeend, 1974). The gold placer deposits formed from the settlement of auriferous gravel, alluvial sediment deposited from ancient rivers during the Eocene epoch (Whitney, 1880). As more and more placer gold was discovered, miners looked for optimal mining techniques to extract rock material and move sediment (Yeend, 1974). In 1853, modern hydraulic mining was developed near Nevada City by a Connecticut miner, Edward Matteson (Paul, 1947). Matteson and mining associates fabricated an early hydraulic monitor, a three-foot tapered metal funnel clamped to a canvas hose with an iron nozzle at the end (Isenberg, 2005). Miners transported water from higher elevations and redirected it into narrowing channels, thereby providing pressured water for the monitors. The technique effectively created a jet of water that could erode mountainsides with ease, but it also had damaging environmental impacts both onsite and downstream (Figure 3) (Yeend, 1974).

By 1867, the North Bloomfield Gravel Mining Company (NBGMC) had been established and sought to hydraulically mine placer gold within auriferous gravel at Malakoff Diggins (Jackson, 1967). Auriferous gravel is comprised of loose alluvial material that is easily mobilized when sprayed with hydraulic monitors (Jackson, 1967). An estimated 39 million cubic yards of rock and soil were displaced which resulted in the creation of the Malakoff Diggins 1.3 mile (2.1 km) long, 0.6 mile (0.1 km) wide mine pit (DWR, 1987). Hiller Tunnel, built as part of an earlier private mining claim owned by Dr. Hildersheidt, is a 557 foot (170 m) long tunnel that currently transports surface water runoff from Malakoff Diggins downstream towards Diggins Creek, which coalesces with

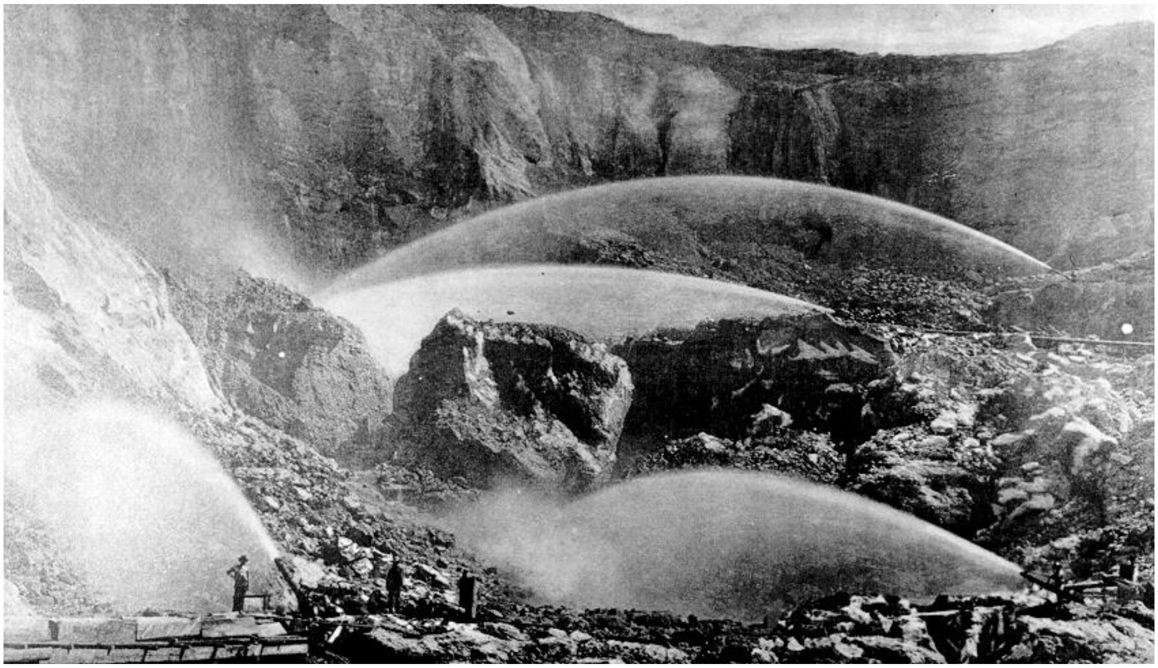

Figure 3. Historic photograph of Malakoff Diggins Hydraulic Mine. Four monitors are being used to wash material through bedrock cuts to sluices. (Watkins Photo-Bancroft Negative #8111 in California Department of Conservation California Geological Survey Library, 1880).

Humbug Creek and ultimately drains into the South Yuba River (Jackson, 1976; CSP, 2015; Mark Selverston personal communication August 26, 2015). In 1874, NBGMC completed the North Bloomfield Tunnel, a deep underground tunnel with eight air shafts that served as a supplementary drainage to transport the gravel and water downstream, out of Malakoff Diggins Pit (Jackson, 1967). The 7,847 foot (2,392 m) long North Bloomfield Tunnel starts in the pit north of Hiller Tunnel, runs south beside Humbug Creek and eventually drains into Humbug Creek (Jackson, 1967; CRWQCB, 1976).

Malakoff Diggins has seen controversy over water-related issues dating back over 100 years ago when downstream valley farmers and stakeholders were flooded out and inundated by sediment debris as a result of major rains (Sawyer, 1884; Jackson, 1976). The growing concerns of Malakoff Diggins hydraulic mining effects on downstream fields and towns led to the Sawyer Decision in 1884. Judge Lorenzo Sawyer declared that North Bloomfield Gravel Mining Company infringed upon the rights of individuals downstream since the company damaged landscapes and watersheds (Sawyer, 1884; Jackson, 1976). Sawyer determined that hydraulic mining was legal; however, miners must contain mine debris on their property rather than dump it into local rivers (Sawyer, 1884; Jackson, 1976). The decision restricted hydraulic mining at Malakoff Diggins, which at the time was the largest and most profitable hydraulic mining operation in the world (Sawyer, 1884; Jackson, 1976). The Caminetti Act of 1893 modified Judge Sawyer's decision and allowed hydraulic mining to occur only if the movement of sediment was controlled by debris-retaining dams (James, 2005). By 1910, miners had completely stopped hydraulic mining in the region. After these decisions, the North Bloomfield Tunnel became blocked with mine waste and runoff around 1930 (Jackson, 1967).

As part of the hydraulic mining process to recover and separate the gold from other heavy minerals, mountainside debris was sluiced with the addition of liquid mercury through riffles and troughs (Alpers et al., 2005). Mercury was sometimes released over the bank of a hillslope and washed down within the gravel and water into the sluices (Jackson, 1967), but was more often used to line the sluice. The first 2000 feet of the North Bloomfield tunnel was used as a sluice. Mercury (Hg) is a very heavy liquid metal at normal pressure and temperature that amalgamates with gold (Rose and Newman, 1986). In addition, mercury is not soluble in water and does not form amalgams with many other materials in the sluices, making it an ideal element for the extraction of gold (Alpers et al., 2005). California State Mineralogist Report, II (1882) states that 1,147.5 pounds of mercury were used in the Malakoff Diggins North Bloomfield mine sluices and undercurrents during each run (Jackson, 1967). A North Bloomfield run was conducted approximately every 12 days, and used 15 mercury flasks that each weighed 76 pounds (Bowie, 1898; Jackson, 1967). After the gold-mercury amalgamations settled, the compounds were removed from sluices and heated in an iron or steel distillation retort (Bowie, 1898). Some mercury in the heating process was released as vapor while remaining elemental mercury could be reused. A final product resulted, mercury-free gold.

The hydraulic mining method washed contaminated water and sediment downstream into streams and rivers and left mercury at the site (Fleck et. al, 2010). From 1850 to 1881, an estimated 26 million pounds of mercury were extracted from the California Coast Ranges and transported to Sierra Nevada mining operations (Churchill, 2000). Of this amount, approximately 10 million pounds were lost to the environment in placer mining operations and 3 million pounds were lost from hard rock mining within the Sierra Nevada (Churchill, 2000). At Sierra Nevada mine sites, it is estimated that 10 to 30 percent of the mercury used for the hydraulic mining amalgamation process was lost to the environment in the slurry discharge, corresponding to several hundred pounds (Bowie, 1905; Hunerlach et al., 1999). The mercury lost can be attached to sediment and particulate matter, which is deposited in the Malakoff Diggins Pit floor and tunnel tailings (Nepal, 2013). Furthermore, mercury can be bound to suspended sediment in water or exist in organic form as methylmercury (Wentz et al., 2014).

Significance

Since 2011, the nonprofit organization The Sierra Fund and CDPR have been working together to evaluate and remediate the physical and chemical hazards at Malakoff Diggins, including the mercury and sediment discharge from the site. The Sierra Fund's Reclaiming the Sierra Initiative addresses historic mining impacts in California. More specifically, goals of the project at Malakoff Diggins include 1) reducing contaminated discharge from the abandoned mine site, 2) preserving Malakoff's anthropological cultural values as a relic of the past, and 3) developing an effective scientific remediation approach that can be replicated across comparable sites within California (TSF, 2015). One option to reduce sediment and metal discharge to Humbug Creek could include redirecting the Rim Trail tributary streams with diversion channels around the Malakoff Diggins Pit (TSF, 2015). Other surface water and sediment abatement engineering options include a sediment detention and water filtration structure within the pit, north of the Hiller Tunnel inlet (TSF, 2015). These remediation options could impact downstream vegetation, water quality, and wildlife. This thesis fills a critical data gap as the research of Hiller Tunnel, Rim Trail subwatersheds, and respective tributary surface water, metal concentration, and TSS loads are important towards understanding environmental impacts and the effectiveness of remediation options, facilitating future projects, and promoting environmental issue awareness.

CHAPTER II

LITERATURE REVIEW

Previous research at Malakoff Diggins State Park provides relevant background data on the hydrology and water quality impairments that help inform future research efforts to fill data gaps. A review of literature on the use of box modeling and the Rational Method for hydrologic analyses provides a framework for the study results and interpretation.

Malakoff Diggins Hydrology and Water Quality

Hydraulic mining transformed the landscape of the Humbug Creek watershed and altered surface and subsurface flow of water for hundreds of years. The Nevada County Resource Conservation District report in 1979 on Malakoff Diggins water quality states that tributary streams which drain from the upper watershed by sheeting and seeping action on the pit's barren cliffs flow through the Malakoff Diggins Pit and out through Hiller Tunnel (Nevada County Resource Conservation District [NCRCD], 1979a). Chico State Master's Thesis by Harihar Nepal (2013) looked at sediment and mercury load sources to Humbug Creek from Malakoff Diggins and also identified hydrologic features of the mine site. During storm events, the water moving into the pit erodes sides of the pit and creates minor channels and alluvial fans (Nepal, 2013). Within Malakoff Diggins Pit, surface water can form braided channels on the ground (Nepal, 2013). Surface water that flows along the southern edge of the pit eventually reaches

Hiller Tunnel whereas water from the northern pit rim coalesces at Diggins Pond and then flows out to Hiller Tunnel (Nepal, 2013). Diggins Pond water levels fluctuate and the pond does not dry out even during the dry summer (Nepal, 2013). Nepal (2013) also states that the pond acts as a small reservoir within the pit. Ephemeral streams from storm events at Malakoff Diggins, particularly located at the north rim and pit floor, are important to understand because they contribute to the transport of sediment, water, nutrients, chemicals, and debris, as well as the connectivity within the watershed (Levick et al, 2008). The hydrologic features and flow paths are important because they help describe the transport of surface water into, within, and out of Malakoff Diggins Pit and can provide a greater understanding of the source and transport mechanism for sediment and metals.

Infiltration, the downward entry of water into a soil (or sediment) and infiltration rate, the rate at which a volume of water will move downward into a soil surface area per unit time (Soil Science Society of America, 1956), are important components of hydrologic processes. Infiltration is commonly measured from field measurements, using infiltrometers which can provide site specific data on the amount of water draining into the soil over time (Johnson, 1963). The infiltration rate of a soil surface is impacted by a number of factors including precipitation rate, soil type, soil compaction, antecedent moisture conditions, and vegetation cover (Horton, 1933; Green, 1962; Johnson, 1963; Black, 1997). Knowledge of this hydrologic parameter can provide insight to processes such as surface runoff, erosion, flooding, soil and water pollution, and mobilization of sediment (Horton, 1933; Black, 1997). Infiltration at Malakoff

Diggins Pit was studied as part of David Demaree's Master's Thesis (2013). Demaree (2013) noted that sediment deposited in the pit was not uniformly compacted by park usage which may lead to relatively higher infiltration rates in certain areas of the pit. Cracks in the ground surface of the pit and macropores caused by vegetation can also increase infiltration rates (Ward and Elliot, 1995). In contrast, soil containing fine grain sand and clay commonly seen within the pit can slow water infiltration rates (Ward and Elliot, 1995). Demaree (2013) observed that drainage of water into surface sediment (sandy loam and loam) at boring sites north of the Hiller Tunnel inlet was faster than subsurface drainage and that little to no subsurface drainage occurred due to bedrock geology within the pit. The study also qualitatively suggested that slow groundwater drainage from Malakoff Diggins Pit may be supported by the perennial nature of Diggins Pond (Demaree, 2013). The study indicates that surface water may readily infiltrate through a surface layer of unconsolidated sediment within the pit and easily mobilize this sediment because the water cannot infiltrate deeper due to impermeable metamorphic bedrock. More information on infiltration rates of sediment in the pit is needed to inform proposed remediation solutions within the pit and proposed remediation activities such as a sediment detention basin structure and /or Rim Trail tributary diversion ditches.

Malakoff Diggins Sediment and Mercury Loads

Mercury lost to the environment from past hydraulic mining can be bound to sediment and move downstream through the South Yuba watershed (Fleck et al., 2010). Previous studies have measured sediment and mercury loads in Humbug Creek (NCRCD, 1978, 1979 a and b, 1980; DWR, 1987; Fleck et al., 2010; Marvin-DiPasquale et al., 2011, Nepal, 2013; TSF, 2015).

From 1978 to 1980, the Nevada County Resource Conservation District (NCRCD) performed a four-part study to determine sediment sources and propose ways to reduce sediment levels to better manage Malakoff Diggins State Historic Park (NCRCD, 1978, 1979 a and b, 1980). Phase I of the study reviewed material related to the Park's hydrology and natural resources and determined that a thorough survey of erosion was necessary to detect sediment sources and develop a management plan. Phase II of the NCRCD study collected a single storm sample at the Hiller Tunnel outlet in Diggins Creek to measure concentrations of arsenic, lead, iron, manganese, and other metals (mercury omitted) and documented elevated sediment concentrations in Diggins Creek. Suspended sediment yield ranged up to 1.2 tons/min (1089 kg/min) at the outlet of Hiller Tunnel and the majority of the material was in the sand and silt particle size class during storm event discharge. The trout fishery at Humbug Creek was impacted by sediment loads from Malakoff Diggins as a result of reduced spawning grounds, microhabitats, and possible food supply (Schultze and Cropper, 1979). In contrast, Gard (2002), a study on the impacts of sediment loads from Malakoff Diggins to the South Yuba River, reported that sediment loads no longer had major impacts on trout survival or reproduction; however, the fish species Sacramento pike minnow appeared to be affected by both water temperatures and sediment loadings (Gard, 2002). Phase III of the NCRCD study analyzed stream flow, water quality parameters, chemical content, particle size distribution, and precipitation data from Part II. Silt and clay sediment load at the outlet of Hiller Tunnel was measured during a storm event on 2/14/1979; the instantaneous TSS load was 18.63 kg/s (1,118 kg/min) at an estimated flow of 31 ft^3/s (NCRDC, 1979b; DWR, 1987). DWR (1987) reports that the total amount of precipitation at Malakoff Diggins (North Bloomfield) during the month of February in 1979 was 13.5 inches. The Phase III Progress Report concluded that unfiltered water samples (combination of heavy metals in sediment with sample solution) had chromium, iron, manganese, and lead in amounts that exceeded water quality criteria. In contrast, filtered water samples did not exceed recommended drinking limits (NCRCD, 1979b). Phase IV consisted of recommended management strategies to limit sediment mobilization from Malakoff Diggins.

The California Department of Water Resources (DWR, 1987) assessed erosion and sedimentation at Malakoff Diggins to evaluate remediation efforts. The agency reported that during storm events, Hiller Tunnel (Malakoff Diggins Pit outlet) discharged approximately 1,537 kg of sediment per second. Discharge emitted from the Malakoff Diggins site, in violation of CVRWQCB water quality standards for sediment, led the California Department of Parks and Recreation (CDPR) to evaluate erosion and sediment yield, as well as propose solutions such as settling basins (Macdonald, 1989). The study monitored water quality at upper reaches of the watershed and compared the sediment contributions to barren cliffs below the Rim Trail (Macdonald, 1989). The upper watershed was not affected by sediment; drainage streams were observed as clear (but not tested) before reaching the pit (Macdonald, 1989).

The USGS studied sediment and mercury loads emitted by the Malakoff Diggins Pit that accumulated at the confluence of Humbug Creek and the South Yuba River to further understand downstream mobilization of pollutants within the Humbug Creek watershed (Marvin-DiPasquale et al., 2011). The USGS report discusses that an increase in inorganic ‘reactive’ mercury, ($Hg(II)_R$) and (or) methylmercury (MeHg) concentrations in microcosms is associated with an increase in suspended sediment particles from the South Yuba River-Humbug Creek confluence. In addition, smaller suspended sediment particles (silt and clay less than 0.063 millimeters) had greater amounts of mercury associated with them when compared to larger particles in the slurry discharge, which may be attributed to increased surface area-to-volume ratios (Fleck et al., 2010; Marvin-DiPasquale et al., 2011). These studies results indicate that retaining suspended fine grain sediment in the pit may be an effective way to reduce mercury mobilization to downstream environments.

Additional monitoring of Malakoff Diggins sediment and mercury loads was conducted by The Sierra Fund (2015) and partners in The Humbug Creek Watershed Assessment. The report is the result of the first phase (over five years of data collection, research, and analysis) of the Malakoff Diggins Project, which is under the Reclaiming the Sierra Initiative. The report included water samples collected at multiple sites during WY 2012 and WY 2013 on Humbug Creek (upstream and downstream from the Diggins Creek confluence) and from Hiller Tunnel discharge from multiple storm events. A stage-discharge relationship was established to calculate total suspended sediment and particulate-bound mercury loads to Humbug Creek below the Humbug Creek and

Diggins Creek confluence. Humbug Creek sediment load calculations show that Water Year 2012 reported a sediment load of 474 tons (474,000 kg); storm events contributed 71% of the sediment (TSF, 2015). Water Year 2013 reported a sediment load of 570 tons (570,000 kg); storm events contributed 47% of sediment (TSF, 2015). Particulate-bound mercury load from Humbug Creek during WYs 2012 and 2013 was calculated to be at least 100 g/yr (0.22 lb/yr) (TSF, 2015). Consistent with sediment load, annual mercury load was also driven primarily by storm events (70% of the annual load was from storm events) (TSF, 2015). The findings indicate that over half of annual TSS and mercury loads in Humbug Creek are driven by storm events. The Sierra Fund (2015) found that during storm events, metals (mercury, copper, nickel, zinc, lead, and iron) and sediment from Diggins Creek (Hiller Tunnel discharge) moves downstream to Humbug Creek. A background site at the Relief Hill Road crossing in Humbug Creek above the confluence of Humbug Creek and Diggins Creek showed lower concentrations of metals than downstream below the confluence, confirming the significant contribution from Diggins Creek/Hiller Tunnel. Water samples at Hiller Tunnel and below the confluence showed that mercury and other metals were primarily in the particulate bound form (TSF, 2015). The study also found that particulate-bound mercury concentrations were correlated to TSS concentrations below the confluence in Humbug Creek.

Methylmercury and Sediment Impacts

Exposure to methylmercury has adverse health effects on fish, wildlife, and people (Wolfe et al., 1998; Shilling et al., 2010; Grandjean and Landrigan, 2014). Industrial and mining activities can discharge inorganic mercury (Hg) into rivers, lakes, and oceans; Hg can then become converted to methylmercury (MeHg) by microorganisms and bioaccumulate within the aquatic food chain (WHO, 1990).

Shilling et al. (2010) studied a region high in mercury-contaminated fish and subsistence fishing at the Sacramento/San Joaquin Rivers Delta, downstream of the Sierra Nevada. The study reports that the majority of fish caught were for subsistence, including ethnic families with children and women of childbearing age (who are more susceptible to exposure effects). Consumption of these fish was the primary way methylmercury was exposed to the study's demographics. Calculated rates of mercury from fish consumption in these families were above the EPA reference dose, 0.0001 mg/kg-bodyweight/day, which can be estimated to 17.5 g/day (assuming an average adult body weight of 70 kg) (Shilling et al., 2010).

Toxic methylmercury exposure can occur at various trophic levels and durations. A study on the consequences of human exposure to neurotoxins including methylmercury was conducted by Phillipe Grandjean and P.J. Landrigan in 2014. Results of the study show that neurotoxins can cause impaired central nervous system function and kidney damage, autism, sensory disturbances, difficulty with coordination, peripheral vision or blindness, slurred speech, and developmental susceptibility (Grandjean and Landrigan, 2014). Furthermore, a review of studies by Wolfe et al. (1998) on the effects of mercury on wildlife states that ingestion of sufficient methylmercury in prey and drinking water by birds and mammals can lead to damage to nervous, excretory and reproductive systems (Wolfe et al., 1998). Remediation of the Malakoff Diggins site would benefit the Humbug Creek watershed and reduce potential methylmercury bioaccumulation and health concerns to wildlife and humans.

Aquatic watershed health can also be affected by suspended sediment. Shultze (1975), a fisheries impact survey, reported on the effects of the mobilization of sediment from Malakoff Diggins on Humbug Creek. The survey states that turbidity from suspended sediment can reduce light penetration within the water, and hinder primary production which can inhibit fish productivity (Schultze, 1975). Fine sediment particles can clog gills of aquatic organisms and cover aquatic vegetation within the benthic zone, which can disturb food chain processes (Schultze, 1975). The exposure of toxic methylmercury to fish, wildlife, and humans as well as sedimentation within watersheds highlights the importance for water quality regulations (and compliance) to educate the public and remediate contaminated sites.

Physical and Chemical Properties of Water Relevant to Water Quality

Water quality refers to a number of characteristics that determine the suitability of water relative to the requirements of its intended use, such as human consumption and industrial processes. The measurement of specific properties can provide background information and indicate water quality impairments to address water quality problems. This section provides a brief overview of relevant water properties that were measured in this study.

Water Temperature

As temperature increases, the rate of reactions in a water body generally speeds up (Michaud, 1991; Petrucci et al., 2006). Water at higher temperatures can dissolve more minerals from rocks and leads to a higher electrical conductivity (Michaud, 1991). Water temperature also influences biological activity in a water body (e.g., a decrease in temperature leads to a decrease in dissolved oxygen).

Electrical Conductivity (EC)

Electrical conductivity is a measure of the ability of water to conduct an electrical current and is expressed in units of milliSiemens per meter (mS/m) or microSiemens per cm (μS/cm) (Gupta and Mrinal, 2013).There is a positive correlation between electrical conductivity and total dissolved solids (Gupta and Mrinal, 2013). Inorganic dissolved solids, negatively charged ions such as chloride, or positively charged ions such as aluminum can affect EC (Gupta, 2013). A higher EC value indicates the presence of conductive ions such as salts, metals, and total dissolved solids (Gupta and Mrinal, 2013).

Dissolved Oxygen (DO)

DO is an important water quality parameter as it is a measure of the concentration of dissolved oxygen in surface water; it is expressed in mg/L or % saturation. Swiftly flowing waters, such as mountain streams or rivers, usually have higher dissolved oxygen concentrations compared to stagnant water such as ponds (Michaud, 1991). Dissolved oxygen is necessary for aquatic organisms and DO measurements can indicate the health of a water body (Michaud, 1991).

pH

pH measures how acidic or basic an aqueous solution is, within a logarithmic range of 0 to 14 (pure water has a pH of 7.0 at 25 °C) (Michaud, 1991). Heavy metals become more soluble in solutions with lower pH, which can increase the metal toxicity (Michaud, 1991).

Oxidation-Reduction Potential (ORP)

ORP or Redox Potential is a measure of the system capacity to lose electrons and oxidize or acquire electrons and thereby be reduced (Bier, 2009). Large ORP values can indicate possible contamination by an excess contaminant such as chlorine (large positive ORP) or hydrogen sulfide (large negative ORP) (Bier, 2009).

Box Modeling

Hydrologic models are informative visual tools that can display a system of reservoirs and connected fluxes within a defined watershed (Singh and Frevert, 2005). Early hydrologic modeling was performed by Crawford and Linsley (1966) at Stanford University, who modeled the hydrologic cycle and its components. Over time, hydrologic models have become a major tool in providing a greater understanding of a watershed's hydrological, biological, ecological, socioeconomic, and environmental impacts and can be essential for integrated water resource management and decision making (Singh and Woolhiser 2002; Singh and Frevert, 2005). For the purpose of this thesis, a simple box model can be defined as a system with a central reservoir (the box) that receives inputs from distinct sources and simultaneously has an output (or sink) (Singh and Frevert, 2005). The term flux is defined as the transfer of material (such as water) from one reservoir to another. For example, during storm events precipitation represents a flux of water from the atmosphere to the Rim Trail tributary streams and their subwatersheds. The principle of conservation of mass is implemented in model simulations to budget each variable (Zhang et al., 2002). When "budgeting" water, the one common factor for all watersheds is that the total amount of water inputs, outputs, and storage in the system is conserved; change in storage (ΔS) = inputs − outputs (Singh and Frevert, 2005). Additionally, box models or water balances/budgets can act as tools for the assessment of water quality conditions and linking pollutants to receiving streams within a watershed (Arnold et al., 1998; James, 2004; Fargo, 2002; Sloto and Buxton 2005).

Sloto and Buxton (2005) utilized a box model approach to understand basin water budgets within five unique watersheds in the Delaware River Basin for water supply and water-use planning. This U.S. Geological Survey (USGS) study helped determine the feasibility of utilizing available data for water budgets in disturbed watersheds. The study defined a range of water systems based on urbanization and geological settings and notably defined a natural water system budget. The data used to develop each basin's box model were acquired from long-term hydrological and meteorological stations, as well as water regulatory agencies. In a natural water system budget, water inputs include precipitation (P) while outputs occur as streamflow (SF) (surface runoff plus groundwater discharge to streams) and evapotranspiration (ET). A classic water budget equation is used in the study with the following equation: $P = SF + \Delta S + ET$, (ΔS is defined as change in storage). Precipitation data were obtained from NOAA (National Ocean and Atmospheric Administration) precipitation gages in or near the basin watersheds. ArcGIS analysis was applied to quantify a number of water-budget components. The box model approach helped the study determine the allocation and comparison of inputs and outputs from five unique watersheds for urban planning.

A quantification of current and anticipated future water exports outside of the Bellamy River watershed in New Hampshire was explored by Fargo (2002). The report measured the water budget through an analysis of the hydrologic cycle and determined that key regional factors influence the apportionment of water in a watershed. Factors include land cover, land slope, soil permeability, and climate, and other fluxes such as evapotranspiration and transpiration which are generally approximated (Fargo, 2002). Through regional studies of large watersheds and smaller basins, estimates for water flow components have been developed within the Bellamy River watershed. Within the region, hydrologists estimated that half of Bellamy River precipitation returns to the atmosphere through evaporation and transpiration (Fargo, 2002). Evapotranspiration data from an upstream USGS gaging station at Oyster River was compared to and agreed with estimated total evapotranspiration losses in the watershed (Fargo, 2002). After an examination of historic regional precipitation records, the average annual input of water to the region was determined, and used to estimate the total water input of the watershed per year (Fargo, 2002). Average daily discharge of the Bellamy River was determined by multiplying river discharge by the watershed area. From the daily discharge estimate, the study calculated an average total annual discharge for years 1994-1999. The annual discharge for this period was approximately seven percent greater than the estimated annual river discharge based on a separate method using long-term precipitation data and evapotranspiration water loss. The study is a clear example of the use of a water budget to estimate fluxes and comparison of results using long term data sources. Comparable use of a water budget equation and analysis was used to help guide thesis research, such as the apportionment of fluxes at Malakoff Diggins.

Rational Method

The Rational Method is a simplistic method to estimate peak discharge from a storm event in drainage basins of up to 200 acres (Chow, 1964). The Rational Method was developed by Kuichling (1889) for small drainage basins in urban areas to understand the relationship between rainfall and sewer discharge. Peak discharge is calculated as the product of a dimensionless runoff coefficient c, rainfall intensity, and watershed drainage area. The Rational Method runoff coefficient c corresponded to the percentage of precipitation that runs off the ground surface during a storm event (the ratio of runoff to rainfall) (Hayes and Young, 2006). Runoff coefficients range from 0 to 1.0; a value of 0 indicates that none of the precipitation generates runoff while a value of 1.0 indicates that all of the precipitation falling produces runoff (Hayes and Young, 2006). Precipitation that does not become discharge can be lost to interception, transpiration, evaporation, infiltration, and depression storage (Hayes and Young, 2006). The coefficient can also vary with seasonal and antecedent moisture conditions (Hayes and Young, 2006). Previous literature and documentation shows that runoff coefficients for similar ground cover types are quite variable. Table 1 shows runoff coefficients from select sources that are comparable to an approximate runoff coefficient with Malakoff Diggins Rim Trail tributary subwatersheds. Runoff coefficient values were used as background information to help determine the most accurate runoff coefficient and provide additional information about potential water contribution towards Hiller Tunnel during storm events.

Purpose of the Study

The overall goal of this study was to quantify surface water discharge, metal concentrations, and sediment loads from the input Rim Trail tributary streams and at the Hiller Tunnel output to identify sources of surface water and contaminants for mine site remediation.

The following research questions were addressed:

1) How much instantaneous discharge do the Rim Trail tributaries (inputs) contribute towards the Hiller Tunnel (output) instantaneous discharge during storm events?

2) Does the surface water that enters and exits Malakoff Diggins Pit contain mercury, copper, nickel, and zinc in concentrations that exceed common regulatory criteria thresholds for surface water of California set by the Regional Water Quality Control Board?

3) How much total suspended sediment concentration and load do the Rim Trail tributaries contribute toward the Hiller Tunnel total suspended sediment concentration and load measurements?

4) What are the approximate storm event water budgets of the Rim Trail sub-watersheds using field measurements, box modeling, the Rational Method, and ArcGIS software?

TABLE 1. SELECT RATIONAL METHOD RUNOFF COEFFICIENTS

Source	Ground Slope	Ground Cover	Soil Type	Runoff Coefficient, c
USGS (Hayes and Young, 2006)	--	Forest	Variant on Hydrologic Soil Group A, B, C, D	0.25
California Department of Transportation [CADOT] (2006)	Hilly, 10-30%	Woodland	Well drained light or medium Cohasset cobbly loam textured soils	0.34
Knox County, TN Stormwater Management Manual (AMEC Earth & Environmental, Inc., 2008)	>6%	Forest	Variant on Hydrologic Soil Group A, B, C, D	0.14-0.25
Natural Resources Conservation Service [NRCS] (2013)	10-30%	Woodland	Sandy loam	0.30
Oregon Department of Transportation (ODOT) Hydraulics Manual (Shoblom, 2014)	Hilly, >10%	Woodland, forest	Variant on Hydrologic Soil Group A, B, C, D	0.20

CHAPTER III

METHODOLOGY

Study Design

The study consisted of multiple parts: a) quantified surface water discharge (ft^3/s) from upstream Rim Trail tributaries and Hiller Tunnel, b) measured metal concentration and total suspended sediment (TSS) (to calculate instantaneous TSS load in mg/s) at upstream Rim Trail tributaries and Hiller Tunnel to determine water quality, c) used delineated watersheds from ArcGIS software and the Rational Method to estimate storm event water budgets of the Rim Trail watersheds, and d) estimated storm event/sample day precipitation, surface runoff, evapotranspiration, and storage, as volumes (ft^3) at the Malakoff Diggins Rim Trail watersheds for box model analysis.

Sample Site Locations

In order to determine where tributary streams along the north rim flow and enter the Malakoff Diggins Pit, the Malakoff Diggins Rim Trail was hiked during a surface runoff event on 2/9/2014. The Rim Trail runs along the upper rim of the pit for 3.29 miles (5.29 km). Seven tributary streams had surface water discharge that traversed the Rim Trail and ran into the pit. Some of the streams sampled were ephemeral and only flowed in direct response to storm event precipitation while others were perennial and flowed all year (with varying discharge) and are fed by springs. Each stream was described with an 'R' in front to denote its Rim Trail location, a site description, and unique GPS coordinate. The GPS information was measured using a DeLorme Earthmate

PN-40 (accuracy of ± 10 meters or 32 feet). The GPS data were exported to ArcGIS for stream site mapping. Figure 2 shows the approximate stream sample locations on a map and Table 2 displays the GPS point data. Each Rim Trail tributary has a respective ArcGIS delineated watershed that influences outflow discharge. The largest-to-smallest watershed areas are as follows: R4, R2, R8, R7, R3, R5, and R6. To reduce measurement error from two streams converging, discharge and water sample measurements were taken at well-mixed steady flow locations. This sampling methodology technique was performed at all sampling sites, R1-R8 (R1 was later omitted – to be discussed below).

TABLE 2. TRIBUTARY SAMPLE LOCATIONS

Site ID	Datum: Google Earth GPS Point		Location
	Latitude	Longitude	
Hiller Tunnel	N 39.3674721°	W 120.9215818°	Hiller Tunnel outlet
R1	N 39.3674394°	W 120.9303578°	Southwest pit rim
R2	N 39.37365°	W 120.9259722°	Northwest pit rim
R3	N 39.3754963°	W 120.9234101°	North pit rim
R4	N 39.377836°	W 120.9192196°	North pit rim
R5	N 39.3817313°	W 120.9163756°	Northeast pit rim
R6	N 39.3826698°	W 120.9149545°	Northeast pit rim
R7	N 39.3834694°	W 120.9128177°	Northeast pit rim
R8	N 39.383464°	W 120.9100083°	Northeast pit rim

In accordance with the North Carolina Division of Water Quality (NCDWQ) *Methodology for Identification of Intermittent and Perennial Streams and their Origins* (2010), Rim Trail tributaries R2-R8 were evaluated for approximately a 100-foot (31 m) reach of each stream to determine stream characteristics and average conditions. Five stream geomorphic indicators were studied: continuity of channel bed and bank, sinuosity of the channel, stream headcut, particle size distribution of stream substrate (Wolman pebble count methodology as cited in Bevenger and King, 1995), and average channel dimensions (width and depth). The first four indicators were described with a magnitude – absent, weak, moderate, or strong – respective of the evaluated Rim Trail tributary and are defined in detail in NCDWQ (2010) (Table 3). Width and depth measurements (from 7 to 12 at each Rim Trail tributary based on storm event) were taken for each storm and averaged to get the tributary channel dimensions. These measurements are approximate as storm event surface runoff can modify stream width/depth and the observations were made during late season baseflow. Qualitative and quantitative results of the sample sites are described in the Results section.

TABLE 3. DEFINITIONS OF NCDWQ SCORING CATEGORIES

Category	Definition
Absent	The character is not observed
Weak	The character is present but you have to search for ten or more minutes to find and evaluate it
Moderate	The character is present and observable with one or two minutes of searching and evaluation
Strong	The character is easily observable and quickly evaluated

R1 is located on the southwestern side of the pit and flows over the Rim Trail. Topographic watershed analysis using ArcGIS showed that R1 discharge questionably contributed to Hiller Tunnel. To verify the ArcGIS-modeled runoff flow, R1 was hiked down its stream flow path, which revealed that it did not flow into the pit but rather below North Bloomfield Road. North Bloomfield Road runs between Malakoff Diggins Pit and Humbug Creek. The road acts as a partition that allows surface water runoff out of Hiller Tunnel to run into a second tunnel below the road, where it then flows towards downstream creeks. Because R1 does not flow into the Malakoff Diggins Pit it was omitted from hydrologic box models and certain research questions; however it may still contribute water towards Humbug Creek.

Water Quality Measurements

A one-time sampling of metal concentration, hardness, and total suspended sediment was taken from streams R1 (does not flow into pit), R2, R4, R5, R7, R8 and Hiller Tunnel on February 9, 2014, during storm conditions (Figure 4, Table 2). The sampling procedure carefully followed the Clean Hands Dirty Hands Method (EPA Method 1669) to ensure accuracy of measurement. Tributaries R3 and R6 were not sampled because of lower observed discharge. Samples were stored on ice and sent to Brooks Rand Labs (BRL) overnight, following BRL field sampling protocols (Brooks Rand Labs, 2014). Under EPA Method 1669, samples were kept cold to prevent biological activity and to halt chemical reactions. Water samples from 2/9/2014 (Hiller, R1, R2, R4, R5, R7, R8) were analyzed for total and dissolved aluminum (Al), arsenic (As), barium (Ba), beryllium (Be), calcium (Ca), chromium (Cr), copper (Cu), iron (Fe), mercury (Hg), magnesium (Mg), nickel (Ni), lead (Pb), and zinc (Zn) by Cold Vapor Atomic Fluorescence Spectrometry (EPA 1600 Series Method) and according to Brooks Rand Labs Standard Operating Procedures (SOPs) (USEPA, 2002). The EPA Method 160.2 was used to calculate TSS with a detection limit of 0.3 mg/L (USEPA, 1971). The

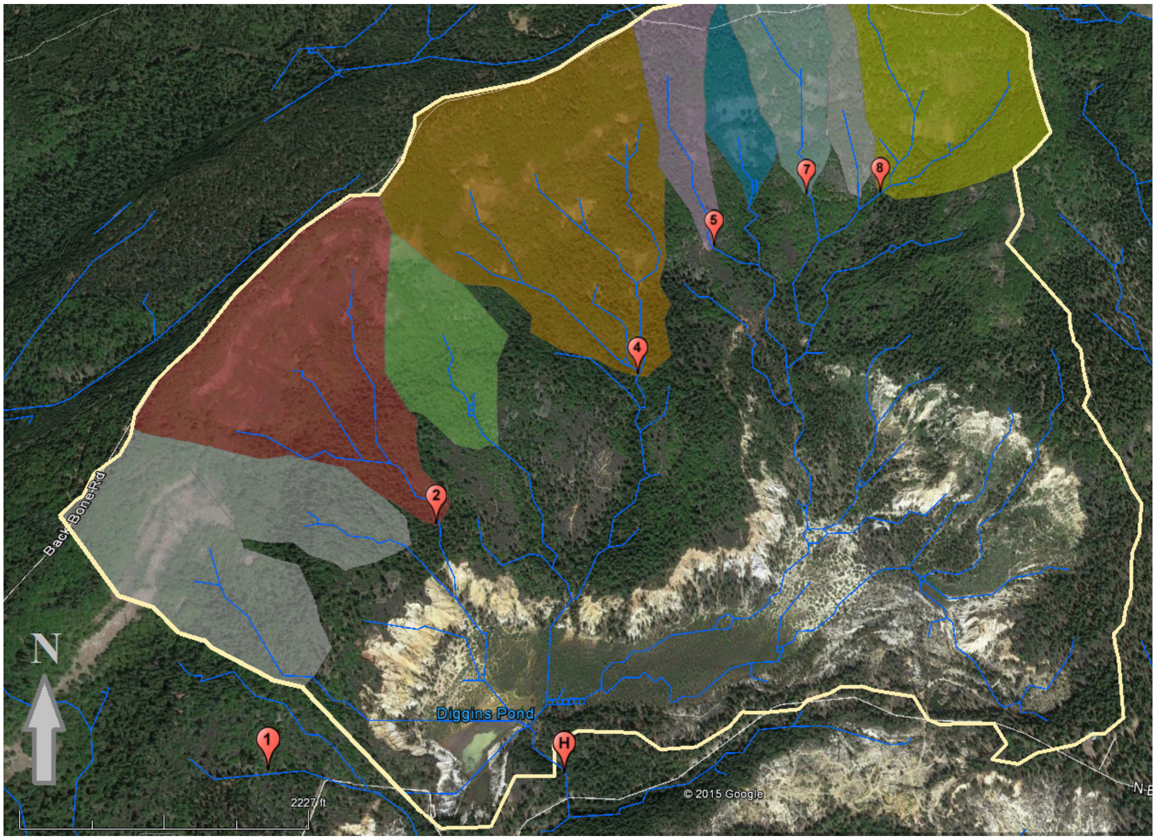

Figure 4. Malakoff Diggins Water Quality Sample Sites on 2/9/2014. Samples sites are shown in red and include Rim Trail sites 1, 2, 4, 5, 7, and 8 and Hiller Tunnel (H). ArcGIS projected water flow paths are shown in blue (Google Earth, 2015).

hardness (mg eq $CaCO_3$/L) of the water samples was calculated using the measured concentrations (mg/L) of calcium and magnesium with Standard Method (SM) 2340 B (American Public Health Association [APHA], 2005). The Hiller Tunnel total method detection limit (MDL) was 2.88 mg eq $CaCO_3$/L while the tributary total MDL ranged from 0.16 to 0.29 mg eq $CaCO_3$/L. The MDLs and the method reporting limits (MRLs) for the metals of interest are shown in Table 4. As seen in the table, the reported MRLs are well below their respective CTR MCLs, allowing for an accurate water quality assessment.

TABLE 4. METHOD DETECTION LIMITS AND METHOD REPORTING LIMITS: MERCURY, COPPER, NICKEL, AND ZINC

Metal	Method Detection Limit (MDL)	Method Reporting Limit (MRL)
Mercury	0.15 ng/L	0.40 ng/L
Copper	0.42 µg/L	1.3 µg/L
Nickel	0.42 µg/L	2.1 µg/L
Zinc	0.060 µg/L	2.1 µg/L

EPA Method 1669 is an EPA standard protocol for water sampling, filtration, and measurement for the purpose of determining total and dissolved metals. The protocol applies to a number of metals including mercury, nickel, zinc, and copper (USEPA, 1996b). Water samples that are not filtered for particulates and sediment are used for total metal analyses (USEPA, 1996b). Total metal concentration is the sum of the dissolved metal and the particulate-bound metal concentrations (USEPA, 1996b). Water samples that are filtered with a 0.45µm pore diameter membrane filter do not contain particulates or sediment and are used for dissolved metal analyses (USEPA, 1996b). The particulate-bound metal concentration is determined by subtracting the dissolved metal concentration from the total metal concentration.

On five sampling days, 2/9/2014, 3/2/2014, 3/30/2014, 12/13/2014, and 2/8/2015 (Table 5), a YSI 556 Multi-Probe System (MPS) was used to record temperature, electrical conductivity (EC), dissolved oxygen (DO), pH, and oxidation-reduction potential (ORP) of surface water discharge at R1-R8 and at Hiller Tunnel. Periodically, over the course of the study, the YSI 556 MPS was carefully calibrated (based on a 3-point calibration using buffer solutions at pH 7, 4, and 10) to ensure greater measurement accuracy in the field (YSI Inc., 2010).

TABLE 5. SAMPLE DAY METHODOLOGY

Storm Event	Sample Date	Water Quality		Discharge Measurements
		Grab Samples	Measurements	
1	2/9/2014	Yes	Yes	Yes
2	3/2/2014	No	Yes	Yes, (R2, R3)
3	3/30/2104	No	Yes	Yes
4	12/13/2014	No	Yes	Yes, (R3)
5	2/8/2015	No	Yes	Yes, (R6)

Note: Tributaries not measured for discharge during a storm event are denoted within parentheses.

Total Suspended Sediment Load Measurements

Total suspended sediment was measured from grab samples taken from streams R1, R2, R4, R5, R7, R8 and Hiller Tunnel on February 9, 2014. Brooks Rand Labs analyzed each sample for TSS using method EPA 160.2. In brief, the method filtered a homogenous grab sample through a glass fiber filter and the remaining residue on the filter was then dried (USEPA, 1971). Errors introduced in this sampling method are defined briefly. The total suspended sediment concentration sampled is assumed to represent the entire stream flow section. The grab sample method does not assess the portion of bedload-transported downstream. Disturbance of the stream regime can occur with water samples and high variance in stream discharge can affect sediment mobility and concentration measurements.

The total instantaneous suspended sediment load was calculated with sample day one measured discharge according to the relationship: Sediment concentration (mg/L) * tributary discharge (L/s) = total suspended sediment load (mg/s). The TSS (mg/L) was multiplied by the measured stream discharge (L/s) to obtain an instantaneous TSS load (mg/s or kg/s).

Surface Water Discharge Measurements

Surface water measurements of the input Rim Trail streams and the output Hiller Tunnel stream were made on five sample days using the velocity-area methods (Buchanan and Somers, 1969; Hach, 2014) (Figure 5). A highly sensitive flowmeter (Hach Portable Velocity Meter FH950 flowmeter) was used to measure water velocity (ft/s). Surface flow is quantified as discharge, defined as the volume of water that passes through a channel cross section in a specific period of time (Buchanan and Somers, 1969; Olson and Norris, 2007). The product of section stream velocity (v) and section stream area (A) (depth times width) is equal to the respective sectional discharge (Q) in cubic feet per second (ft^3/s or cfs) of the stream (Figure 5). The sum of the sectional discharge measurements taken in a single cross section equals the total stream discharge (Buchanan and Somers, 1969; Olson and Norris, 2007).

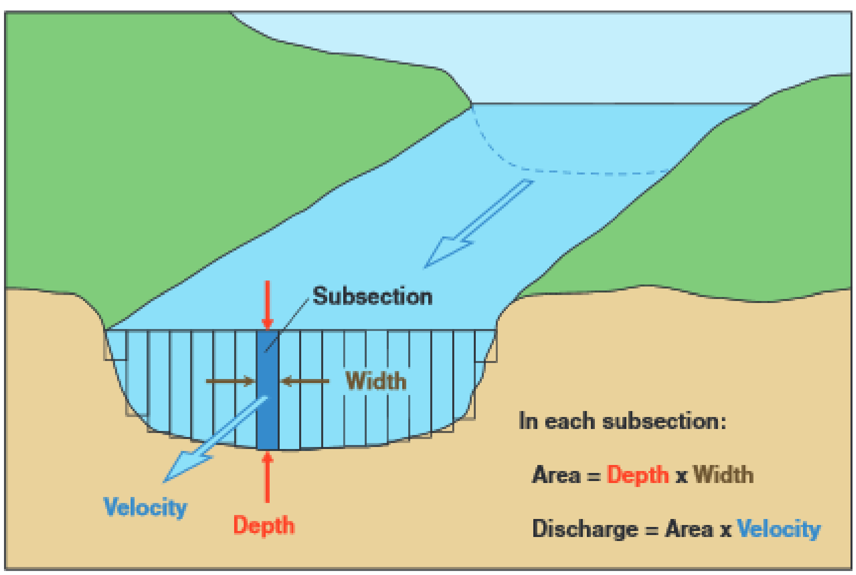

Figure 5. Conceptual Model: Velocity-Area Methodology (U.S. Geological Survey Streamgaging, Olson & Norris 2007).

To get accurate velocity-area readings, stream sections that had uniform water levels were chosen with as few rocks and debris in the flow path, but where all of the flow was present, and not in a side channel (Buchanan and Somers, 1969; Rantz et al., 1982). Subsections of each stream (ten for more precision) were chosen based on the total width of the stream. The height from the stream bottom to water surface of each subsection was recorded by using the top setting wadding rod. In waters less than 2.5 feet (0.76 m) deep, mean stream velocity measurements were taken at 60% of the stream depth below the water surface (Rantz et al., 1982). For each velocity measurement, the flowmeter sensor was adjusted to 60% of the depth for each subsection and was carefully faced upstream into the flow. After a stable sensor reading of velocity, data were recorded in a field notebook and repeated for each subsection. To determine the total stream discharge, the stream subsection discharges were summed.

Rain Gages and Precipitation

The Department of Water Resources' California Data Exchange Center (CDEC) Our House Dam (OHD) weather station, located within the Yuba River Basin four miles (6.4 km) northeast of Malakoff Diggins, reports long term accumulated and incremental precipitation (DWR, 2015a). The OHD gage, a Vaisala Model 444B tipping bucket, was located approximately at latitude N 39.41200° and longitude W 120.99640° at an elevation of 1,960 feet (597 m). The Vaisala Model 444B tipping bucket rainfall resolution is 0.04 inches while accuracy is stated to be ±3.0% (up to 4.0 inches/hour) (Vaisala, Inc., 2000). Precipitation and temperature data were available from 12/19/2006 and were accessible on the CDEC website (DWR, 2015a). For box modeling purposes, Our House Dam precipitation data were used to approximate precipitation inputs within the Malakoff Diggins watershed. The OHD data were used to fill in data gaps during WY 2014 (sample days one, two, and three) because a closer secondary gage within the Malakoff Diggins Pit was not active during these dates.

In addition to the OHD rain gage, a tipping bucket rain gage, HOBO Data Logging Rain Gage (Onset Part No: RG2), was placed in the Malakoff Diggins Pit to record WY 2015 precipitation. The HOBO gage rainfall resolution is 0.01 inches while accuracy is stated to be ±1.0% (up to 1.0 inches/hour) (Onset Computer Corporation, 2015). The gage was located approximately at latitude N 39.371667° and longitude W 120.910278° at an elevation of 3,158 feet (963 m) (Figure 2). The HOBO gage recorded precipitation from 11/11/14 to 3/15/15, which includes sample day four and five.

Evapotranspiration

For the purpose of this study, evapotranspiration or ET is defined as the evaporation of water from the ground surface soils, as well as plant interception and transpiration (Hanson, 1991; Brooks et al., 2012).

The study used reference evapotranspiration data from the California Irrigation Management Information System (CIMIS). The statewide CIMIS system uses over 145 computerized weather stations and remote satellite data to calculate daily ET values throughout California. Yet, because California has diverse regions and climates, many locations lack true representation of ET. Spatially distributed ET values or ET maps (ET Zones Map) allow for reference evapotranspiration to be estimated across California regional boundaries. CIMIS Reference Evapotranspiration Zones for the State of California (1999) was created by DWR and UC Davis using five years of archived monthly average ET data. The map divides California into 18 zones; Malakoff Diggins lies within the Northern Sierra Nevada zone (Zone 13). The referenced ET months for the study include February (1.96 inch/month), March (3.10 inch/month), and December (0.93 inch/month). The map notes that up to a 0.02 inches/day variability can occur during winter months (December, January, February in the Northern Hemisphere) in Zone 13.

Hydrologic Modeling: ArcGIS Software

ArcGIS, a geographic information system, was used to calculate hydrologic flow in watersheds based on an input of precipitation and other factors. ArcGIS 10.2.2 was utilized to better quantify tributary watershed discharge and ultimately Hiller Tunnel discharge. ArcGIS computerized watershed and drainage delineation (Parmenter and Melcher, 2012), used 2-foot contour LiDAR data, sample GPS points, and Spatial Analyst: Hydrology tools to quantify each watershed's discharge. Parmenter and Melcher (2012) details the tools and delineation process in *Watershed and Drainage Delineation by Pour Point in ArcMap 10*. LiDAR data and aerial photography of the Malakoff Diggins and Humbug Creek watersheds were collected by the USGS-and accessed in December 2014.

The Hiller Tunnel watershed was divided into seven smaller hydrological connected watersheds (R2-R8) and three (A, B, and C) non-measured watersheds using the watershed delineation tool in ArcGIS. Based on this delineation, surface water discharge during a storm was estimated with box model methodology. The calculation of each watershed's contributing discharge provided a greater understanding of where storm surface discharge had the power to mobilize and transport sediment from Malakoff Diggins Pit to Hiller Tunnel.

After delineation of the measured Rim Trail watersheds, gaps between watersheds existed within the Hiller Tunnel watershed (Figure 2). Projected streamlines based on topography from ArcGIS showed that these areas had potential contributing drainages to the Malakoff Diggins Pit. These non-measured watersheds were important to acknowledge as they also contribute to the mobilization and transport of sediment within the pit. Using the Rational Method and hydrologic box model methodology, these select non-measured watersheds were compared to measured watersheds. Instantaneous peak discharges were compared between the measured and non-measured watersheds (of similar areas and slopes) for storm events four and five. The measured non-measured watershed pairings are: R7 with A, R5 with B, and R6 with C. The instantaneous peak discharges of non-measured watersheds A, B, and C were extrapolated over their respective storm events and volumes were determined based on the paired comparisons with neighboring watersheds. In all, non-measured watersheds addressed data gaps at areas above the pit and helped by providing additional information about potential water contribution towards Hiller Tunnel.

Data Analysis

Discharge Measurements

Surface water discharge (Q) was determined with a velocity-area methodology (Buchanan and Somers, 1969; Olson and Norris, 2007) and is calculated by the following summation formula:

$$Q = \sum(v \times A) \quad (1)$$

where Q is the total discharge (measured in ft^3/s or cfs) and summation of velocity-area measurements, v is the time-averaged velocity (ft/s) of water taken at 0.6 of the water level depth (measured by a Hach Portable Velocity Meter FH950 flowmeter), and A is the area (ft^2) of the cross-section (calculated by multiplying width of the cross-section with the stream depth).

The stage-discharge relationship was developed by The Sierra Fund in the Humbug Creek Watershed Assessment and Management Recommendations in April 2015 (TSF, 2015). The discharge at Gage 3 on Humbug Creek, 100 feet (30 m) below the confluence with Diggins Creek (Figure 6), was calculated to develop a stage-discharge

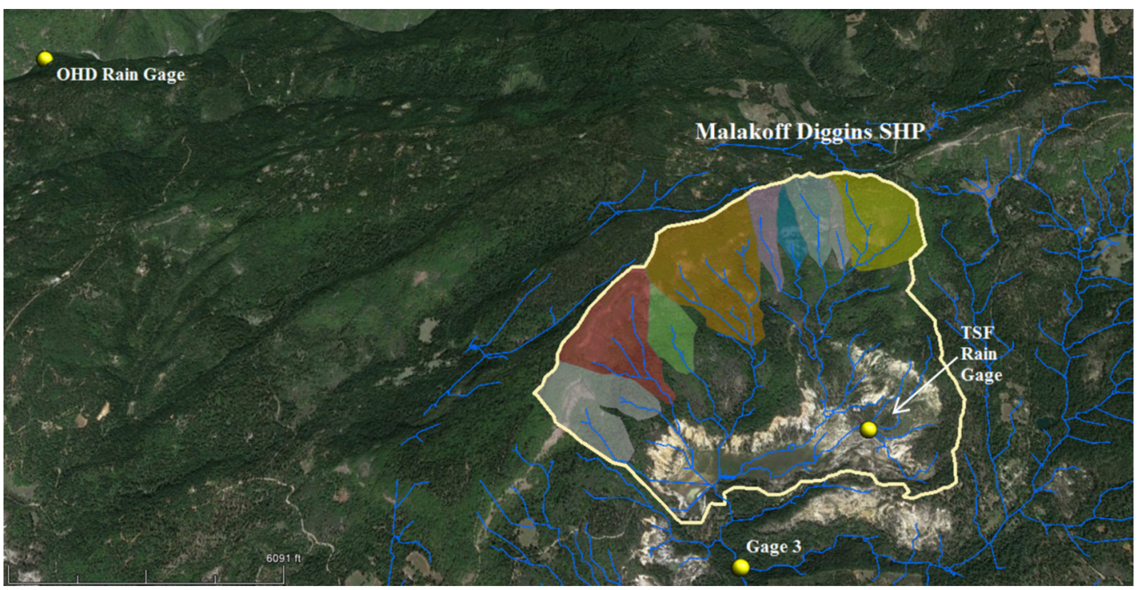

Figure 6. Approximate Gage Locations: OHD Rain Gage, TSF HOBO Rain Gage, and Gage 3.

relationship with the following formula:

$$Y_Q = MX_S + C \quad (2)$$

where Y_Q is the calculated discharge, X_S is the stage reading of the pressure transducer data logger, and M and C are constants derived from the relationship. The stage-discharge relationship was used to calculate discharges for WY 2014 and WY 2015 during sample day storm events. The nine paired pressure readings and discharge measurements collected during WY 2012, WY 2013, and WY 2014 were evaluated in the statistical program R; discharge ranged from 2-18 ft^3/s during the collection period (TSF, 2015). A pressure transducer at the Humbug Creek gage site (Gage 3) was programmed to take measurements every 15 minutes. Pressure readings were adjusted, to account for sediment build up after large storms. The gage pressure readings were also adjusted after the gage was cleaned between water years, inside the pressure transducer meter casing (makeshift stilling well). The adjustments between water years were to make summer baseflow approximately 3 cfs. During WY 2012, 0.46 psi was subtracted after large spring storms for 3/26/2012-4/27/2012 (TSF, 2015). During WY 2013 0.169 psi was added for 10/1/2012-9/30/2013 because the meter had been previously elevated by sediment in WY 2012 (TSF, 2015). The adjusted stage-discharge relationship developed by TSF (2015) $y = 14.03x + 0.58$, ($n = 9$, $R^2 = 0.57$) where y is the discharge and x is the stage reading of the pressure transducer, was used to align a new stage discharge relationship for this study during WY 2014 and WY 2015.

Instantaneous Total Suspended Sediment Load

The instantaneous total suspended sediment load for R2, R4, R5, R7, R8 and Hiller Tunnel during a single storm event on 2/9/14 was calculated. The calculation shows how much total suspended sediment load the tributaries contribute towards the Hiller Tunnel load result. The bedload is not included in the TSS_i calculation.

Instantaneous Total Suspended Sediment Load (mg/s) is calculated by the following formula:

$$TSS_i = [TSS_i] \times Q_i \qquad (3)$$

where TSS_i is the instantaneous total suspended sediment load (mg/s) on the i^{th} sample day, $[TSS_i]$ is the total suspended sediment concentration (mg/L) as sampled on the i^{th} sample day (analyzed by Brooks Rand Labs), and Q_i is the instantaneous discharge (L/s) on the i^{th} sample day.

Rational Method

The Rational Method was used to determine the potential non-measured watershed discharge. After a non-measured watershed’s peak discharge was determined, it was correlated with Humbug Creek’s hydrograph and the discharge was extrapolated over its respective storm event based on a relationship coefficient between the tributary discharge and the calculated continuous discharge at the TSF gage on Humbug Creek (Gage 3 site). Ultimately, the discharge was determined for each non-measured watershed during the storm event based on the relationship to the calculated discharge downstream in Humbug Creek and the watershed area. Relevant associated assumptions and limitations of this methodology include: precipitation is uniformly distributed over each drainage area, precipitation intensity is constant throughout the storm event, and basin storage effects are negligible (Hayes and Young, 2006).

In the Rational Method, discharge is calculated by the following formula:

$$Q = c\ i\ A \quad (4)$$

where Q is the peak discharge (ft^3/s), c is the Rational Method runoff coefficient (dimensionless), i is the rainfall intensity (inches/hour), and A is the watershed drainage area (acres).

Data from sample days four and five were used to determine potential non-measured watershed discharge. Sample days four and five were presumably more accurate than sample days one, two, and three because the rainfall intensity data came from the local rain gage within Malakoff Diggins Pit (Onset HOBO Data Logging Rain Gage RG2). The instantaneous discharge measured at the Rim Trail tributaries on sample days four and five were aligned with Humbug Creek's calculated discharge (fifteen-minute intervals) at a matching time interval. The instantaneous discharge field measurements for the subwatersheds were extrapolated over the storm event time, assuming they followed Humbug Creek's hydrograph pattern and response to rainfall. After the subwatershed/tributary discharge was extrapolated for the storm event, peaks in discharge were noticeably visible. An instantaneous peak discharge, Q, (ft^3/s) from each measured tributary during the sample day was identified. This instantaneous peak discharge was input into the Rational Method to back calculate a runoff coefficient c for its respective watershed during that sample day. Based on runoff coefficient factors, hydrologic soil group and ground slope, the optimal runoff coefficient for the sample day was determined. An associated c coefficient was generated for each storm event for each measured Rim Trail watershed. Since the calculated c values were low (<0.1) in comparison to reviewed Rational Method c value literature, the greatest c value of the storm event was chosen to be representative of the other measured watersheds. The optimal c value (assuming each watershed had the same c value) was input in the Rational Method to calculate peak discharge Q for non-measured watersheds A, B, and C for sample days four and five. This optimal c value was chosen to represent all the Rim Trail subwatersheds based on similarity in localized watershed characteristics such as soil type, slope, adjacency, location of precipitation, and canopy type. After each non-measured watershed peak discharge was determined, this peak discharge was plotted and correlated to align with the Humbug Creek's peak discharge during the storm event. Each non-measured watershed's instantaneous discharge point was then extrapolated over the storm event and a volume of total discharge for that non-measured watershed was determined.

Box Model Analysis

Box models were utilized for this study at Malakoff Diggins to estimate storm event water budgets for the Rim Trail subwatersheds. A box model for each Rim Trail watershed (R2-R8 and non-measured A, B, C) was determined using the formulas below. The conceptual hydrologic model (Figure 7) assumed that there was no artificial water supply or output water use such as drinking and agricultural use. Groundwater flow inputs and outputs to each watershed were not quantified since they were difficult to measure and were grouped under the storage term ΔS to simplify box model volume estimates.

- ❑ Measured discharge from tributary:

$$A_{Rwshed} P_i = R_{QMi} + A_{Rwshed} ET + \Delta S \quad (5)$$

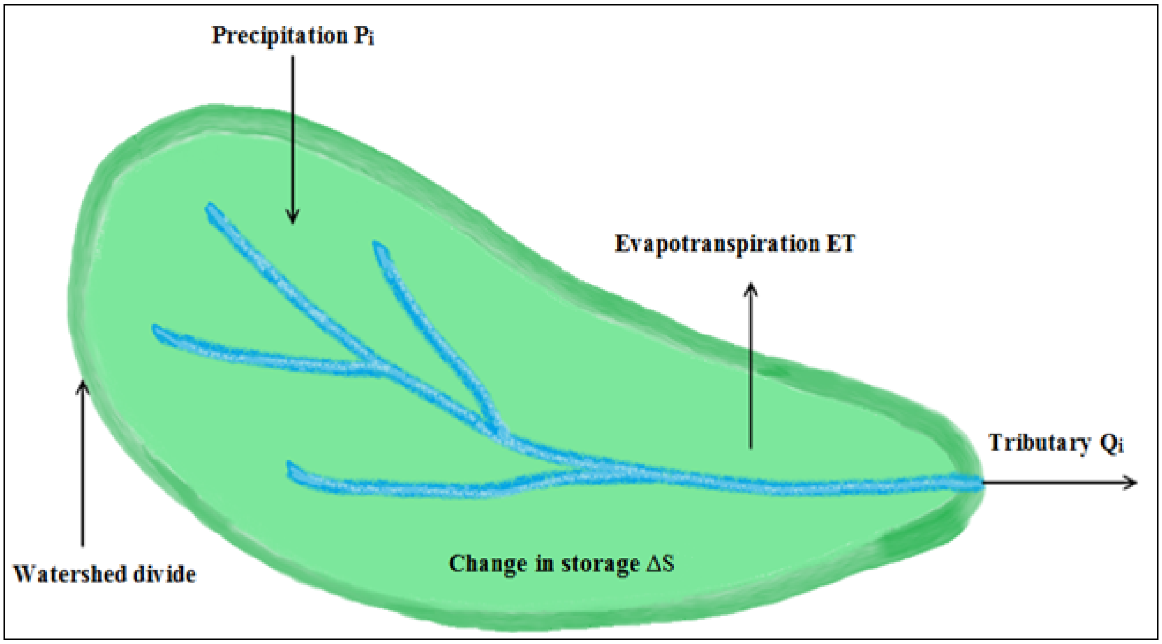

Figure 7. Conceptual Model: Hydrologic Box Model of Rim Trail Tributary Watershed (Modeled after figure from Chow et al., 1988).

- ❑ Non-measured discharge from tributary:

$$A_{Rwshed} P_i = R_{QNi} + A_{Rwshed} ET + \Delta S \tag{6}$$

where:

i = sample dates (1, 2, 3, 4 or 5)

A_{Rwshed} = area of Malakoff Diggins tributary (R) watershed (ft^2)

P_i = precipitation of tributary (R) watershed area, for the i^{th} Malakoff Diggins sample day (ft)

R_{QMi} = stream discharge from Rim Trail tributaries R2-R8 for the i^{th} Malakoff Diggins sample day (ft^3

R_{QNi} = stream discharge from non-measured Rim Trail tributaries A-C for the i^{th} Malakoff Diggins sample day (ft^3)

ET = evapotranspiration from tributary watershed area, the sum of land surface evaporation plus plant transpiration (ft^3)

ΔS = storage in tributary watershed area; change in groundwater and soil water (ft^3)

For example, the measured discharge R2 box model on sample day one is defined as $A_{R2wshed} P_1 = R_{2M1} + A_{R2wshed} ET + \Delta S$.

CHAPTER IV

RESULTS

Sample Site Locations

Channel characterization at sample site locations (R1-R8) is described by five stream geomorphic indicators: continuity of channel bed and bank, sinuosity of the channel, stream headcut, particle size distribution of stream substrate (Wolman pebble count), and average channel dimensions (width and depth). These features were evaluated and are presented in Table 6. Categorical determinations of respective features, such as strong, moderate, weak, or absent are defined in Table 3. Additional text descriptions are included to further distinguish sample site locations.

R1 is located on the southwestern side of the pit and flows over the Rim Trail. This stream does not contribute water to the Malakoff Diggins Pit and instead flows below North Bloomfield Road.

R2 is a tributary located at the northwestern side of the pit and the R2 watershed is 93 acres. The R2 sample point is the closest to the pit and the Hiller Tunnel inlet; ArcGIS flowpath analysis estimates a distance of 2,150 feet (655 m) between R2 and Hiller Tunnel. When R2 discharge was observable, its source was from precipitation and sometimes from a nearby spring; water flowed out from the side of the hillslope and down into the stream bank during more than one storm event. The R2 sample point has a high percentage of canopy cover (which is also seen at R3, R4, R5, and R6).

TABLE 6. CHANNEL CHARACTERIZATION: R1-R8

Tributary	Channel bed continuity	Sinuosity	Headcut	Sediment size distribution	D_{50} (mm)	D_{16} (mm)	D_{85} (mm)	Stream width (ft)	Stream depth (ft)
R1	Moderate	Strong	Strong	Strong	110	70	210	2.0	0.2
R2	Strong	Moderate	Strong	Strong	100	40	160	1.6	0.17
R3	Strong	Weak	Strong	Strong	70	30	150	2.0	0.3
R4	Strong	Moderate	Strong	Strong	200	80	500	2.6	0.5
R5	Strong	Moderate	Moderate	Strong	200	120	360	1.9	0.12
R6	Weak	Absent	Weak	Weak	50	30	100	2.1	0.1
R7	Strong	Moderate	Moderate	Strong	120	80	180	1.4	0.13
R8	Strong	Strong	Moderate	Strong	100	80	180	1.5	0.19

R3 is a stream located north of the pit and the R3 watershed area is 34 acres. R4 is located north of the pit, about 200 feet southeast of the Rim Trail. The site is situated immediately after two upstream flows merge. The R4 watershed area is 93 acres.

R5 is located farther north of the pit, downstream of a small pool of standing water that can be seen from the Rim Trail. Water (possibly from the small pool) is exfiltrated downslope out of the soil from small ground water channels (perhaps from macropores) to form the tributary. This transport of water is indicative of a preferential flowpath. These channels limit the amount of water released from the standing pool of water, and ultimately what moves downstream into the Malakoff Diggins Pit. The R5 watershed area is 30 acres.

R6, located northeast of R5, uses the Rim Trail landscape as a flow path for about 200 feet and then flows south. The R6 watershed area is 18 acres.

R7 is located far northeast of the pit at a location where a small upper stream flows down and over the Rim Trail. Except for R8 (with comparable canopy), the R7 sample point has a qualitatively lower canopy cover in comparison to the rest of the tributaries. Likewise, the R7 and R8 streams are similar in slope and steeper than the other streams. The R7 watershed area is 37 acres.

R8, the most northeast sample location, is a tributary that flows over the Rim Trail. The R8 watershed area is 96 acres.

Rain Gages and Precipitation

Water Year 2014 was a dry year as defined by the Sacramento River Index for the Malakoff Diggins region (State Water Resources Control Board [SWRCB], 1995).

The Our House Dam (OHD) precipitation data showed three major storm events (Figure 8). Sample day one (February 9, 2014) was performed on the largest storm of the water year while sample day two (March 2, 2014) and three (March 30, 2014) were performed at the end of a chain of smaller storms. The OHD rain gage during the study recorded precipitation of 8.0 inches (20 cm) on sample day one, 2.7 inches (6.9 cm) on sample day two, and 2.7 inches (6.9 cm) on sample day three. The OHD rain gage recorded a maximum of 23.61 inches (60.0 cm) of rain during WY 2014.

During the Water Year 2015 study period, sample days four (December 13, 2014) and five (February 8, 2015) were conducted during relatively intermediate storm events. The HOBO rain gage recorded 4.6 inches (12 cm) on sample day four and 5.3 inches (14 cm) on sample day five (Figure 9). The HOBO rain gage recorded a total of 30.14 inches (76.56 cm) during its operation from November 11, 2014 to March 13, 2015.

The Our House Dam rainfall data for WY 15 were compared to the HOBO rain gage for the time period for which there were data from both, 11/11/2014 to 3/15/2015 (Figure 10). The HOBO rain gage data were interpolated to match the time resolution of the OHD gage, where data were taken every 15 minutes. The interpolated HOBO data were graphically correlated with the OHD data to determine a relationship. For this time period, the two data sets had a strong linear correlation; $R^2 = 0.971$ and $p < 0.001$ with an equation $y = 1.42x$, where y is the HOBO rain gage precipitation and x is the OHD rain gage precipitation (Figure 11). It can be seen from Figure 11 that the correlation $y = 1.42x$ is notably best for the smaller storm events (accumulated

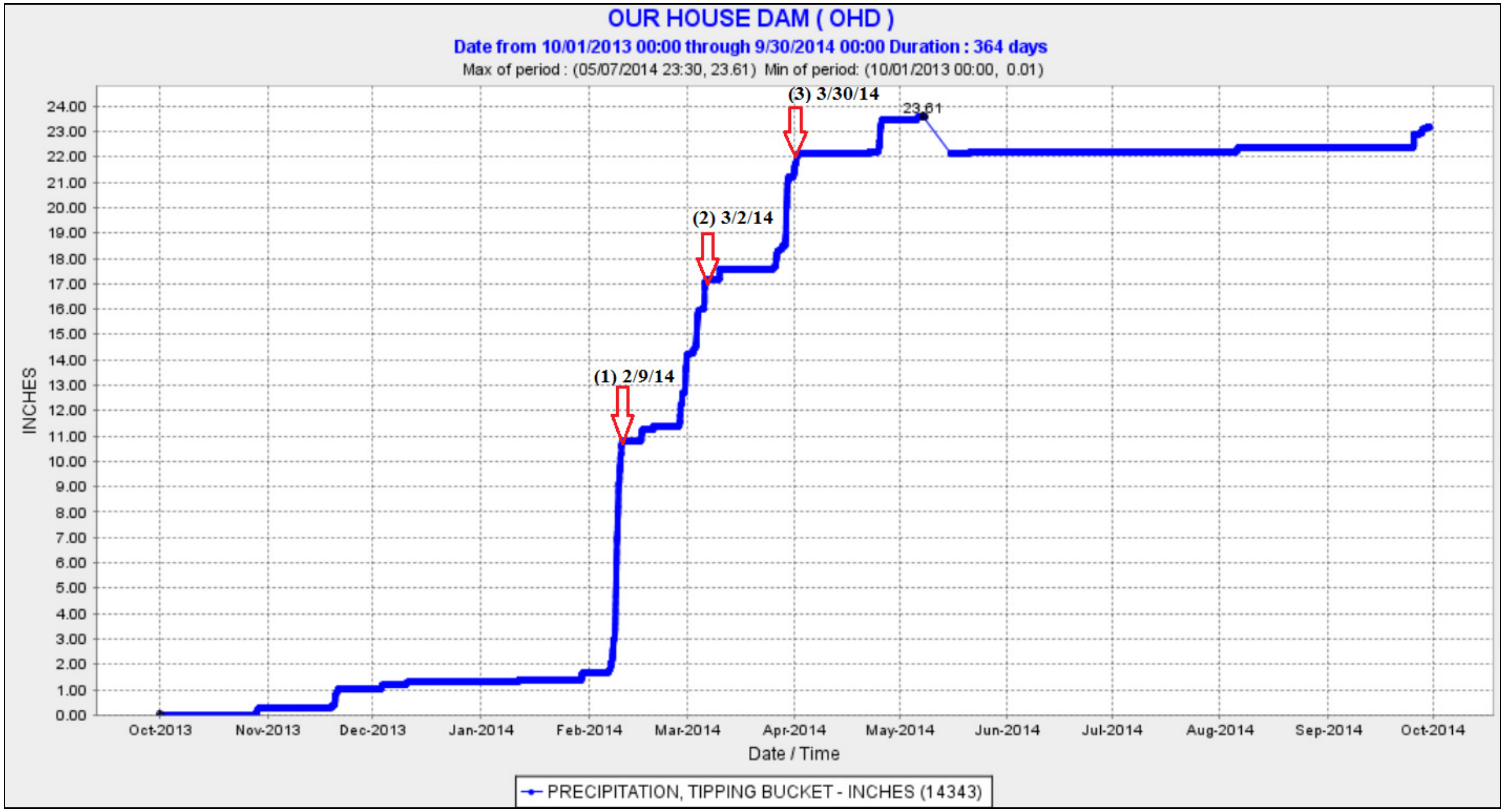

Figure 8. Our House Dam, CA hydrograph for WY 2014 (10/1/2013 – 9/30/2014). Shown is the accumulated precipitation (inches) for sample days 1, 2, and 3.

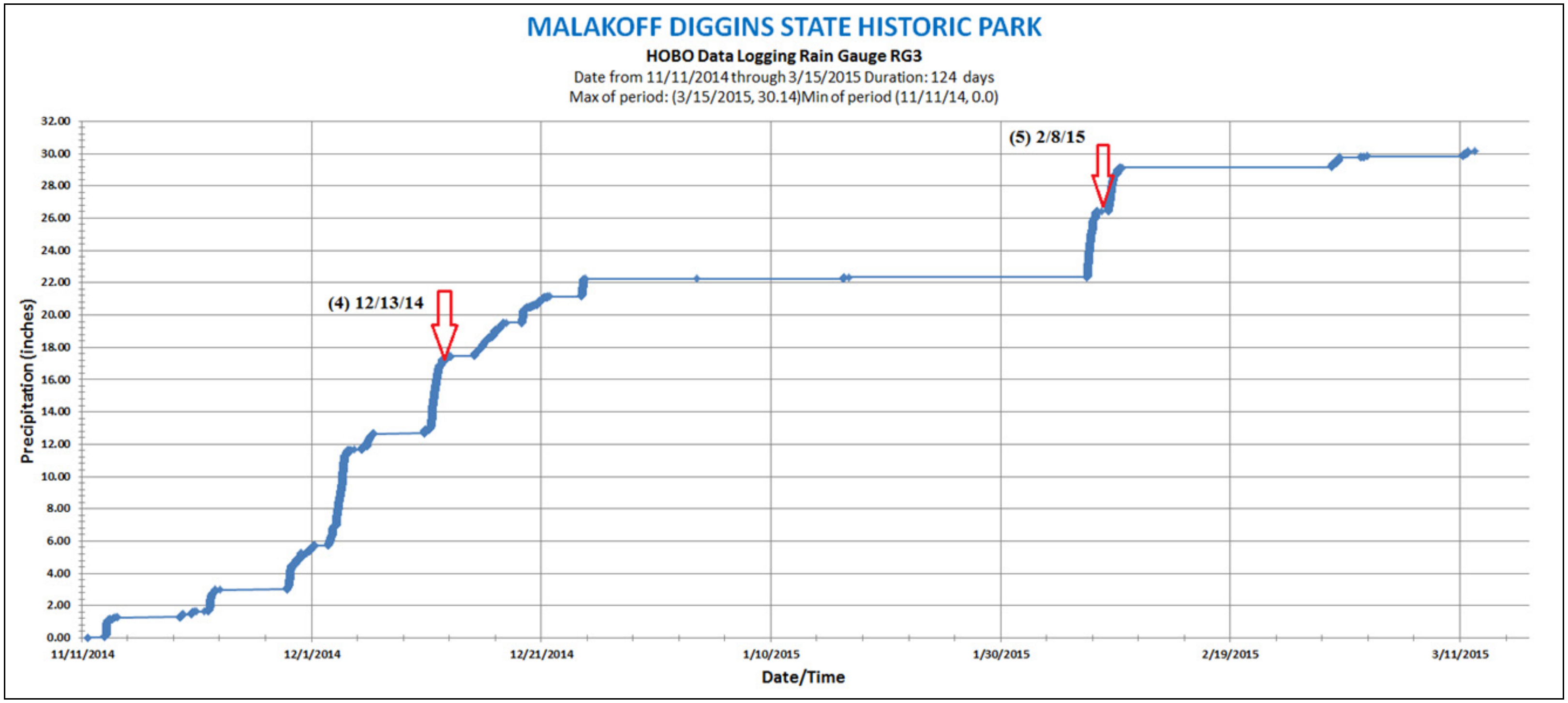

Figure 9. Malakoff Diggins SHP, CA Hydrograph For WY 2015 (11/11/2014 – 3/13/2015). Shown is the accumulated precipitation (inches) from The Sierra Fund tipping bucket rain gage for sample days 4 and 5.

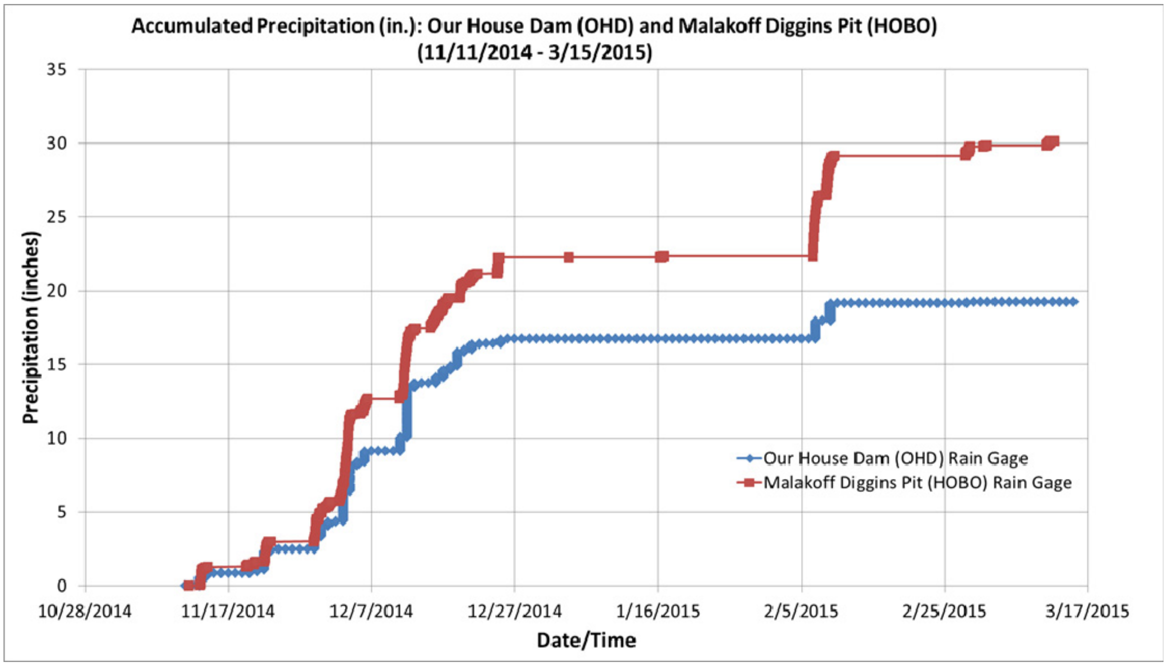

Figure 10. Hydrograph comparison: OHD rain gage vs HOBO rain gage (11/11/2014-3/15/2015). Shown is accumulated precipitation (inches).

precipitation up to 16.7 inches at OHD and 22.5 inches at HOBO) (Figure 11). For the large storm in early February 2015 (Figure 10) it can be seen that the precipitation rate at the HOBO site increased relative to that of the OHD site (Figure 11). Overall, the HOBO rain gage showed consistently higher (approximately 1.42 times) accumulated precipitation than the OHD rain gage over the time period (Figure 11). The OHD data for storm events 1, 2, and 3 were adjusted (by using the slope of the y = 1.42x equation) to better estimate storm event conditions at the Malakoff Diggins Pit for the previous water year (WY 2014). Respective storm event accumulated precipitation from the first three storm events were denoted as *Adjusted* (Table 7) and used for box model and overall study analysis.

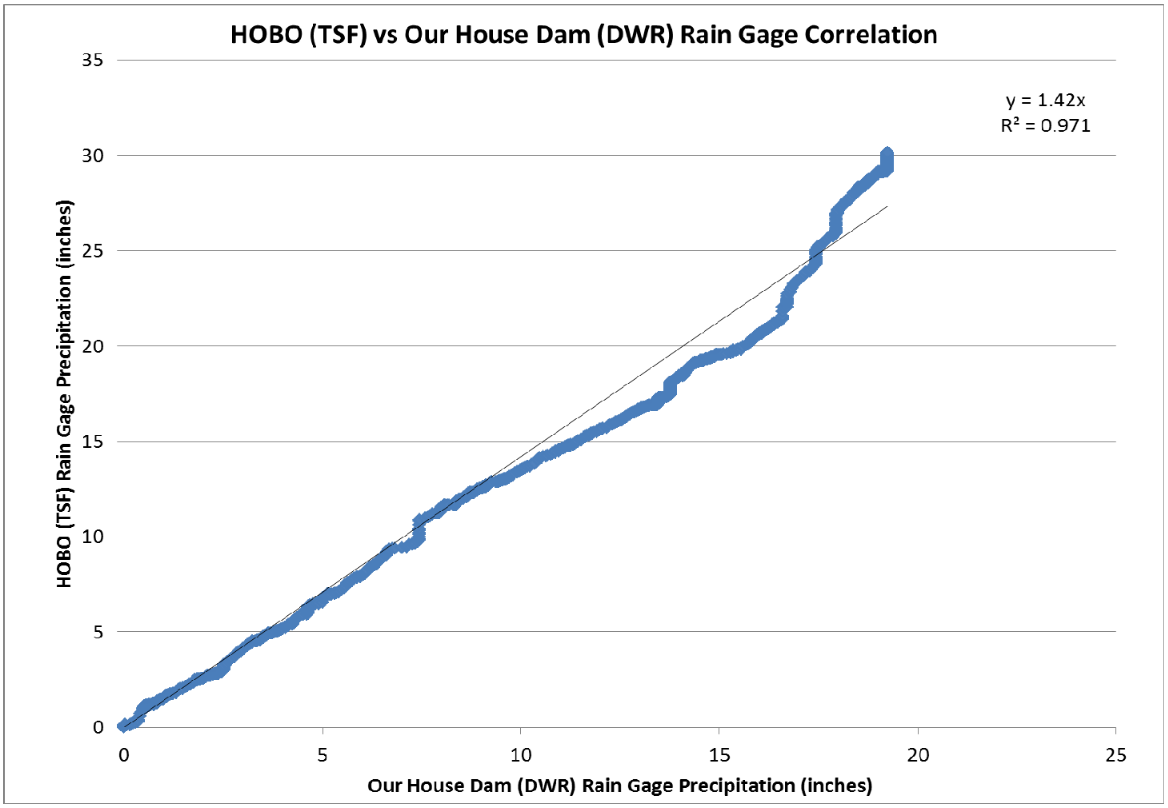

Figure 11. Rain gage correlation: OHD rain gage vs HOBO rain gage (11/11/2014-3/15/2015).

TABLE 7: MALAKOFF DIGGINS STORM EVENTS & PRECIPITATION

Sample Day	Storm Event Start	Storm Event End	Storm Event Approximate Duration (hr)	Storm Event Total Precipitation (inches)	Storm Event Total Precipitation (inches) *Adjusted*
1	2/6/2014 8:00 PM	2/9/2014 3:00 PM	67	8.0	11.4
2	2/26/2014 9:00 PM	3/2/2014 3:00 PM	90	2.7	3.8
3	3/29/2014 3:00 AM	3/30/2014 3:00 PM	36	2.7	3.8
4	12/11/2014 7:00 AM	12/13/2014 3:00 PM	56	4.6	--
5	2/6/2015 1:00 PM	2/8/2015 3:00 PM	50	5.3	--

The cumulative precipitation up to each storm sampling event is shown in Table 8, with the precipitation values for storm events 1, 2, and 3 adjusted to be consistent with the relationship between the OHD and HOBO gages. Storm event one (2/9/2014) had the least precipitation before its occurrence. Storm event three had the greatest precipitation before its occurrence (based on an adjusted cumulative precipitation value).

TABLE 8: CUMULATIVE STORM EVENT PRECIPITATION

Storm event	Station/rain gage	Cumulative precipitation up to study storm event (inches)	Total annual precipitation during rain gage operation (inches)
1 (2/9/2014)	Our House Dam (OHD) (DWR) Tipping Bucket	2.57 *	33.5 *
2 (3/2/2014)	Our House Dam (OHD) (DWR) Tipping Bucket	16.5 *	33.5 *
3 (3/30/2014)	Our House Dam (OHD) (DWR) Tipping Bucket	26.4 *	33.5 *
4 (12/13/2014)	Malakoff Diggins Pit HOBO Rain Gage	12.67	30.14
5 (2/8/2015)	Malakoff Diggins Pit HOBO Rain Gage	22.34	30.14

Note: OHD rain gage data is for WY 2014 (10/1/2013-9/31/2014) and HOBO rain gage data is from part of WY 15 (11/11/2014-3/13/2015). An asterisk (*) denotes an *Adjusted* quantity (derived from the multiplication of OHD precipitation data and the slope y = 1.42x of the OHD & HOBO gage correlation).

Water Quality Measurements

Water quality measurements include the YSI 556 measurements performed in the field (water temperature, electrical conductivity, dissolved oxygen, pH, and oxidation-reduction potential) and the water sample metal and sediment lab analyses performed by Brooks Rand Lab.

YSI 556 Water Quality Measurements

The field water quality values that were collected over the five sample days (2/9/2014, 3/2/2014, 3/30/2014, 12/13/2014, and 2/8/2015) are given in Appendix C.

Temperature values of the tributaries ranged from 7.30 °C at R4 (sample day 1) to 9.89 °C at R5 (sample day 5). Hiller Tunnel temperature values ranged from 5.86 °C (sample day 4) to 8.8°C (sample day 5), and were consistently lower than the tributary values with the exception of sample day 5 (8.8°C vs 8.5°C for R3).

Electrical conductivity (EC) values of the tributaries ranged from 49 µS/cm at R4 and R7 (sample day 1) to 91 µS/cm at R3 (sample day 3). There was considerable variation in the tributary EC values over the five sample days. For example, for R4 and R8 the EC values ranged over 49-86 µS/cm and 51-84 µS/cm respectively. Two of the tributaries, R6 and R7, were fairly consistent, with ranges of 71-79 µS/cm and 49-60 µS/cm respectively. The Hiller Tunnel EC values ranged from 99 µS/cm (sample day 4) to 770 µS/cm (sample day 1). The values for sample days 2-5 ranged from 99 µS/cm to 146 µS/cm, so the 770 µS/cm value on sample day 1 stands out (the sample day 1 measurement occurred during the largest storm event of the study).

Dissolved oxygen (DO) values were converted from % saturation to mg/L. The DO saturation level (mg/L) in water depends on the water temperature, so temperature is used to convert the % saturation level to mg/L. A DO saturation chart, shown in Appendix A was used to perform the conversions (Welch, 1948). In using the chart, for a given water temperature and % saturation, a line is drawn from the water temperature value on the temperature scale to the % saturation value on the % saturation scale and then extended down to the oxygen (ppm) scale to find the equivalent mg/L value (1 ppm = 1 mg/L). The DO values of the tributaries, in units of mg/L, ranged from 9.6 mg/L (R5 on sample day 4) to 11.3 mg/L (R1 on sample day 1). Hiller Tunnel DO values ranged from 10.5 mg/L (sample day 5) to 12.5 mg/L (sample days 2 and 4). All measured DO values were greater than 7.0 mg/L, the dissolved oxygen water quality threshold (for waters designated cold) set by the Central Valley Regional Water Quality Control Board (CVRWQCB) within the Basin Plan (CRWQCB, 1998).

The pH values of the tributaries ranged from 5.80 (R7 on sample day 5) to 7.50 (R4 on sample day 2). All other tributary pH values were in the range 6.41-7.22. Hiller Tunnel pH values ranged from 6.20 (sample day 4) to 7.83 (sample day 2).

Oxidation-reduction potential (ORP) values of the tributaries ranged from 41.8 mV (R8 on sample day 3) to 146.2 mV (R7 on sample day 4). Hiller Tunnel ORP values ranged from −22 mV (on sample day 2) to 151.6 mV (on sample day 4).

<u>Brooks Rand Lab Water Quality Measurements:</u>

The results of the water quality assessment performed by Brooks Rand Lab for water samples collected during sample day 1 are presented in Table 9 for the Rim

TABLE 9. DISCHARGE AND METALS AT MALAKOFF DIGGINS: INFLOW AND OUTFLOW, STORM EVENT 1, 2/9/2014

	Sample Site Sample Time	Discharge (cfs)	TSS (mg/L)		Hardness (mg eq CaCO3/L)	Hg (ng/L)	Al (µg/L)	As (µg/L)	Ba (µg/L)	Be (µg/L)	Ca (µg/L)	Cr (µg/L)	Cu (µg/L)	Fe (µg/L)	Mg (µg/L)	Ni (µg/L)	Pb (µg/L)	Zn (µg/L)
Primary Regulatory Levels						50**	1000*					180**	9**			100*	15*	120**
Secondary Regulatory Levels														300’	50’	52**	2’’	5000’
Outflow	Hiller Tunnel	46.5	2560	Total	65.90	500.00	26,900	1.13	293	2.43	13000	91.8	136.00	36700	8120	109	37.80	158
	10:30 AM			Dissolved	17.70	4.28	52.70	0.114	33.4	0.526	3680	0.53	2.19	34.7	2060	8.14	0.07	3.42
--	R1	0.417	2.5	Total	12.60	11.50	1160	0.360	13.9	0.526	3100	0.53	2.64	589	1190	0.42	0.250	1.09
	11:00 AM			Dissolved	12.60	9.43	544	0.281	12.8	0.526	3090	0.53	2.07	282	1190	0.42	0.145	0.71
Inflow	R2	0.103	2.4	Total	19.50	21.50	4030	0.641	24.4	0.526	4760	3.22	4.30	1440	1840	1.50	0.567	3.43
	11:30 AM			Dissolved	18.50	13.50	1300	0.538	21.0	0.526	4540	0.77	3.08	709	1740	0.65	0.283	1.86
Inflow	R4	1.967	6.1	Total	13.60	11.90	1960	0.291	21.0	0.526	3250	0.62	2.42	1270	1320	0.43	0.405	1.93
	12:30 PM			Dissolved	13.20	6.56	916	0.223	17.9	0.526	3150	0.53	1.88	590	1300	0.42	0.198	1.46
Inflow	R5	0.155	11.3	Total	17.60	9.40	2080	0.308	29.7	0.526	4490	1.39	2.53	1500	1550	0.54	0.599	2.23
	1:00 PM			Dissolved	15.80	5.42	491	0.215	21.7	0.526	3990	0.53	1.51	343	1410	0.42	0.129	5.92
Inflow	R7	0.317	3.1	Total	12.70	8.06	292	0.19	14.4	0.526	3140	0.53	2.00	149	1180	0.42	0.109	0.63
	2:00 PM			Dissolved	11.70	5.98	102	0.176	12.6	0.526	2900	0.53	1.73	39.2	1090	0.42	0.063	0.63
Inflow	R8	0.7164	4.1	Total	13.00	12.70	565	0.297	16.0	0.526	3060	0.53	2.07	389	1300	0.42	0.176	0.82
	2:30 PM			Dissolved	12.30	5.40	52.60	0.14	12.80	0.53	2870.00	0.53	1.32	14.70	1240	0.42	0.06	0.039

Note: Regulatory sources for metals: MCL CDPH*; CTR CCC**; CDPH’; and PHG OEHHA’’ (No samples from R3, R6)
Brooks Rand Labs analysis shows that R5 dissolved Zn concentration was greater than the R5 total Zn concentration and states that this concentration should be omitted. The dissolved zinc concentration maximum at R2 (1.86 ng/L) was the new maximum.

Trail tributaries and Hiller Tunnel. The Rim Trail tributary and Hiller Tunnel discharges measured on sample day 1 are also listed.

The Hiller Tunnel effluent had a total hardness of 65.90 mg eq C_aC_{O3}/L, which was over three times higher than the largest Rim Trail total hardness of 19.50 mg eq C_aC_{O3}/L at R2, indicating a greater concentration of calcium and magnesium compounds. The Brooks Rand Lab analysis (USEPA Method 1638) reported that the Hiller Tunnel, R7, and R8 Fe samples revealed calcium interference. Due to the specific measurement technique used, the high levels of calcium in these samples created an unknown high bias in the reported Fe levels (Tanner and Baranov, 1999). As a result, the concentrations of Fe for these sample locations are estimated.

The total metal concentrations of the Rim Trail tributaries were generally higher than the dissolved metal concentrations; however, in some instances, the dissolved metal concentrations were equal to the total metal concentrations (Table 9). There were equal concentrations of total and dissolved beryllium at R2, R4, R5, and R7. Also, there were equal concentrations of total and dissolved chromium and equal concentrations of total and dissolved nickel at R7 and R8. In one case, for beryllium at R8, there was a slightly greater concentration of dissolved than total. When the concentration of a dissolved metal exceeds its total metal concentration, analytical error and/or interference in the measurement is indicated. For Hiller Tunnel, the total metal concentrations were significantly greater than the dissolved metal concentrations.

The Rim Trail tributaries sampled on 2/9/2014 (R1, R2, R4, R5, R7, R8) had dissolved mercury, copper, nickel, and zinc concentrations below the Regional Water

Quality Control Board thresholds for the Maximum Contaminant Level (MCL) for the consumption of water and aquatic organisms set by the California Toxics Rule (CTR) under USEPA in 2000 (USEPA, 2000). While R1 does not flow into the Malakoff Diggins Pit, it can impact the Humbug Creek water quality. The dissolved mercury, copper, nickel, and zinc concentrations measured for Hiller Tunnel on 2/9/2014 did not exceed the CTR MCLs.

The total mercury concentrations for the Rim Trail tributaries ranged from 8.06 ng/L at R7 to 21.5 ng/L at R2 (Table 9). The dissolved mercury concentrations ranged from 5.40 ng/L at R5/R8 to 13.5 ng/L at R2 (Table 9). No tributary sample had a higher dissolved Hg concentration than the 13.5 ng/L; 50 ng/L is the MCL for the consumption of water and aquatic organisms set by the CTR under USEPA (USEPA, 2000). The total mercury concentration for Hiller Tunnel was 500 ng/L. The Rim Trail tributary and Hiller Tunnel total mercury concentrations are shown in Figure 12 and the corresponding dissolved mercury concentrations are shown in Figure 13.

The total copper concentrations ranged from 2.00 µg/L at R7 to 4.30 µg/L at R2 (Table 9). The dissolved copper concentrations ranged from 1.3 µg/L at R8 to 3.1 µg/L at R2 (Table 9). The CTR MCL for dissolved copper is 9 µg/L. Total nickel ranged from 0.42 µg/L at R7/R8 to 1.50 µg/L at R2 (Table 9). Dissolved nickel ranged from 0.42 µg/L at R4/R5/R7/R8 to 0.65 µg/L at R2 (Table 9). The CTR MCL for nickel is 12 µg/L. Total zinc ranged from 0.63 µg/L at R7 to 3.43 µg/L at R2 (Table 9). Dissolved zinc ranged from 0.4 µg/L at R8 to 1.86 µg/L at R2 (Table 9). The CTR MCL for zinc is 120 µg/L.

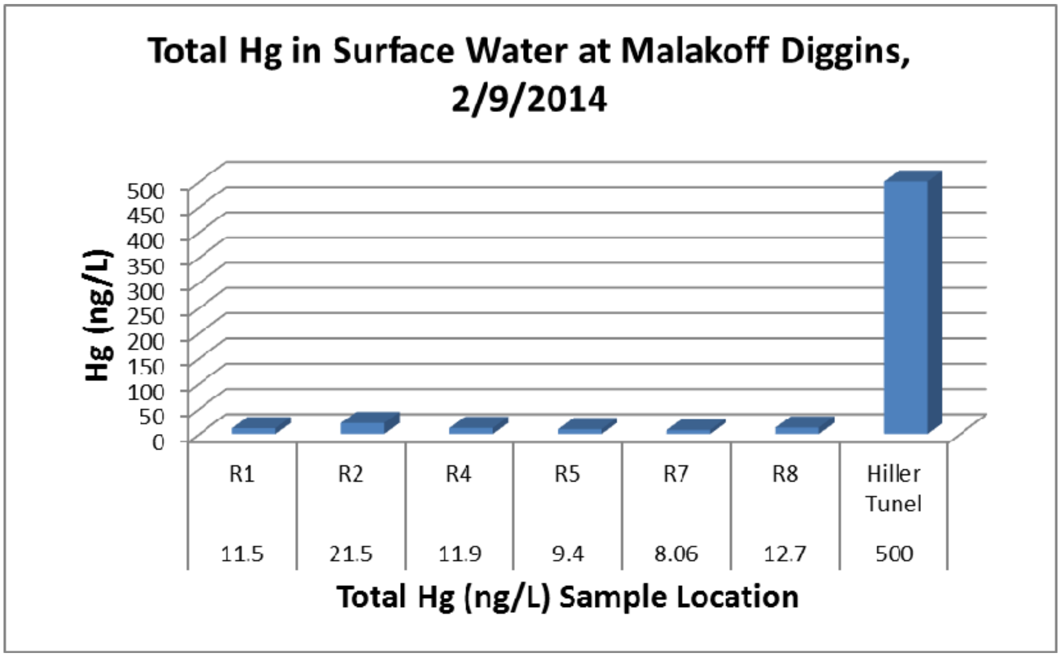

Figure 12. Total Hg from Rim Trail tributaries and Hiller Tunnel, Storm Event One, 2/9/2014.

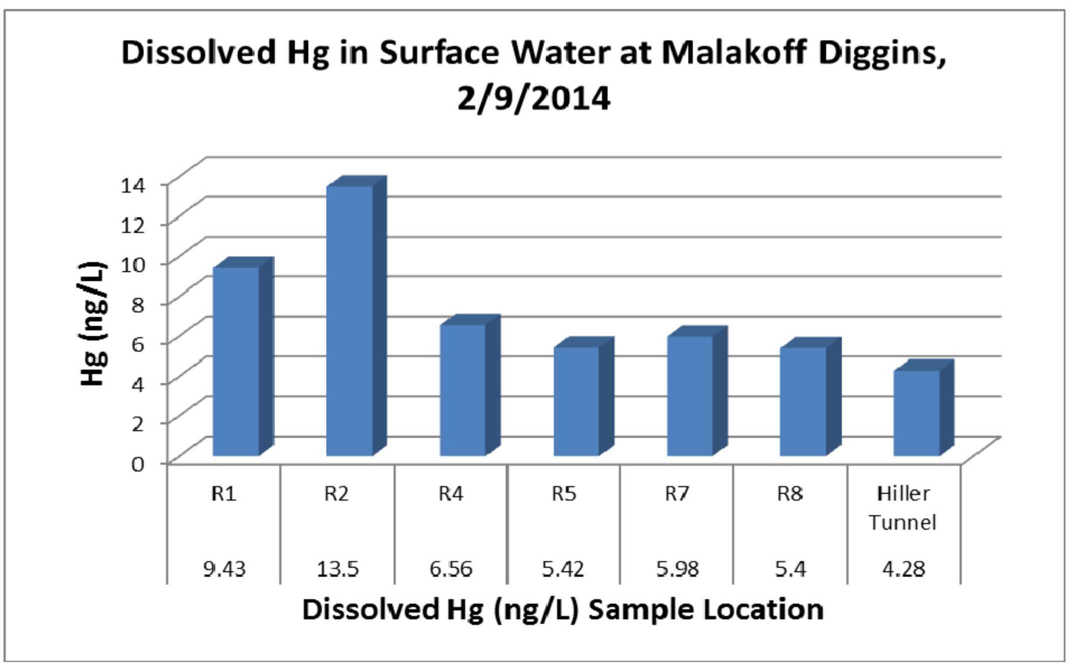

Figure 13. Dissolved Hg from Rim Trail tributaries and Hiller Tunnel, Storm Event One, 2/9/2014.

The dissolved aluminum, nickel, and lead concentrations for the Rim Trail tributaries and Hiller Tunnel were below the respective California Department of Public Health (CDPH) MCLs of 1000, 100, and 15 μg/L. The Hiller Tunnel total aluminum, nickel, and lead concentrations were 26,900 μg/L, 109 μg/L, and 37.80 μg/L respectively. The dissolved lead concentrations in the Rim Trail tributaries and Hiller Tunnel were also below the Public Health Goal (PHG) threshold of 2 μg/L set by the California Office of Environmental Health Hazard Assessment (OEHHA).

The study showed that the surface water that entered Malakoff Diggins Pit, measured at Rim Trail tributaries R2, R4, R5, R7, and R8, met the common regulatory thresholds for surface waters of California set by the Regional Water Quality Control Board. Total metal concentrations within the Hiller Tunnel discharge that exceeded the CDPH regulatory source levels were 500 ng/L (Hg), 136 μg/L (Cu), 109 μg/L (Ni), 158 μg/L (Zn), 36,700 μg/L (Fe), 8,120 μg/L (Mg), 38 μg/L (Pb), and 26,900 μg/L (Al).

Total Suspended Sediment Load Measurements

The Rim Trail tributaries sampled on 2/9/2014 (R1, R2, R4, R5, R7, and R8) contained total suspended sediment (TSS) that ranged from 2.0 mg/L at R2 to 11.0 mg/L at R5. Tributaries R3 and R6 were not sampled for TSS due to limited sampling bottles and because at the time these streams were lower priority due to small amounts of discharge. Tributaries R3 and R6 respective discharges were 0.08 ft^3/s and 0.46 ft^3/s.

Total instantaneous suspended sediment load ranged from 7 mg/s at R2 to 340 mg/s at R4 on 2/9/2014 (Table 10). The Rim Trail tributaries contributed approximately

TABLE 10. INSTANTANEOUS TOTAL SUSPENDED SEDIMENT LOAD ON 2/9/2014

Sample Site	Q (L/S)	[TSS] mg/L	Instantaneous TSS Load (mg/s)
Hiller Tunnel	1,317	2,560	3,400,000
R2	2.93	2.40	7
R4	55.7	6.10	340
R5	4.36	11.3	50
R7	8.98	3.10	28
R8	20.3	4.10	83

508 mg/s (0.02 %) cumulatively towards the Hiller Tunnel instantaneous TSS load (3,400,000 mg/s) on 2/9/2014 (Table 10).

Surface Water Discharge Measurements

The Rim Trail tributary discharge measurements ranged from a minimum of no surface water runoff (--) at R2 (3/2/2014), R3 (3/2/2014 and 12/13/2014), and R6 (2/8/2015) to a maximum of 1.97 ft^3/s at R4 (2/9/2014) (Table 11). The minimum observable runoff was measured to be 0.01 ft^3/s at multiple sampling locations on 3/30/2014 (R2 and R6) and 12/13/2014 (R2 and R7). The measured instantaneous discharges are plotted in Figure 14. The greatest-to-smallest total tributary instantaneous discharge order is as follows: sample day 1, 5, 3, 4, 2 (2/9/2014, 3/2/2014, 3/30/2014, 12/13/2014, 2/8/2015) (Table 11).

The lowest total discharge measured at all tributaries corresponded with the lowest Hiller Tunnel discharge on sample day two, 3/2/2014. Sample day two did not have observable or measureable discharge at R2 and R3, sample day four (12/13/2014) did not have observable or measurable discharge at R3, and sample day five (2/9/2015)

TABLE 11: MALAKOFF DIGGINS INSTANTANEOUS DISCHARGE MEASURED AT TRIBUTARIES: SAMPLE DAYS 1-5

Sample Day	1 2/9/2014	2 3/2/2014	3 3/30/2014	4 12/13/2014	5 2/8/2015
Discharge (ft^3/s) at sampling location					
R2	0.10	--	0.01	0.01	0.20
R3	0.08	--	0.09	--	0.29
R4	1.97	0.22	0.34	0.36	0.80
R5	0.15	0.06	0.07	0.04	0.07
R6	0.46	0.03	0.01	0.09	--
R7	0.32	0.02	0.07	0.01	0.24
R8	0.72	0.06	0.07	0.05	0.07
Total R2-R8	3.8	0.4	0.66	0.55	1.7
Hiller Tunnel	47 (35-59)	2.5	7.6	4.3	6.5
Total R2-R8 contribution (%) towards Hiller Tunnel	8 (6.5-11)	16	9	13	26
(-- = no runoff measured)					

did not have observable or measureable discharge at R6. The total R2-R8 tributary instantaneous discharges ranged from 0.4-3.8 ft^3/s, while the Hiller Tunnel instantaneous discharge ranged from 2.5 to 47 $ft^3/s \pm 25\%$ (Table 11). The sample day one (2/9/2014) R2-R8 tributaries contributed a total instantaneous discharge of 3.8 ft^3/s (8%) towards the Hiller Tunnel instantaneous discharge of 47 ft^3/s (Table 11). This percent contribution was artificially low because the Hiller Tunnel discharge was likely calculated as too high because of velocity-area discharge sampling limitations during high flow. The upper limit of this range, 47 ft^3/s, has an error range of 35 to 59 ft^3/s, based on a 25% measurement error assumption for storm event one (2/9/2014) at Hiller Tunnel (Table 11). The range of the Rim Trail tributary percent contribution associated with 25% error at Hiller Tunnel on

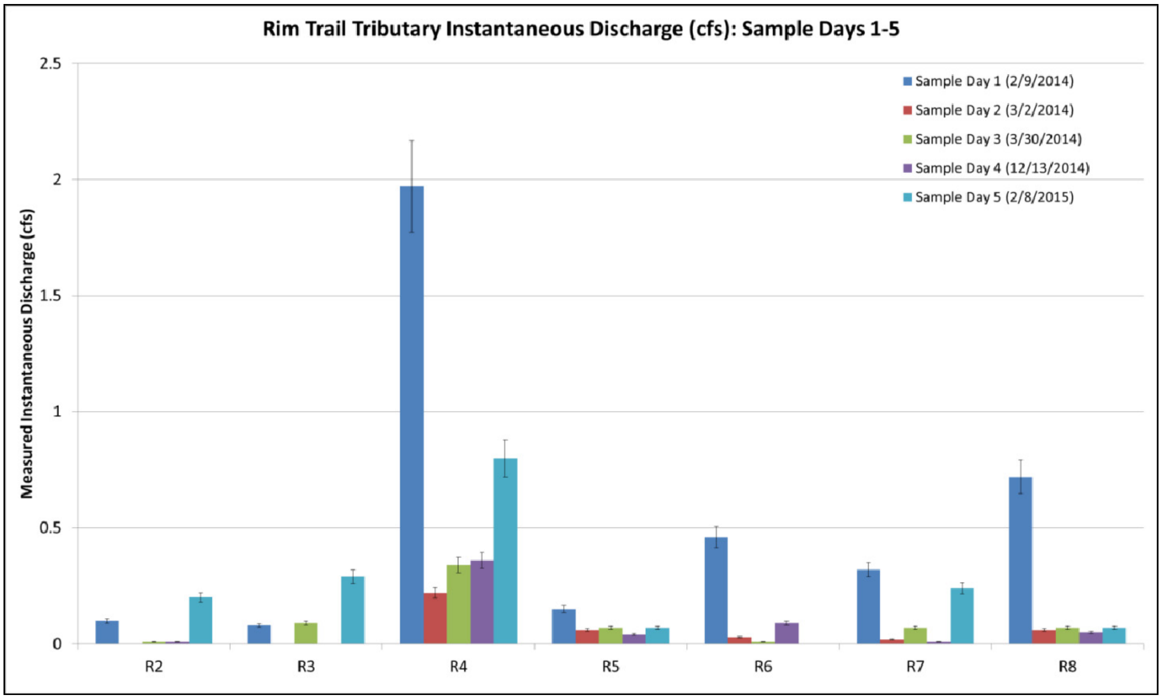

Figure 14. Distribution of Rim Trail tributary instantaneous discharge over sample days 1-5 (with 10% error as the sum of instrument error and field error).

storm event one, 2/9/2014, was 6.5-11%. With these percent error adjustments, the Rim Trail tributaries (inputs) contributed approximately 6.5-26% towards Hiller Tunnel (output) discharge over five sample days (Table 11). During the smallest storm (based on total R2-R8 and Hiller Tunnel discharge), the sample day two R2-R8 tributaries contributed a total instantaneous discharge of 0.4 ft^3/s (16%) towards the Hiller Tunnel instantaneous discharge of 2.5 ft^3/s (Table 11).

The storm event total accumulated precipitation and the total Rim Trail tributary instantaneous discharge show a generally positive relationship (Figure 15). Sample day one had the greatest storm event precipitation, 11.4 inches (*Adjusted*), and corresponding Rim Trail instantaneous discharge, 3.8 ft^3/s (Figure 15). Sample day two

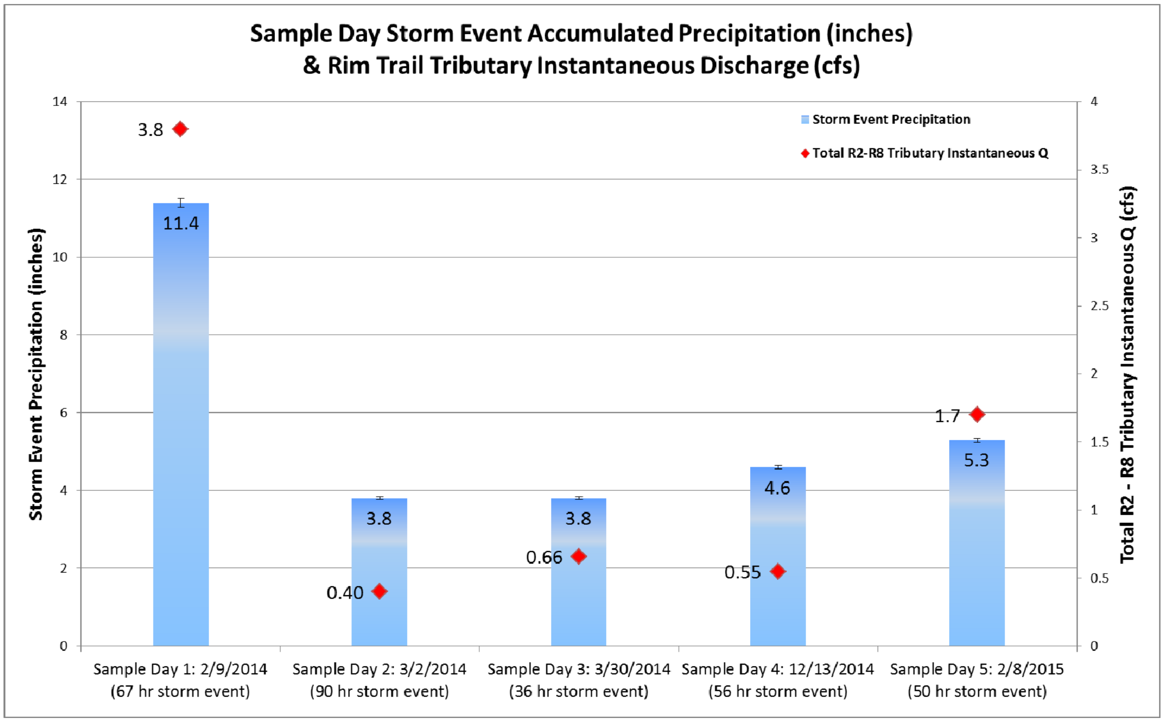

Figure 15. Storm event accumulated precipitation and field measurements of total rim trail tributary instantaneous discharge over sample days 1-5. Note: Sample day 1-3 precipitation data are from Our House Dam (OHD) rain gage and are *Adjusted* values, while sample days 4 and 5 precipitation data are from the HOBO rain gage within the Malakoff Diggins Pit (with 1% error as instrument error).

(a 90 hour storm event) and sample day three (a 36 hour storm event) had the same total rainfall, 3.8 inches (*Adjusted*), for their respective storm event (Figure 15). Sample day three showed a greater amount of total Rim Trail instantaneous discharge, 0.66 ft^3/s, when compared to sample day two, 0.4 ft^3/s (Figure 15). Sample day four had 4.6 inches (12 cm) of rain yet the total tributary instantaneous discharge was 0.55 ft^3/s, 17% lower than sample day three. The OHD rainfall data for sample day four was similar to the HOBO gage, with accumulated rainfall at 4.2 inches (11 cm) of rain. Sample day five had the second greatest storm event precipitation, 5.3 inches (14 cm), and tributary instantaneous discharge, 1.7 ft^3/s (Figure 15). The OHD rainfall data were lower than the HOBO gage for sample day five, and recorded an accumulated rainfall of 1.5 inches (3.8 cm) of rain, whereas the HOBO rain gage recorded 5.3 inches (14 cm).

Rim Trail Tributary-Humbug Creek (Gage 3) Discharge

The discharge at Humbug Creek (Gage 3) was calculated using the linear equation y = 14.03x + 0.58 developed by TSF (2015) (Figure 16) for WY 2014 data (11/15/2013-9/30/2014) and WY 2015 data (10/1/2014-3/6/2015). This relationship, where x is the Gage 3 stage (psi) and y is the calculated discharge (cfs), was established using data from water years 2012, 2013, and 2014, for a total of nine stage-discharge readings between the flows of 3-17 cfs (TSF, 2015).

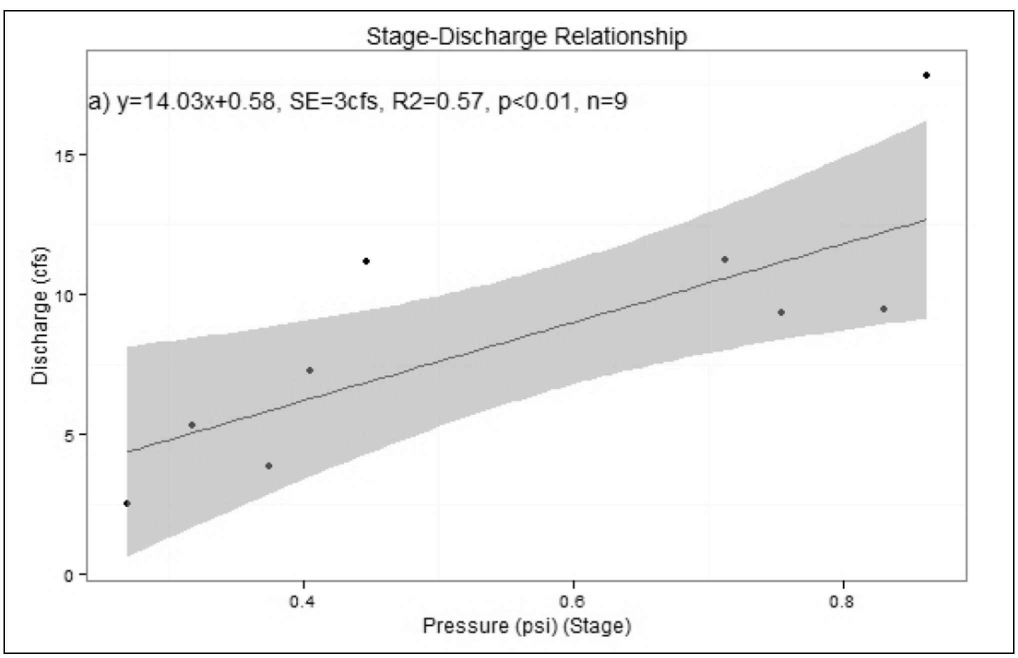

Figure 16. Stage-discharge relationship for Humbug Creek (with ± 10% error for discharge) (TSF, 2015).

In calculating the Humbug Creek discharge a baseflow of 3 cfs was assumed for low water periods, when the Gage 3 pressure transducer was not immersed in water. The 3 cfs baseflow was applied to the start of the WY 2014 discharge data (11/15/2013) and the start of the WY 2015 discharge data (10/1/2014). The fifteen-minute interval pressure -transducer (stage) readings from Humbug Creek were adjusted to account for sediment that enters the stage pressure-transducer casing during large storm events (TSF, 2015). The sediment can act to artificially lower or raise the gage pressure reading (TSF, 2015). Pressure readings were adjusted for WY 2014 by adding 0.168 psi, the adjustment needed to establish the 3 cfs baseflow at the beginning of WY 2014. Pressure readings were also adjusted during WY 2015 by adding 0.1995 psi (10/1/2014-12/26/2014) to establish the starting 3 cfs baseflow and by subtracting 0.0385 psi (12/27/2014 to 3/6/2015) following a large storm event. The pressure adjustments served to make the baseflow discharge comparable for the 2014 and 2015 water years at 3 cfs. Baseflows measured in 2013 for Humbug Creek ranged from 2-4 cfs (TSF, 2015). A hydrograph of Humbug Creek using TSF stage data from 11/15/2013 to 3/6/2015 is shown in Figure 17.

The instantaneous field measurements of the Rim Trail tributary and Hiller Tunnel discharges were extrapolated using 15-minute pressure transducer readings from the Humbug Creek gage. The sample day five discharge is shown in Figure 18 to illustrate the hydrograph extrapolation. Because the Humbug Creek discharge from the Gage 3 site is consistently larger than the Rim Trail tributary discharge, the hydrographic depiction of the Rim Trail tributary discharge flattens after extrapolation. Figure 18 is representative of a complete storm event with peak discharge and rising/falling limbs,

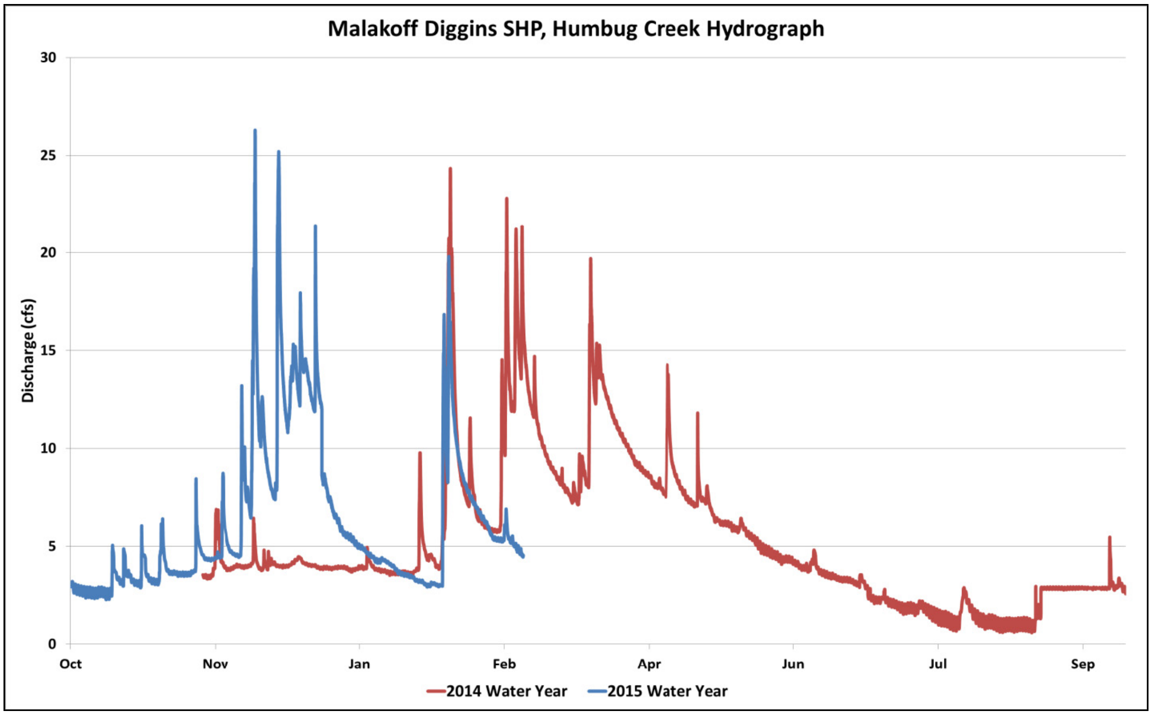

Figure 17. Hydrograph of calculated discharge (ft^3/s) at Humbug Creek (Gage 3) (11/15/2013 to 3/6/2015). A baseflow of 3 ft^3/s is assumed for low water periods when the pressure transducer was not in the water (TSF, 2015).

however it does not account for lag time between the Rim Trail tributary discharge and Humbug Creek. These data were used to calculate volumes (ft^3) of tributary discharge during storm events for each Rim Trail subwatershed box model.

Hiller Tunnel-Humbug Creek
(Gage 3) Discharge

The study's discharge measurements at Hiller Tunnel are depicted in Figure 19. The Hiller Tunnel instantaneous discharge during the first storm event (sample day one) was considerably larger than the storm events that followed.

A stage-discharge relationship between the stage (psi) at Humbug Creek (Gage 3) and the instantaneous discharge (cfs) at Hiller Tunnel was developed (Figure

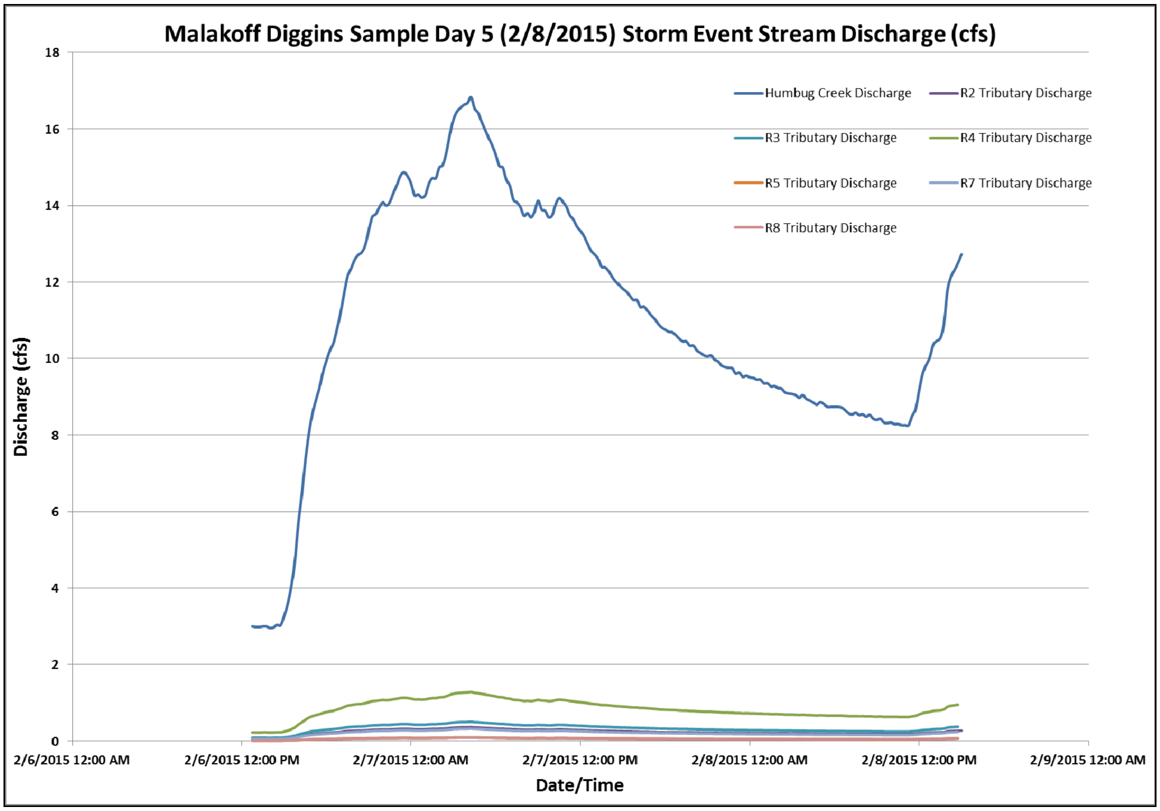

Figure 18. Hydrograph of Humbug Creek discharge during sample day five storm event with extrapolated Rim Trail tributary discharge. Note: Tributary R6 is omitted because there was no observable runoff.

20). This stage-discharge relationship is not common because it establishes a relationship between two different locations on a single waterway (Hiller Tunnel and Humbug Creek) as opposed to a single location. Diggins Creek, upstream of Humbug Creek, is primarily composed of Hiller Tunnel discharge, and contributes water to Humbug Creek. However, there is additional contributing area that is not quantified between the Hiller Tunnel discharge and the Gage 3 site. Because Hiller Tunnel does not have continuous discharge measurements (such as a gage that can record stage for discharge calculations), the stage-discharge relationship provides an estimate of the Hiller Tunnel discharge during storm

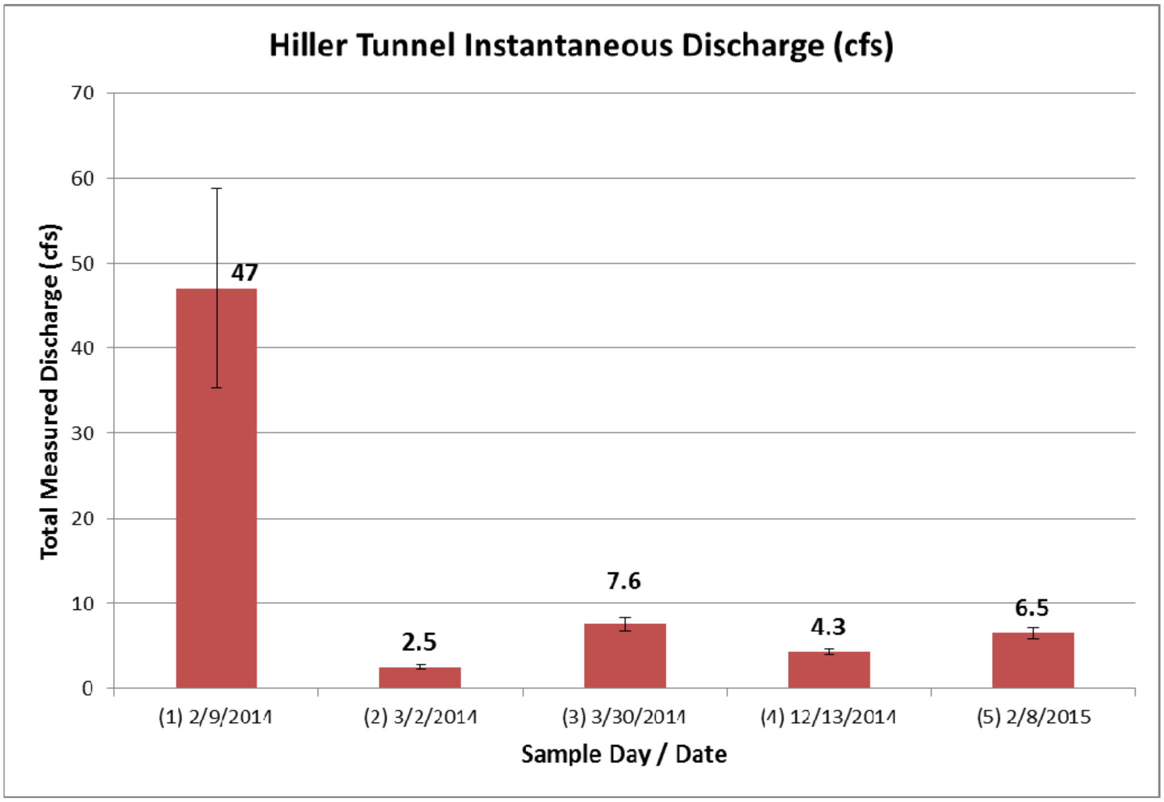

Figure 19. Field measurements of Hiller Tunnel discharge over five sample days (sample day 1 has ±25% error, while sample days 2-5 have ± 10% error).

events. Using the linear equation y = 5.386x – 0.984 where x is the Humbug Creek (Gage 3) stage (ft) and y is the Hiller Tunnel discharge (cfs), the Hiller Tunnel discharge was calculated for the study period. Twenty-nine Hiller Tunnel discharge measurements were plotted as a function of the Humbug Creek Gage 3 stage data from 2011 to 2015. There are 25 baseflow measurements shown in blue from previous studies while four yellow points represent storm event (2, 3, 4 and 5) discharges measured during the study. The Hiller Tunnel discharge from storm event one (47.0 ft^3/s) was omitted because it was outside the range of this relationship. A linear regression line (best fit) was plotted to depict the relationship between the Hiller Tunnel discharge and the Humbug Creek stage.

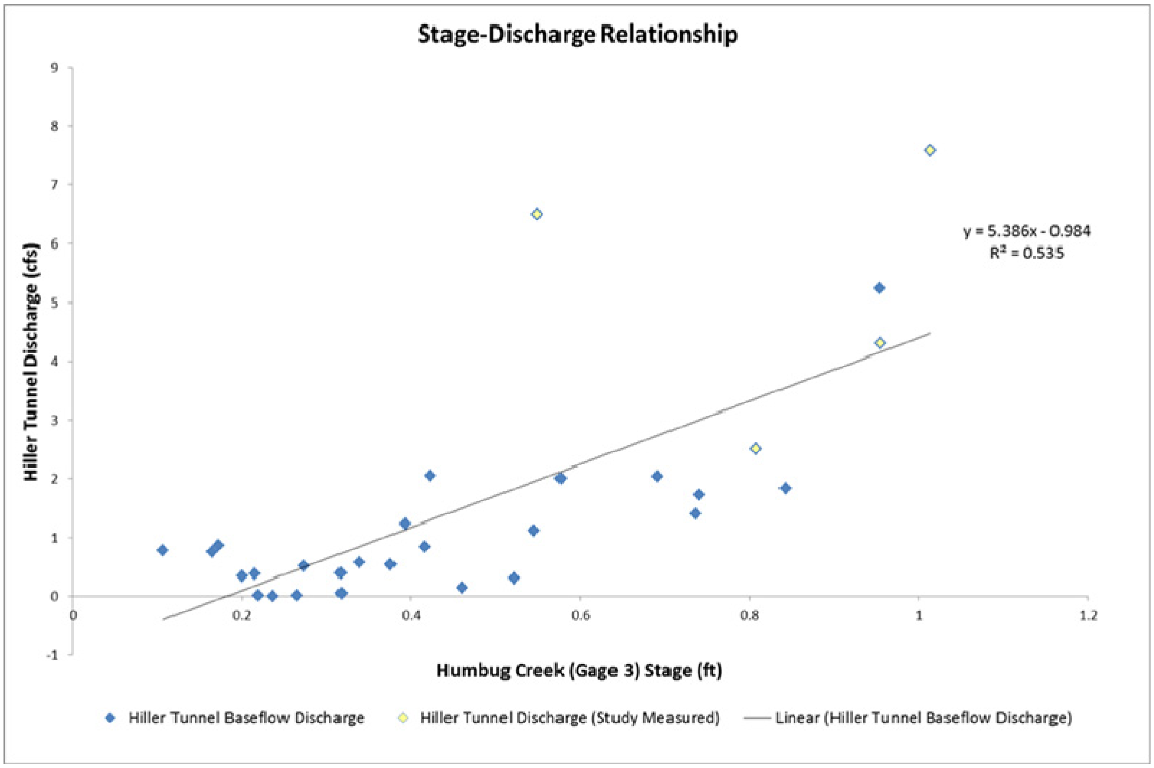

Figure 20. Stage-Discharge Relationship Between Hiller Tunnel Discharge (cfs) and Humbug Creek Stage (ft).

Based on the trend line, the points along this line are predicted values of the Hiller Tunnel discharge. The R^2 or coefficient of determination displayed a positive correlation of 0.54 between the Hiller Tunnel discharge and the Gage 3 stage. A larger R^2 value (better correlation) was obtained with a best-fit line with an intercept, i.e., not forcing the line through the origin.

The difference between the measured and predicted Hiller Tunnel discharges can be seen in Figure 21. The smallest-to-largest difference between measured and predicted Hiller Tunnel discharges ranks as follows: storm event 4, storm event 2, storm event 3, and storm event 5 (Figure 21). With a 10% error consideration, there were no

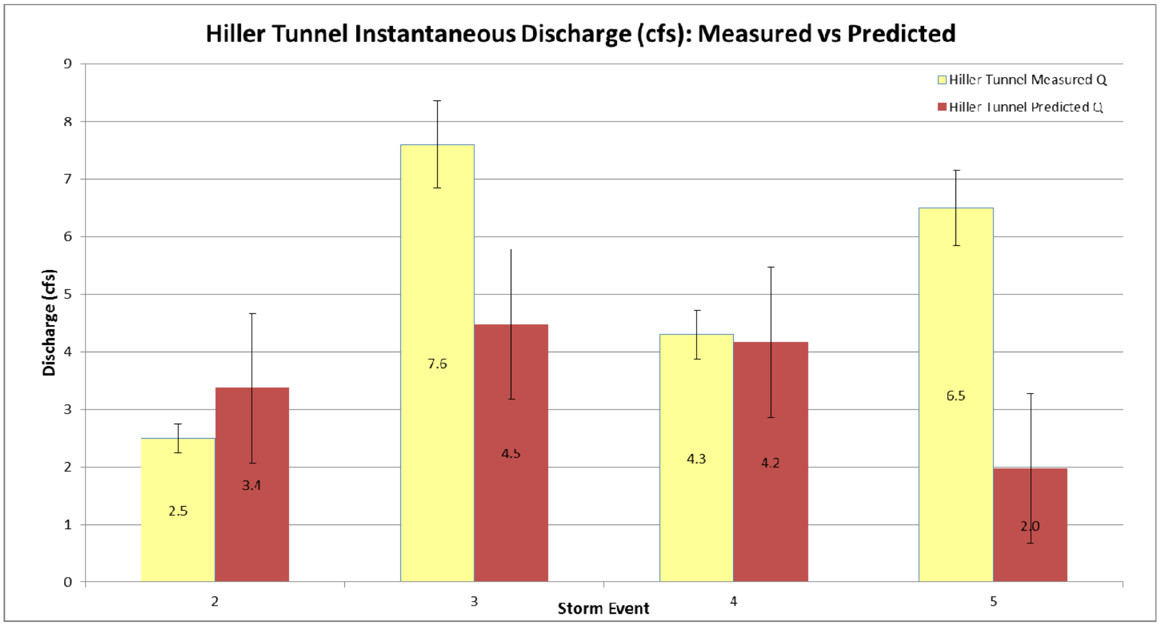

Figure 21. A Comparison of Instantaneous Discharge (cfs) at Hiller Tunnel: Measured (± 10%) vs Predicted (± 1.3 based on the root-mean-square error value).

differences between the storm event 2 and storm event 4 measured discharges and their predicted values from the regression. Also, with a 10% error consideration, storm events 3 and 5 had slightly greater measured discharge when compared to the predicted discharge.

To further assess the accuracy between the measured and predicted Hiller Tunnel discharges, the root-mean-square error (RMSE) was calculated to understand how well the linear fit represents the data. The RMSE value of 1.3 cfs was 52% of the smallest Hiller Tunnel measured value (2.5 cfs) during a storm event and was 17% of the largest Hiller Tunnel measured value (7.6 cfs) during a storm event. The RMSE value indicates that within a discharge range of 0 cfs to 7.6 cfs the measured Hiller Tunnel discharge point can range approximately 1.3 cfs from the best-fit line (predicted Hiller Tunnel discharge). The comparison is limited by the number of measured discharge points and any additional Hiller Tunnel discharge measurements during storm events would strengthen the analysis and reduce the RMSE value.

The stage-discharge relationship was used to develop a hydrograph for Hiller Tunnel over water years 2014 and 2015 (Figure 22). Due to the availability of Gage 3 data, the hydrograph started on 11/15/2013 and ended on 3/6/2015. Fifteen-minute interval Gage 3 stage (ft) data were input into the equation to calculate the Hiller Tunnel discharge. Storm event discharges from the study (consecutively 2, 3, 4 and 5) at Hiller Tunnel were plotted with red "X"s (Figure 22). Discharges measured prior to this study were plotted with purple triangles, and these points are typically lower than the calculated Hiller Tunnel discharge (Figure 22). Hydrographs of storm events two, three, four, and five (Figure 23, Figure 24, Figure 25, Figure 26) were individually plotted to visualize when measurements occurred (from the study's field measurements) during each storm.

Figure 27 pictures tributaries R4 and R8 during storm event five, 2/8/2015 and Figure 28 shows Hiller Tunnel during storm event five, 2/8/2015.

Watershed Delineation

The Malakoff Diggins R2-R8 watersheds were delineated in ArcGIS based on GPS points that were taken at the most downstream stream location that intercepted the Rim Trail where discharge and water quality measurements were taken. The non-measured watersheds were delineated from adjacent Rim Trail points that were located on streamlines determined by ArcGIS analysis. The delineation process created an associated watershed area for the Rim Trail tributaries R2-R8 (Table 12) and the non-

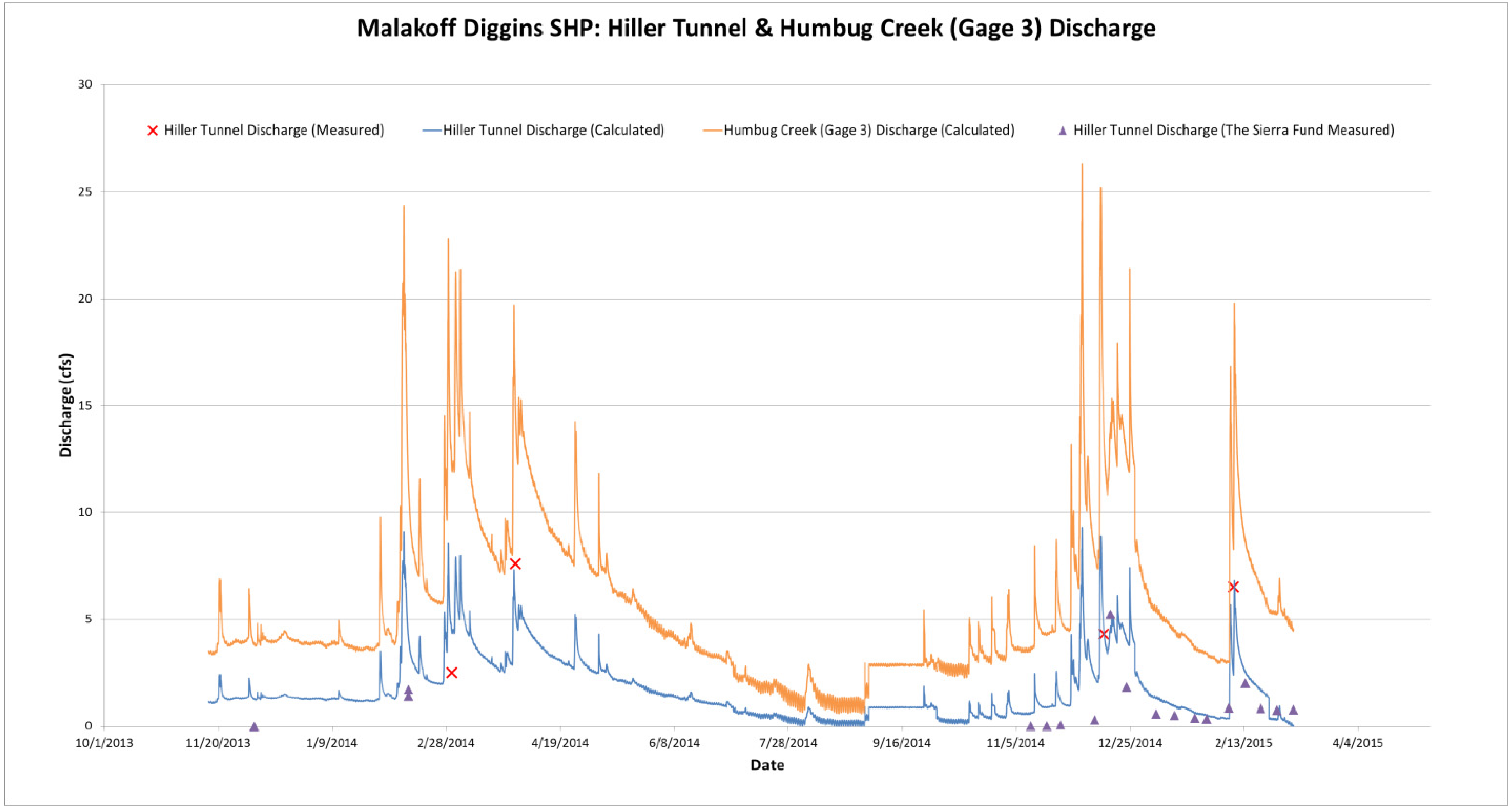

Figure 22. Hydrograph of Humbug Creek (Gage 3) and Hiller Tunnel With Measured Instantaneous Discharge Points Over Water Years 2014 and 2015. Storm events 2, 3, 4, and 5 are indicated from left to right with a red "x."

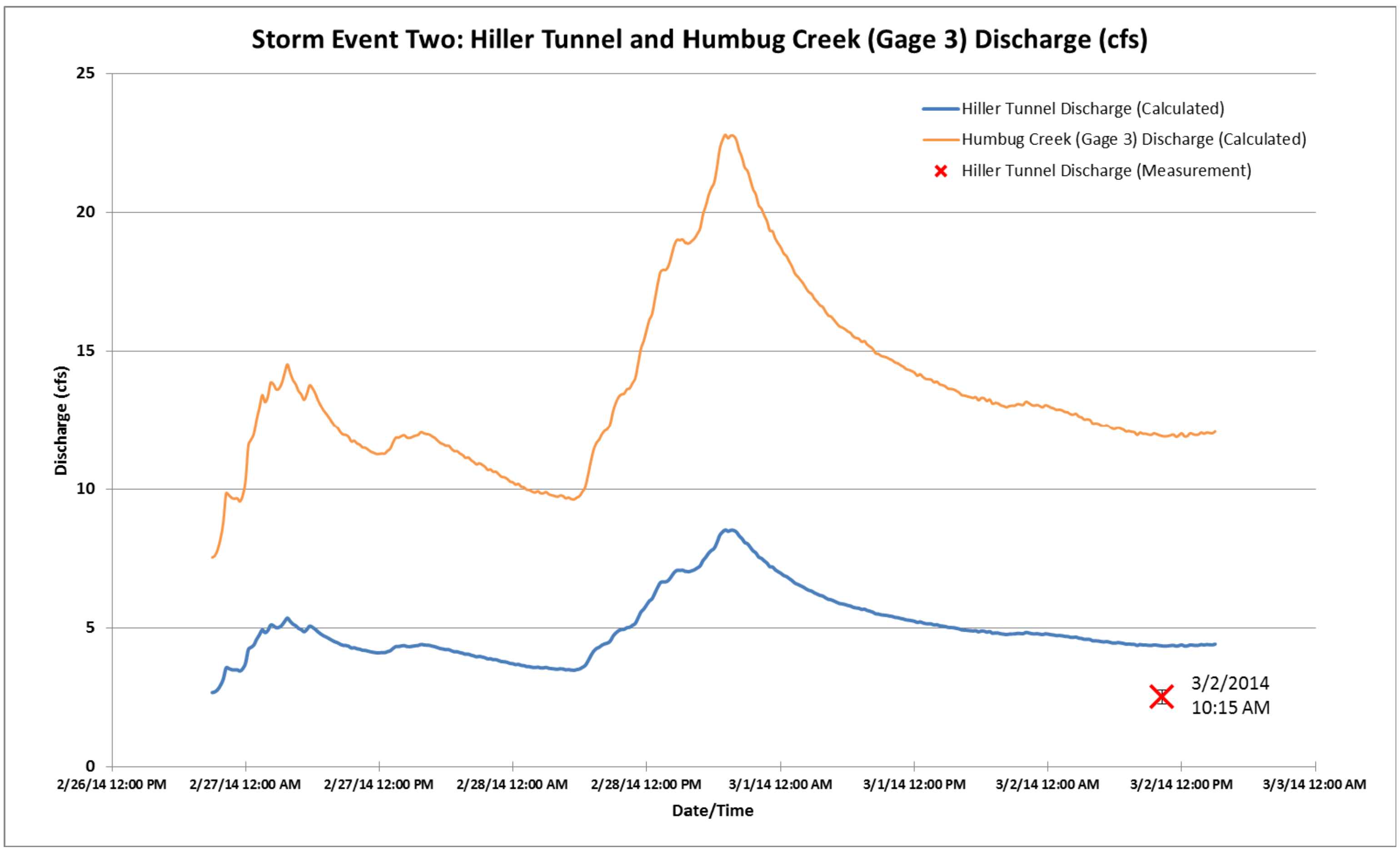

Figure 23. Hydrograph of Humbug Creek (Gage 3) and Hiller Tunnel with measured instantaneous discharge point (3/2/2014 10:15 AM) (± 10% error) over storm event two.

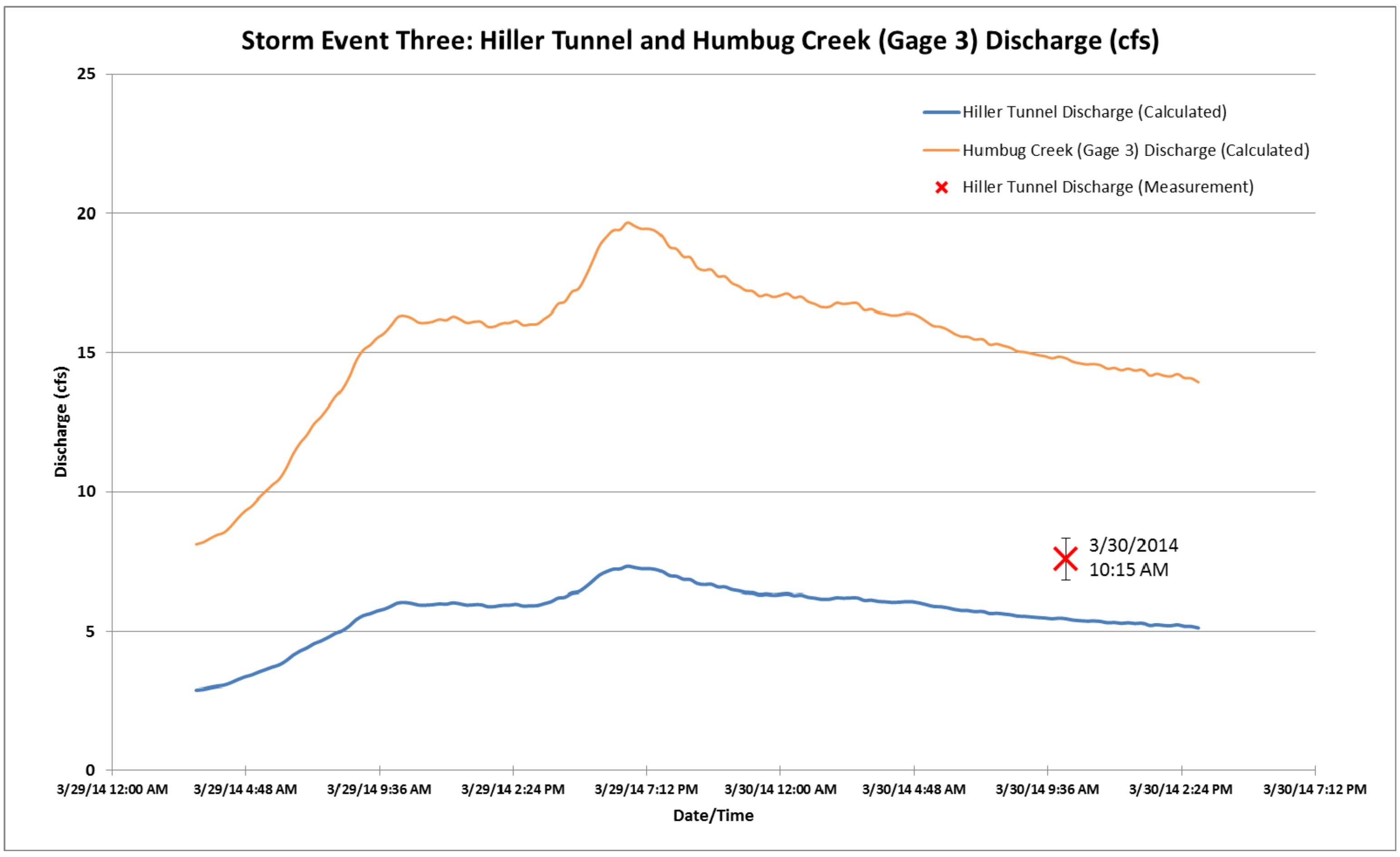

Figure 24. Hydrograph of Humbug Creek (Gage 3) and Hiller Tunnel with measured instantaneous discharge point (3/30/2014 10:15 AM) (± 10% error) over storm event three.

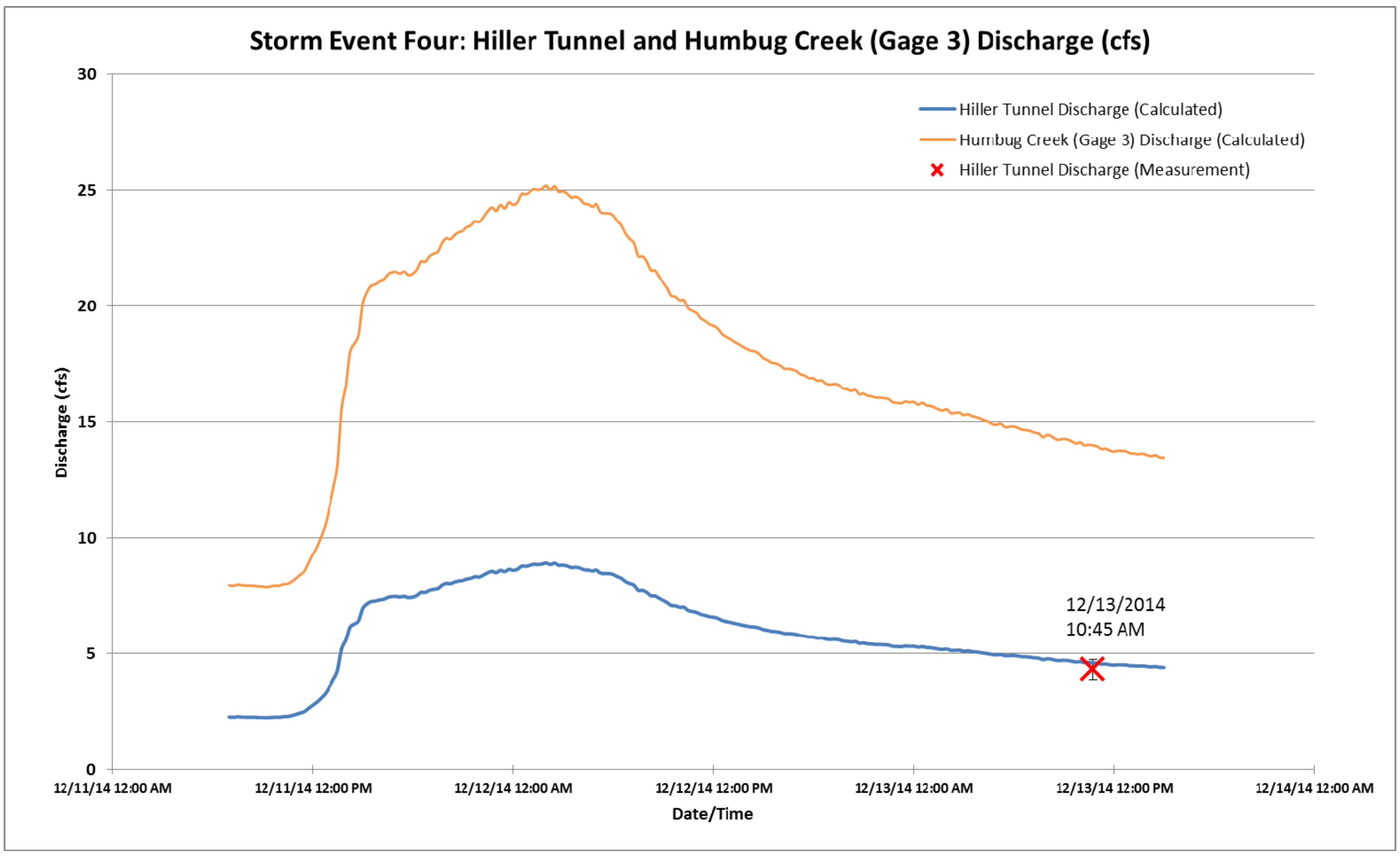

Figure 25. Hydrograph of Humbug Creek (Gage 3) and Hiller Tunnel with measured instantaneous discharge point (12/13/2014 10:45 AM) (± 10% error) over storm event four.

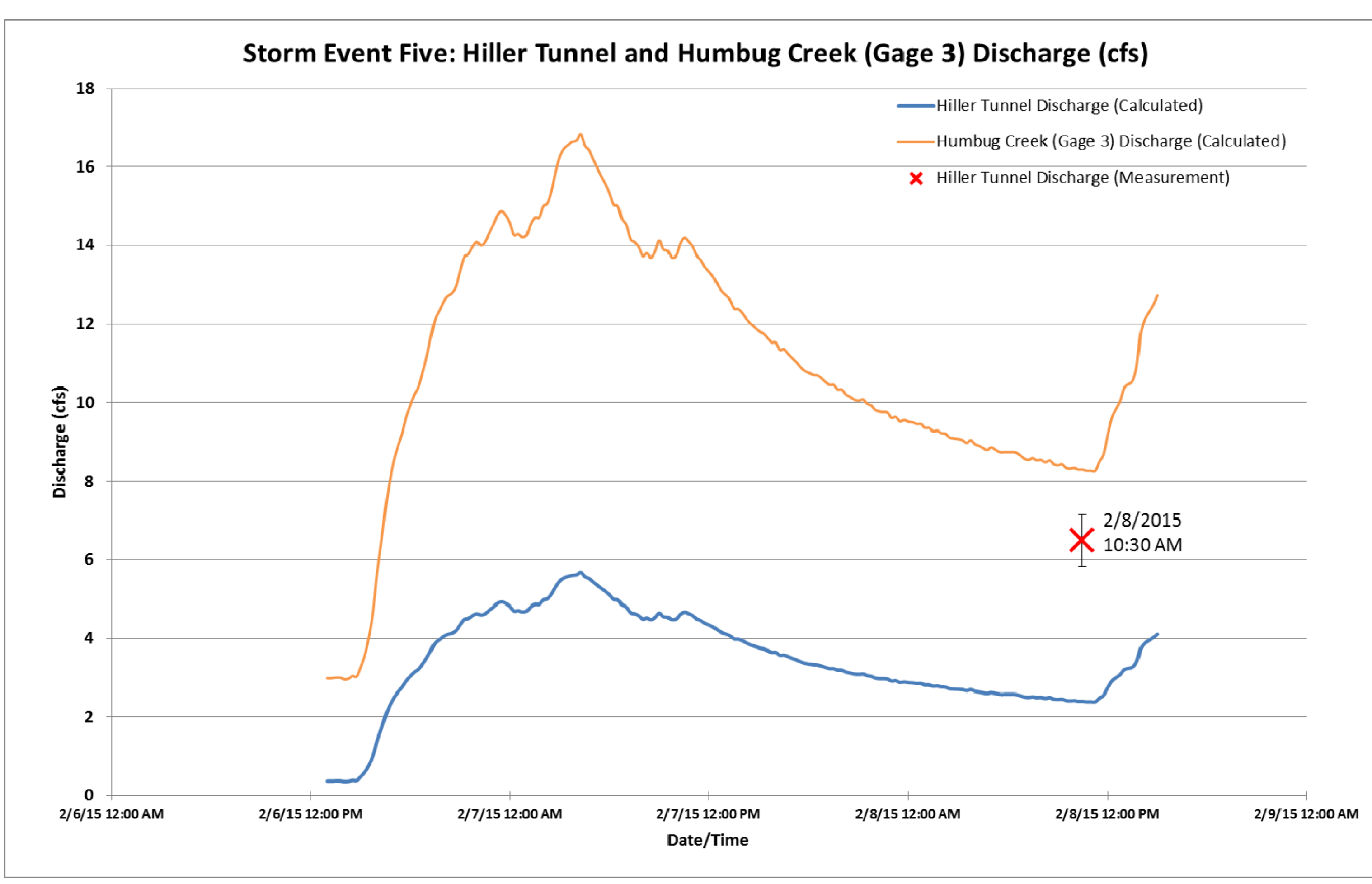

Figure 26. Hydrograph of Humbug Creek (Gage 3) and Hiller Tunnel with measured instantaneous discharge point (2/8/2015 10:30 AM) (± 10% error) over storm event five.

Figure 27. Sample Day Five, 2/8/2015, Rim Trail Tributaries at Malakoff Diggins. Looking south at R4 (left) and north at R8 (right).

Figure 28. Sample Day Five, 2/8/2015, Hiller Tunnel Effluent During Storm Event. High turbidity and discharge (left) and flow downstream to Humbug Creek (right).

TABLE 12. DELINEATED WATERSHED AREAS: MEASURED

Site ID	Area (ft^2)	Area (m^2)	Area (Acres)	Area (km^2)
Hiller Tunnel Watershed	58,273,867	5,413,820	1,338	5.4
R2 Watershed	4,043,684	375,671	93	0.38
R3 Watershed	1,486,549	138,105	34	0.14
R4 Watershed	6,521,755	605,891	150	0.61
R5 Watershed	1,324,902	123,087	30	0.12
R6 Watershed	765,631	71,129	18	0.07
R7 Watershed	1,621,967	150,686	37	0.15
R8 Watershed	4,195,672	389,791	96	0.39

measured tributaries A, B, and C as the area upstream of the monitoring location or pour point (Table 13).

TABLE 13. DELINEATED WATERSHED AREAS: NON-MEASURED

Site ID	Area (ft^2)	Area (m^2)	Area (Acres)	Area (km^2)
Total Non-measured Watershed Area	4,051,300	376,378	93	0.38
Non-measured Watershed A	2,076,579	192,921	48	0.19
Non-measured Watershed B	1,316,303	122,289	30	0.12
Non-measured Watershed C	658,418	61,169	15	0.06

The largest watershed was R4 at 150 acres (Table 12). Tributaries R8 and R2 had comparable watershed areas, respectively 98 and 93 acres. The R2 watershed had approximately the same area as the total of the three non-measured watersheds (A, B, C). Tributaries R3, R5, and R7 had comparable watershed areas, respectively 34, 30, and 37 acres. Tributary R6 was the smallest watershed with an area of 18 acres.

Non-measured Watershed A is the largest non-measured watershed (48 acres) and is located on the southwest side of the Hiller Tunnel watershed (Figure 29). Non-measured Watershed B is adjacent to Non-measured Watershed A and has an area of 30

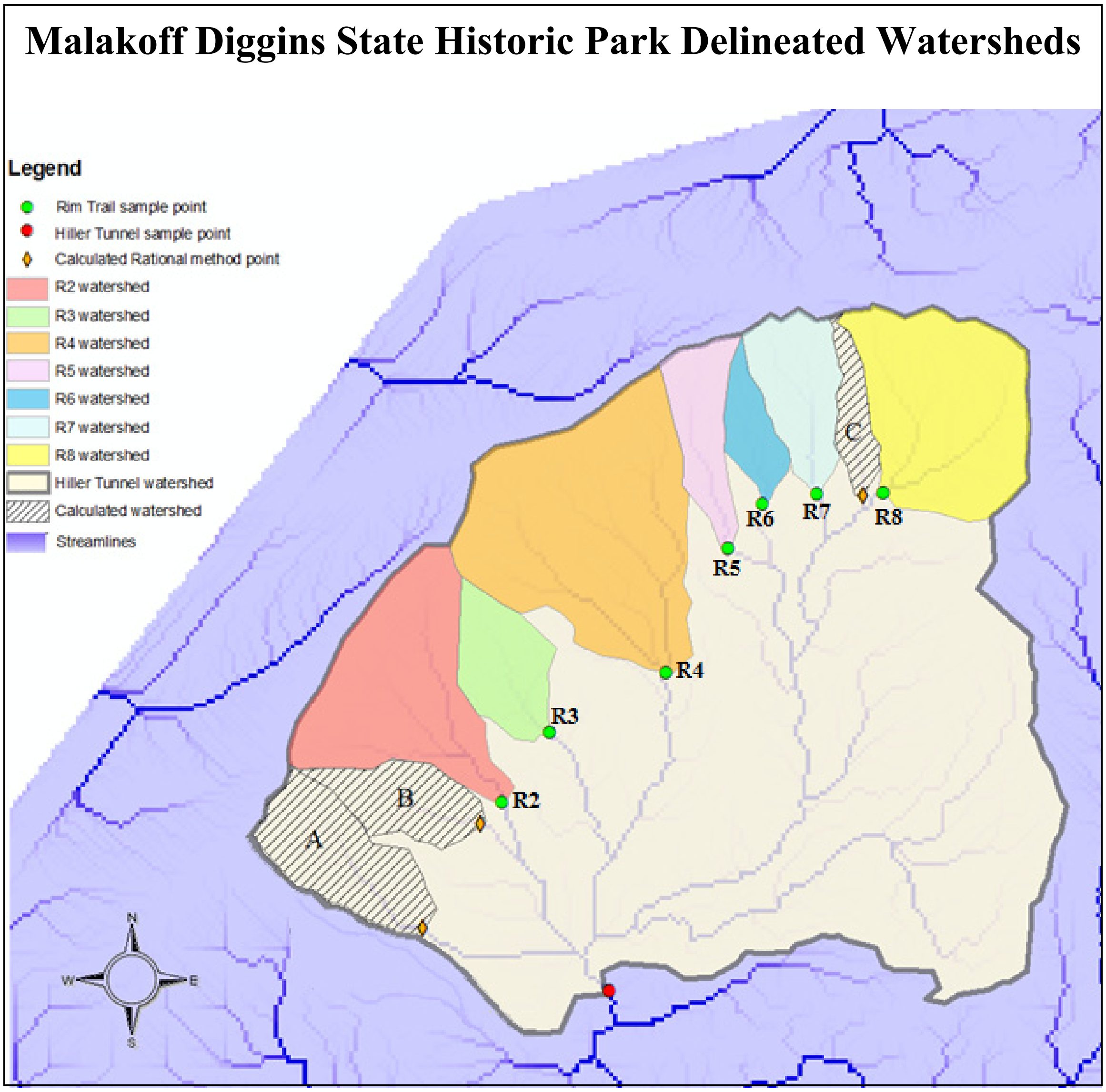

Figure 29. Malakoff Diggins State Historic Park Delineated Watersheds. Shown are the Hiller Tunnel watershed and the Rim Trail subwatersheds. Note: For this figure the term 'calculated watershed' is equivalent to 'non-measured watershed.' The generated streamlines are shown in blue. (ArcGIS 10.2.2; Google Earth, 2015)

acres, comparable to the R3 watershed. Non-measured Watershed C is located between R7 and R8; its location and area of 18 acres makes it comparable to the R6 watershed (Figure 29).

The Hiller Tunnel delineation point was located at the effluent of the tunnel. The Hiller Tunnel watershed size was estimated to be 1,338 acres and encompasses the R2-R8 and the non-measured watersheds, as seen in Figure 29. The ArcGIS Spatial Analyst: Hydrology (Watershed) tool calculator used for the delineation process (raster creation) did not take into account that the Hiller Tunnel streamflow from input to output is within a tunnel and is not an open channel. This detail brings in error within the Hiller Tunnel delineation area. In addition, sample point R1 was omitted from the Hiller Tunnel discharge contribution calculation because the flow from R1 does not enter the Malakoff Diggins Pit, rather it is diverted under North Bloomfield Road to a tributary that runs south of the road into Humbug Creek. R1 is located at the lowermost southwest streamline that flows towards North Bloomfield Road. R1 reaches a manmade diversion channel and crosses south underneath the North Bloomfield Road towards Humbug Creek. The R1 stream was not included in the Hiller Tunnel watershed calculated area. A second streamline north of R1 was carefully analyzed with contour lines and streamline topography. It was concluded that this streamline flow ends its projected streamlines on the North Bloomfield Road, outside the south rim of the Malakoff Diggins Pit. This potential non-measured watershed was excluded from delineation as it does not contribute discharge towards Hiller Tunnel.

Rational Method

The instantaneous peak discharge Q (ft^3/s) for each of the Rim Trail tributaries measured during sample days 4 and 5 was derived from the Humbug Creek hydrograph extrapolation. This extrapolated peak discharge was input into the Rational Method equation to back-calculate a dimensionless runoff coefficient c for its respective watershed. The dimensionless runoff coefficients for sample day 4 (12/13/2014) ranged from c = 0.0024 at R2 to c = 0.11 at R6. The sample day 5 (2/8/2015) dimensionless runoff coefficients ranged from c = 0.0091 at R8 to c = 0.14 at R3. The Rim Trail watershed back-calculated c values were very low and close to the lowest limits of a variety of forest type coefficient ranges. The low coefficient values indicate that almost all precipitation infiltrates. The greatest c value for the Malakoff Diggins relief, soil type, and hill slope was selected: 0.11 on sample day four and 0.14 on sample day five. While field measurements are limited, these selected back-calculated runoff coefficients are the best representation of runoff conditions for similar ground slope, ground cover, and soil type based on reviewed literature (Hayes and Young, 2006; AMEC, 2008; NRCS, 2013; Shoblom, 2014).

The extrapolated peak instantaneous discharge from the Rim Trail tributaries on sample days four and five can be used to estimate peak discharge for the non-measured watersheds. It is important to note that non-measured watersheds A, B, and C did not have any discharge during storm events 1, 2, 3, 4, and 5. However, these non-measured watersheds are located within the upper watershed and were delineated because they are connected to adjacent Rim Trail watersheds. During larger storm events than observed in this study, the non-measured watersheds may contribute surface water to the Malakoff Diggins Pit. Sampled watersheds R7, R5, and R6 and non-measured watersheds A, B, and C were compared based on similar watershed size. Sample Day 4 showed extremely low discharge (0.02 ft^3/s) at R7 when compared to Non-measured Watershed A (0.45 ft^3/s). Tributary R5 showed low discharge (0.07 ft^3/s) when compared to Non-measured Watershed B (0.28 ft^3/s). Tributary R6 (0.17 ft^3/s) and Non-measured Watershed C (0.14 ft^3/s) had similar discharge. The Sample Day 5 extrapolated peak discharge at R7 (0.33 ft^3/s) was less than half of Non-measured Watershed A (0.71 ft^3/s). Tributary R5 showed low discharge (0.1 ft^3/s) when compared to Non-measured Watershed B (0.45 ft^3/s). Tributary R6 did not have any discharge on this sample day when compared to Non-measured Watershed C (0.22 ft^3/s).

The extrapolated peak discharges for R7, R5, and R6 showed variability between sample days. Measured watershed R7 had the lowest peak discharge on sample day four and had the greatest peak discharge on sample day five. In contrast, measured watershed R6 had the greatest peak discharge on sample day four, yet did not have any observable discharge on sample day five. Measured watershed R5 showed a fairly constant peak discharge response between the sample days.

Box Modeling

The Rim Trail watershed volumetric fluxes (ft^3) for each storm event were calculated with the box model formula (1), $A_{Rwshed} P_i = R_{QMi} + A_{Rwshed} ET + \Delta S$. The extrapolated volume (ft^3) of the measured Rim Trail watershed (R_{QMi}), the Rim Trail watershed area (ft^2) multiplied by the total storm event precipitation (ft) ($A_{Rwshed} P_i$), and the Rim Trail watershed area (ft^2) multiplied by the total evapotranspiration (A_{Rwshed} ET), were used to find the storage (ΔS) (defined as the sum of groundwater and soilwater that infiltrated) (Appendix B). On sample days 4 and 5, the non-measured watershed volumes (ft^3) were determined using formula (2), $A_{Rwshed} P_i = R_{QNi} + A_{Rwshed} ET + \Delta S$. The model inputs were the extrapolated volume (ft^3) of the non-measured Rim Trail watersheds (A, B, C) (R_{QNi}), the non-measured watershed area (ft^2) multiplied by the total storm event precipitation (ft) ($A_{Rwshed} P_i$), and the non-measured watershed area (ft^2) multiplied by the total evapotranspiration (A_{Rwshed} ET), and were used to find the storage (ΔS) (Appendix B). The influx of water for each Rim Trail watershed was the total storm precipitation over the watershed area (ft^3). Evapotranspiration was the primary outflux for each watershed. The remaining influx of water was lost to storage (infiltration) and surface runoff. The proportion of the Rim Trail tributary watershed precipitation that is lost to surface runoff, ET, and storage, based on averaging over the watersheds, is given in Table 14 for each storm event (rounded to the nearest %).

TABLE 14. PROPORTION (%) OF EACH RIM TRAIL R2-R8 SUBWATERSHED PRECIPITATION LOST TO SURFACE RUNOFF, EVAPOTRANSPIRATION, AND STORAGE

Storm Event	Input	Output	Output	Output
	Precipitation in Rim Trail R2-R8 subwatershed (P_i)	Surface Runoff (Q_i)	Evapotranspiration (ET)	Storage (ΔS)
1 (2/9/2014)	100%	<1%	1%	98%
2 (3/2/2014)	100%	<1%	9%	90%
3 (3/30/2014)	100%	<1%	3%	96%
4 (12/13/2014)	100%	<1%	2%	98%
5 (2/8/2015)	100%	<1%	3%	97%
Average	100%	<1%	4%	96%

The conceptual hydrologic box model for the Rim Trail tributary subwatersheds is shown in Figure 30. For this study, the average precipitation,

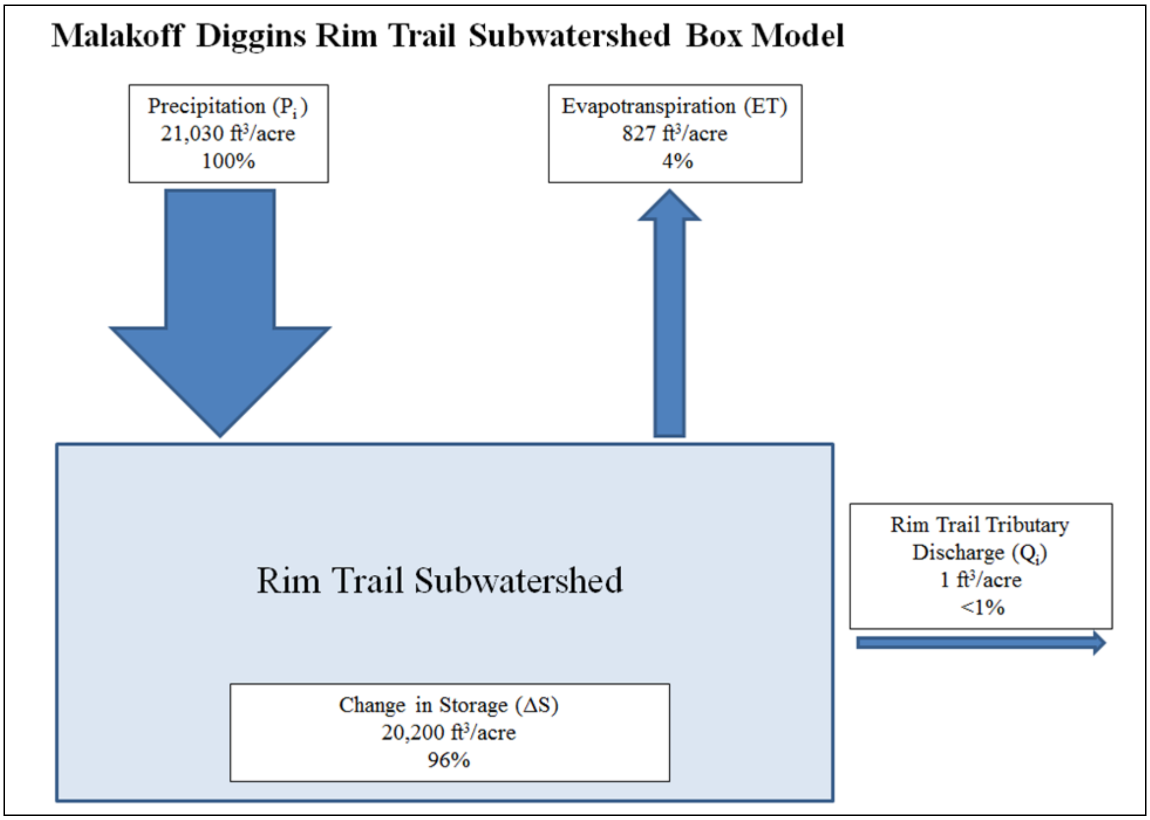

Figure 30. Conceptual Hydrologic Box Model of Rim Trail Tributary Subwatershed With Respective Input/Output Percent Proportions Averaged Over Five Storm Events.

evapotranspiration, change in storage, and discharge per acre for the Rim Trail subwatersheds are indicated. In computing these averages, for each storm event, the precipitation, evapotranspiration, change in storage, and discharge for each watershed were normalized by the respective watershed area. These normalized values were then averaged over the subwatersheds R2-R8 to get average box model values for each storm event. Finally, these average box model values for each storm event were then averaged over storm events 1-5 to obtain the average box model values for the study given in Figure 30. The average precipitation over storm events 1-5 was 21,030 ft^3/acre. This resulted in an average evapotranspiration of 827 ft^3/acre (4%), an average change in storage of 20,200 ft^3/acre (96%), and an average discharge of 1 ft^3/acre (<1%).

The conceptual hydrologic model for the Hiller Tunnel watershed is displayed with the percent proportions averaged over storm events 2-5 (Figure 31). The Hiller Tunnel watershed is shown in Figure 29, and encompasses all the Rim Trail tributary subwatersheds, the non-measured watersheds, and the remaining delineated area. Since

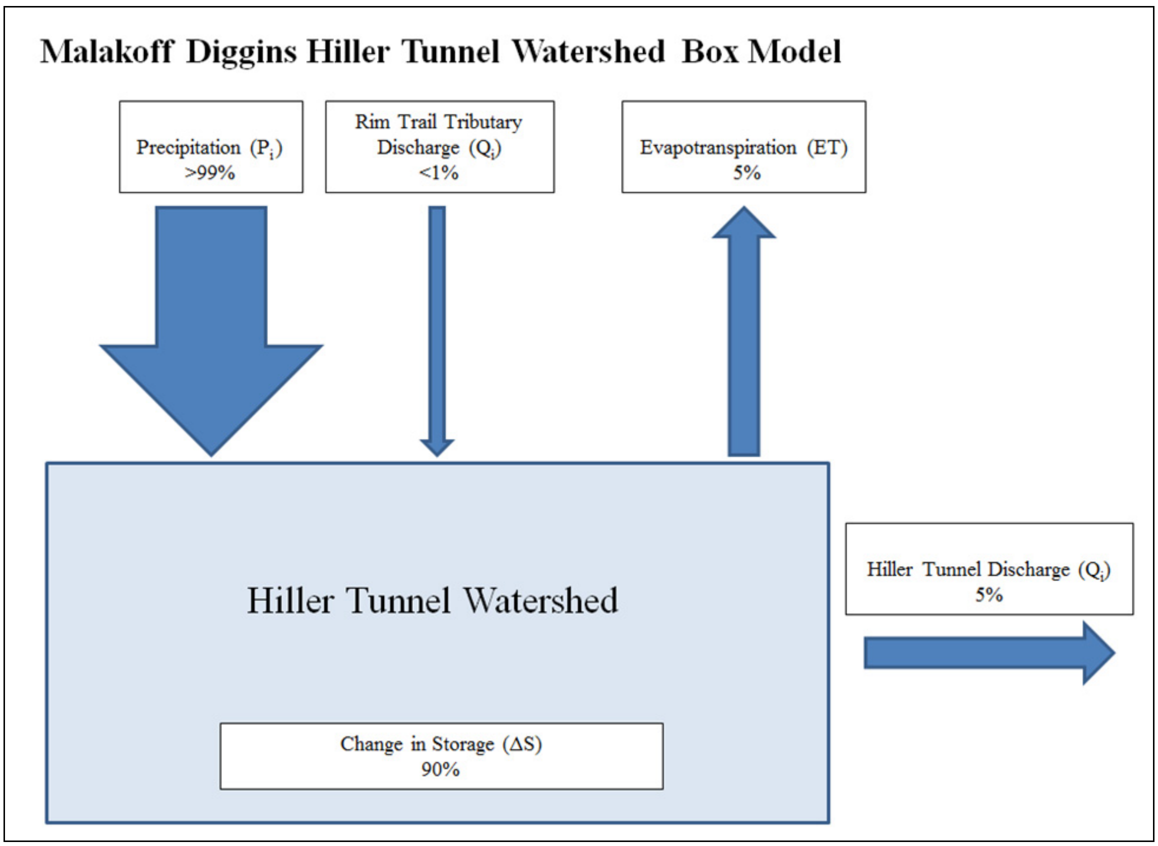

Figure 31. Conceptual Hydrologic Box Model of Hiller Tunnel Watershed With Respective Input/Output Percent Proportions Averaged Over Four Storm Events.

the Rim Trail tributary subwatersheds were quantified, and they represent a source of surface runoff, they are treated as inputs to the Hiller Tunnel watershed. For this model, the precipitation (> 99%) and the Rim Trail tributaries (<1%) are the inputs of water to the Hiller Tunnel watershed while the outputs include surface water discharge at the Hiller Tunnel outlet (5%), evapotranspiration (5%), and storage of water (90%) (Table 15, Figure 31). Storm event 1 was not included because its sample measurement was not incorporated into the Hiller Tunnel-Humbug Creek (Gage 3) discharge relationship used to estimate the total volume at the outlet during storm events. In comparison to the Rim Trail tributary discharge, the Hiller Tunnel outlet discharged approximately 5% of the water in the watershed, while the Rim Trail tributaries discharged less than 1% of the water. A number of factors can account for the difference between volumetric discharge at the Hiller Tunnel outlet and the Rim Trail tributaries. Canopy cover, soil type, and antecedent moisture conditions are several factors that influence the flow of water within a watershed and are discussed in detail in Discussion.

TABLE 15. PROPORTION (%) OF HILLER TUNNEL WATERSHED PRECIPITATION LOST TO HILLER TUNNEL OUTLET, EVAPOTRANSPIRATION, AND STORAGE

Storm Event	Input Precipitation Hiller Tunnel watershed (P_i)	Input Rim Trail tributaries R2-R8 (Q_i)	Output Hiller Tunnel Outlet (Q_i)	Output Evapotranspiration (ET)	Output Storage (ΔS)
2 (3/2/2014)	> 99%	< 1%	9%	10%	81%
3 (3/30/2014)	> 99%	< 1%	4%	4%	92%
4 (12/13/2014)	> 99%	< 1%	5%	2%	93%
5 (2/8/2015)	> 99%	< 1%	2%	3%	95%
Average	> 99%	< 1%	5%	5%	90%

While drainage area was the primary influence on streamflow volume, an increase in watershed size did not always lead to an increase in streamflow. R4 had the greatest watershed size and runoff volumes but also had the greatest discharge variability relative to the precipitation event volume. The field instantaneous discharge measurements (ft^3/s) and extrapolated volumes (ft^3) were not only dependent on watershed size.

The evapotranspiration within watersheds, the product of the watershed area and the evapotranspiration, A_{Rwshed} ET, was calculated as a volume (ft^3) for box model quantification. The CIMIS ET data, referenced for the Malakoff Diggins region, showed lower A_{Rwshed} ET volumes during the coldest (winter) months of the year whereas the maximum rates generally occurred closer to the warmer (summer) season. The study's watershed evapotranspiration was lowest in December, as colder temperatures (WRCC average temperature for December 2014 was 43.21 °F) cause trees to close their stomata and release less water (Hanson, 1991). Sample days two and three (March 2014) were warmer (WRCC average temperature for March 2014 was 50.18 °F) and according to the CIMIS ET map had higher evapotranspiration rates. Higher temperatures cause trees to open their stomata to "breathe" and release water to the atmosphere (Hanson, 1991).

The storage for each watershed showed variability over the water year. Increased precipitation led to greater storage earlier in the region's winter season (sample days one, four, and five). Approximated R2-R8 watershed total storage during the study is as follows: sample day one (0.93 acre-foot/acre), sample day two (0.29 acre-foot/acre), sample day three (0.31 acre-foot/acre), sample day four (0.38 acre-foot/acre), and sample day five (0.44 acre-foot/acre). Sample day one had a significant amount of storage when compared to other storm events likely from greater total precipitation, while sample days two and three had smaller amounts of precipitation and consequently lower storage was observed.

CHAPTER V

DISCUSSION

The study, conducted over WY 2014 and WY 2015 at Malakoff Diggins, quantified the contributions of the Rim Trail tributaries to the Hiller Tunnel discharge, metal concentrations, and total suspended sediment load using field measurements of instantaneous discharge during five storm events. The Rim Trail tributary discharge and sediment load were calculated using Humbug Creek continuous discharge measurements to estimate the tributary and Hiller Tunnel discharge over the duration of a storm. Precipitation measurements and records and regional estimates for evapotranspiration were applied to develop box models for the Rim Trail tributaries. The box models provided an understanding of the watershed inputs and outputs, and ultimately to what extent the Rim Trail subwatersheds contribute to the Hiller Tunnel discharge.

Rain Gages and Precipitation

According to DWR CDEC, California WY 2014 was the third driest water year in 119 recorded years and coincided with California's driest calendar year (DWR, 2015b). During WY 2014, there were three major storm event periods and four relatively smaller storm events. Sample day one occurred during the largest storm event of the water year while sample days two and three were conducted during the end of subsequent smaller storm events.

The California WY 2015 included a series of December storms, yet the lack of rain in 2015 extended the California drought throughout 2015, the fourth consecutive year (DWR, 2015b). All five sample days for which the study was conducted are representative of storm events during relatively dry years.

The total accumulated rainfall (including *Adjusted* precipitation from the regional DWR OHD gage) for the study period (10/1/2013-3/13/2015) was 63.7 inches. While the OHD gage is not located at the Malakoff Diggins study site (it is four miles northeast of Malakoff Diggins), the rain data collected was adjusted to be representative of Malakoff when the HOBO rain gage was not active. For the period when both gages were active, a correlation was performed to establish a precipitation relationship between the OHD and HOBO sites. The two data sets had a strong correlation, but OHD rainfall measurements were overall lower during this time period (Figure 10, Figure 11). From 11/11/2014 to 3/15/2015, the OHD accumulated precipitation was 19.24 inches while the TSF HOBO rain gage was 30.14 inches. While the OHD data were adjusted (by using the slope of the $y = 1.42x$ equation) to represent conditions at Malakoff Diggins Pit for the previous water year (WY 2014), it is important to note that the adjustment may have still underestimated precipitation for the study site during WY 2014 (storm events one, two, and three). If the OHD gage underestimated storm event precipitation, even after adjustments were made, hydrologic relationships will be altered. For example, if there was greater precipitation and discharge remained the same, the storage term would increase. The HOBO rain gage located in the Malakoff Diggins Pit is closer in distance and elevation to the tributary sample sites and Hiller Tunnel than the OHD rain gage, and therefore gives a more accurate representation of precipitation during WY 2015 (sample days four and five). The HOBO total storm event precipitation for storm events four and five are within the scale of all five storm events (Table 7). The adjusted OHD total precipitation for storm events two and three were both 3.8 inches (the lower end of the range) while for storm event one it was 11.4 inches (upper end of the range). The common scale between the HOBO rain gage data from storm events four and five and the adjusted OHD rain gage data, justifies the precipitation adjustment made for storm events one, two, and three.

Water Quality Measurements

The difference between total and dissolved metal concentrations can be attributed to whether the metals were filtered out or not. The study assumed that when metals are filtered out they are likely particulate bound (USEPA, 1996b; Fleck et al., 2010). The degree to which a metal binds to sediment differs between metals and also changes based on the nature of the sediment particles in the water (Csaba and Casaba, 2011). Overall, the results from the 2/9/2014 sample day indicate that metals are bound to sediment because there is a difference between the concentrations of total and dissolved metals, i.e. total is greater than dissolved. Microscopic assessment of heavy minerals obtained from a dredge test (2007) within the South Yuba River and an excavation (2008) in the South Yuba River-Humbug Creek confluence was conducted by the USGS and is reported by Fleck et al. (2010). Fleck et al. (2010) concluded that mercury is commonly attached to sediment (fine silts and clays) that can become mobilized during storm events and deposition of sediment downstream can increase the methylation of mercury. The study supports the concept that mercury, sourced from Malakoff Diggins, can be particulate-bound and contribute to bioaccumulation within the South Yuba River watershed. The Rim Trail tributary total metal concentrations for Hg, Cu, Ni, and Zn were greater than dissolved metal concentrations. The fraction of total metals found to be particulate-bound ranged greatly with sampling location on sample day one. Particulate-bound mercury ranged from 26% of total mercury at R7 to 99% of total mercury at Hiller Tunnel. Particulate-bound copper ranged from 14% at R7 to 98% at Hiller Tunnel. Particulate-bound nickel ranged from 0.02% at R2 to 93% at Hiller Tunnel. Particulate-bound zinc ranged from 24% at R4 to 98% at Hiller Tunnel. The high percentage of particulate-bound metals at Hiller Tunnel highlights the importance of sediment loads in surface water to facilitate the transport of these metals downstream during storm events.

The mobilization of mercury and sediment from Malakoff Diggins Pit and Hiller Tunnel impacts the mercury and sediment concentrations downstream in Humbug Creek and the South Yuba River. Grab samples of suspended sediment collected in Humbug Creek during a storm event on May 5, 2009, indicated storm flow mobilization of sediment (Fleck et al., 2010). Average total mercury concentration in suspended sediment was 43 ng/L with an average TSS concentration of 135 mg/L (Fleck et al., 2010). A downstream sample site, below the South Yuba River-Humbug Creek confluence had lower average total mercury and sediment concentrations than the Humbug Creek grab samples; average total mercury concentration was 17 ng/L and average TSS concentration was 75 mg/L below the confluence (Fleck et al., 2010). Fleck et al. (2010) stated that because the overall streamflow of the South Yuba River watershed (249 mi^2 or 655 km^2) is significantly greater than that of Humbug Creek (11 mi^2 or 28 km^2), TSS loads and total mercury from Humbug Creek are likely to be less than the South Yuba River and that concentrations get diluted when they enter the South Yuba River. The Fleck et al. (2010) study showed that the disturbance of particulate-bound mercury during storm events can increase mercury concentration and load in downstream waters. In comparison, this study recorded that on 2/9/2014 the Rim Trail tributaries above Malakoff Diggins Pit had lower total metal (specifically mercury) and TSS concentrations than Hiller Tunnel (Table 9). The Rim Trail tributary maximum concentration of total mercury was 21.50 ng/L (R2) and maximum TSS concentration was 11.3 mg/L (R5), while the Hiller Tunnel grab sample contained 500 ng/L of total mercury and 2,560 mg/L of TSS. The Rim Trail tributaries therefore did not contribute a significant load of mercury or sediment since concentrations were relatively minimal and overall discharge was small when compared to Hiller Tunnel discharge. However, unlike the Fleck et al. (2010) finding that total mercury and TSS concentrations diluted when they entered a large watershed, the concentrations in Hiller Tunnel increased indicating that the stream power from the tributaries allow for sediment and metals to be transported from the pit to Hiller Tunnel, Diggins Creek, and into the Humbug Creek watershed. Differences in metal and sediment concentrations between the Rim Trail tributaries and Hiller Tunnel illustrate that mercury and other metals are bound to particulate matter, primarily fine grained silts and clay sediments within the pit, from where they are mobilized during storm events.

CVRWQCB Water Quality Thresholds:
Mercury, Copper, Nickel, and Zinc

Trace amounts of heavy metals can enter the environment naturally from weathering, atmospheric deposition, soil erosion, and metal corrosion; however most metal exposure results from anthropogenic activities such as mining processes, agricultural uses, and industrial operations (Tchounwou et al., 2012). The Rim Trail tributary concentrations of mercury, copper, nickel, and zinc did not exceed common water quality thresholds.

The measured mercury concentrations (total and dissolved) of the Rim Trail tributaries were lower than the California Toxics Rule (CTR) MCL of 50 ng/L and the California Department of Public Health (CDPH) MCL of 2 µg/L for drinking water (USEPA, 2000). Tributary R2 had the highest total mercury (21.5 ng/L) and dissolved mercury (13.5 ng/L) concentrations when compared to other sampled tributaries (Table 9). While measured mercury concentrations did not exceed common regulatory criteria thresholds for surface water in California, it is still important to understand why mercury concentrations can be present above Malakoff Diggins Pit. Trace amounts of mercury were identified at a control site at the Relief Hill Road crossing at Humbug Creek east of the Malakoff Diggins Pit and were attributed to atmospheric mercury deposition (Nepal, 2013). It can be hypothesized that the presence of mercury in the Rim Trail tributaries was due to atmospheric deposition as well. Globally, mercury can be released to the atmosphere by natural and anthropogenic sources where it primarily (~95%) exists as elemental mercury (atmospheric residence times can range from 4 months to 2 years) but can also be attached to atmospheric particulate matter (atmospheric residence time of one week) (USEPA, 1997; Butler et al., 2007). Atmospheric wet or dry deposition of mercury onto land or plant surfaces can result in the mercury being re-emitted to the atmosphere or soil, or cause it to become methylated by bacteria (USEPA, 1997; Butler et al., 2007).

Sources of copper, nickel, and zinc likely occur from the physical and chemical weathering of local bedrock composed of low-grade metamorphic rocks as well as igneous rocks (Yeend, 1974). The dissolution and weathering of metals in parent rock is in part influenced by water pH; lower pH waters increase the solubility of heavy metals and their overall toxicity (Michaud, 1991). Water quality measurements show relatively higher pH values at the Rim Trail tributaries—a range from 5.80 (R7 on sample day 5, 2/8/2015) to 7.22 (R6 on sample day 2, 3/2/2014)—when compared to other mine sites (e.g., Iron Mountain Mine) with extremely low pH waters representative of acid mine drainage. The range of pH values measured in the Rim Trail tributaries indicates reduced solubility of heavy metals, which contributes to copper, nickel, and zinc concentrations below CTR MCLs.

The water quality analysis suggests that surface water entering the pit through the Rim Trail tributaries drainages is not a source of elevated contaminants to the Malakoff Diggins Pit or Hiller Tunnel discharge. Instead, the majority of metals and sediment are sourced from the pit, and under storm conditions can mobilize out of the pit through Hiller Tunnel.

Surface Water Discharge Measurements

High-elevation winter season (November-April) storm events contribute toward surface runoff and flooding within the Sierra Nevada region (Pandey et al., 1999).

Figures 8 and 9 show that the total storm event precipitation and resulting surface runoff vary over the winter season. These results are consistent with interannual variability in precipitation and snowfall that is generally observed in the Sierra Nevada. As the study was conducted during a continuous multi-year long California drought, rainfall deficits were observed and resulted in limited surface runoff compared to normal or wet years.

The total tributary discharge is directly related to Hiller Tunnel discharge. An increase in Hiller Tunnel discharge was consistent with an increase in total tributary discharge. The Hiller Tunnel minimum instantaneous discharge occurred on the same storm event as the minimum total tributary instantaneous discharge, storm event two (which had the lowest total precipitation) (Table 7, Table 11). The Hiller Tunnel maximum instantaneous discharge occurred on the same storm event as the maximum total tributary instantaneous discharge, storm event one (greatest total precipitation) (Table 7, Table 11). Over the five storm events, tributary R4 had the largest watershed and greatest instantaneous discharge and was a major contributor to the total Rim Trail tributary discharge towards Hiller Tunnel. Soil type and moisture, vegetation cover, and watershed slope and catchment size are key factors that affect each tributary's discharge (Winkler et al., 2010). A long-term study of storm events would more clearly indicate which tributaries have discharges that are higher or lower in relation to a storm event's duration and size. Overall, the comparison between the measured Rim Trail tributary stream discharges during storm events aids in identifying where the majority of surface water travels from and down toward the Malakoff Diggins Pit. A better understanding of the interconnectedness of Malakoff Diggins as a watershed and its response to precipitation is also obtained.

Hiller Tunnel-Humbug Creek (Gage 3) Discharge

A regression of Hiller Tunnel discharge data versus Gage 3 stage data resulted in the equation $y = 5.386x - 0.984$, where x is the stage (psi) measured at Gage 3 and y is the discharge (cfs) measured at Hiller Tunnel (Figure 20). The $R^2 = 0.54$ indicated that the correlation between discharge at Hiller Tunnel and stage data at Gage 3 may have been influenced by a number of factors. First, Hiller Tunnel surface water that infiltrated downstream before Gage 3 is considered a potential loss of water that is not quantified. Second, variable precipitation during storm events and precipitation lag time between site locations is important to note as these factors can produce different surface runoff conditions and skew hydrographs. However, the most important factor is that other streams with different drainage areas and runoff patterns flow into and contribute toward the Gage 3 discharge and are currently not quantified. Over WY 2014 and WY 2015, Hiller Tunnel discharge contributed < 1% to 38% (average of 28%) toward discharge at Gage 3 (Figure 22). The low percent contribution from Hiller Tunnel is indicative of dry periods without Hiller Tunnel discharge and minimal discharge at Gage 3. During storm events two, three, four, and five (storm event one anomaly omitted), the measured Hiller Tunnel discharge contributed 21% to 78% (average of 45%) towards the discharge at Gage 3 (Figure 22). The box model assumes that total precipitation and precipitation rate is equal for both locations during storm events, but storm event hydrographs show that this is not true. Rainfall patterns influence the hydrograph's rising limbs, peak discharge, and falling limbs. An analysis between the Hiller Tunnel discharge and the Gage 3 stage is discussed for each storm event below. Overall, the Humbug Creek discharge at Gage 3 is assumed to be representative of the Hiller Tunnel discharge hydrograph.

The predicted Hiller Tunnel discharge from the regression of Hiller Tunnel discharge and Gage 3 stage had comparable values to measured Hiller Tunnel discharge for sample days two, three, four, and five (Figure 21). Predicted values represent an instantaneous discharge at the same time as measured discharge during the storm event.

Storm Event Two

With a 10% error consideration, the Hiller Tunnel measured discharge (2.5 cfs) was equal to the predicted Hiller Tunnel discharge (3.4 cfs). This observation may be related to the fact that storm event two was the smallest storm (2.7 inches or 6.9 cm of precipitation over 90 hours) of the study. Field measurements of discharge during low amounts of precipitation and low discharge may be more accurate than field measurements during high discharge.

Storm Event Three

With a 10% error consideration, the Hiller Tunnel measured discharge (7.6 cfs) was somewhat greater than the Hiller Tunnel predicted discharge (4.5 cfs). Storm event three had the same amount of precipitation as storm event two (2.7 inches or 6.9 cm) but with a smaller storm duration (36 hours). The soil in the Malakoff Diggins Pit was likely more saturated during storm event three due to preceding smaller storm events. The predicted Hiller Tunnel discharge was determined from Humbug Creek (Gage 3) stage, which is downstream of the Malakoff Diggins Pit. The Hiller Tunnel predicted discharge may have been a weaker representation of discharge during this storm event because in-field factors such as the wetting up of pit soil can influence the timing and magnitude of discharge.

<u>Storm Event Four</u>

With a 10% error consideration, the Hiller Tunnel measured discharge (4.3 cfs) was equal to the Hiller Tunnel predicted discharge (4.2 cfs). Storm event four occurred after a series of smaller storms, where the soil was likely more saturated. When compared to the other study storm events, storm event four can be classified as an intermediary or medium sized storm.

<u>Storm Event Five</u>

With a 10% error consideration, the Hiller Tunnel measured discharge (6.5 cfs) was slightly greater than the Hiller Tunnel predicted discharge (2.0 cfs). A long period (approximately 45 days) where precipitation did not occur prior to this event likely contributed to higher soil uptake of precipitation, and consequently lower measured discharge. While the peak discharges of both Hiller Tunnel and Gage 3 were lower, the storm was flashier (a rapid rise and fall of surface runoff response to precipitation), which may have led to a larger difference between the measured and calculated Hiller Tunnel discharge. These observations indicate that flashier storm events may lead to a greater discrepancy between the measured and calculated discharges at Hiller Tunnel.

Total Suspended Sediment Load Measurements

Suspended sediment is mobilized by heavy rainfall and seasonally impacts downstream creeks and watersheds (Alpers et al., 2005). Smaller storm events and receding limbs of storm events cause sediment to build up and become temporarily stored as a secondary deposit, which can be remobilized or redistributed during larger storm events. Over the course of a water year, large suspended sediment loads can be carried in downstream waters. In WY 2012 and 2013 approximately 500 tons of suspended sediment came from Humbug Creek (TSF, 2015). A number of studies have reported upon sediment loads downstream of Malakoff Diggins' Hiller Tunnel output (NCRCD, 1978, 1979 a and b, 1980; DWR, 1987; Fleck et al., 2010; Nepal, 2013; TSF, 2015).

Sample day one, 2/9/2014, when compared to the other sample days, yielded the greatest discharge from the tributaries and Hiller Tunnel. Each instantaneous calculated TSS load is proportional to the measured discharge. Tributary R4 had the highest instantaneous TSS load (340 mg/s). This result is likely due to the fact that R4 had the largest watershed and a greater measured discharge (1.97 ft^3/s) compared to the other tributaries. Tributary R2 had the lowest instantaneous TSS load, which corresponded with a low measured discharge (0.1 ft^3/s); its watershed size is 93 acres. The discharges for the other Rim Trail tributaries are: R3 (0.08 ft^3/s), R5 (0.15 ft^3/s), R6 (0.46 ft^3/s), R7 (0.32 ft^3/s), and R8 (0.72 ft^3/s) (Table 11). The Hiller Tunnel instantaneous TSS load, 3.4 kg/s, was far greater than the sum of the TSS loads of the sampled tributaries (Table 11). This result is consistent with the Hiller outlet discharge measured at 47.0 ft^3/s (± 25%), the greatest instantaneous discharge of the study. The result shows a positive relationship between discharge and sediment – the greater the amount of discharge, the more sediment that was mobilized.

The discharge measured on February 9, 2014, can be compared to the NCRCD Phase III Report of Hiller Tunnel on February 13, 1979 (NCRCD, 1979b). Approximately 5.6 inches of precipitation were measured during the storm event from 2/12/1979-2/16/1979 whereas the 2/9/2014 storm event measured 11.2 inches (*Adjusted*). On 2/13/1979, the Hiller Tunnel discharge was measured to be 31 ft^3/s, with an instantaneous TSS load of 18.63 kg/s (1,118 kg/min) (NCRCD, 1979b). On 2/9/2014, the Hiller Tunnel discharge was measured to be 47.0 ft^3/s (± 25%), with an instantaneous TSS load of 3.4 kg/s or 204 kg/min. The TSS load observed on 2/9/2014 was lower than the NCRCD report on 2/13/1978; while higher discharge was recorded, the concentration of total suspended sediment was lower (neither measurements took into account bed load). Both storm events mobilized a considerable amount of sediment out of the pit.

Limitations in the field methods used at Hiller Tunnel during the 2/9/2014 storm event increased the error in surface water velocity measurements and sediment load calculations. During the storm, the water within the three middle subsections of the Hiller Tunnel outlet was moving too fast to stand in. These subsections were approximated with adjacent depth and velocity measurements. An in-field qualitative observation of high surface water velocity also justified the approximation (± 25%) of the three middle subsections, which provided a range of instantaneous discharge at Hiller Tunnel from 35 to 59 cfs. When the low end, 35 cfs, is considered, the R2-R8 percent contribution towards Hiller Tunnel shifts to 11% (Table 11) and the instantaneous TSS load is estimated to be 152 kg/min. When the high end, 59 cfs, is considered, the R2-R8 percent contribution towards Hiller Tunnel shifts to 6.5% (Table 11) and the instantaneous TSS load is estimated to be 257 kg/min. Despite a range of instantaneous TSS load at Hiller Tunnel (152-257 kg/min), the total R2-R8 tributary sediment load contribution remained <1% on storm event one.

The stage-discharge relationship, $y = 5.386x - 0.984$, where y is the Hiller Tunnel discharge and x is the Gage 3 stage can be used to validate whether the relationship is more useful to relate base flows or storm flows. At the approximate in-field discharge measurement timestamp (10:30 AM on 2/9/2014), the stage-discharge relationship predicts Hiller Tunnel discharge on storm event one to be 8.27 cfs. The value 8.27 cfs is lower than the range estimated in the field, 35-59 cfs; this relationship is stronger for storm events two, three, four, and five as predicted values are closer to measured values (Figure 21). The stage-discharge relationship is a useful tool to estimate Hiller Tunnel discharge. However, the relationship loses validity when the measured instantaneous discharge reaches extreme peaks such as in storm event one; therefore, Hiller Tunnel base flow predictions are stronger than storm flow predictions.

Nepal (2013) reported on the mobilization of sediment from Malakoff Diggins Pit and Hiller Tunnel. The study concluded that in WY 2012, sediment load from the pit ranged from 6 mg/s to 75,000 mg/s (0.00036 kg/min to 4.5 kg/min). The highest load of sediment was measured to be 24,000 mg/s from surface water on the floor of the pit along the north side (SS12) (Nepal, 2013). This sediment contribution within the pit is located at the bottom of the pit walls south of the tributaries 5, 6, and 7. In addition, Nepal (2013) measured 7,300 mg/s (4.5 kg/min) of sediment leaving Diggins Pond towards Hiller Tunnel and states that the pond can act as a reservoir for sediment and water sourced from the north end of the pit. During low flow conditions, sediment can become deposited temporarily in the pond, whereas larger storm events can move water across the pit as only a portion (not quantified) may reach the pond (Nepal, 2013). Nepal (2013) also showed that over the course of WY 2012, a TSS load of 1,800,000 kg was calculated below the Humbug Creek-Diggins Creek confluence at the Gage 3 site. Within WY 2012, a January storm totaled 115,212 kg (±8,000 kg) in Humbug Creek downstream of the confluence (Nepal, 2013). Background condition measurements of particulate bound mercury and sediment 500 meters upstream of the confluence at the Relief Hill Road Crossing (Road 1) contributed only 1% to the total load at Humbug Creek during the January storm (Nepal, 2013). Hiller Tunnel, the Malakoff Diggins Pit main outlet, was estimated to contribute about 50% of the particulate bound mercury and sediment load in Humbug Creek (Nepal, 2013).

In comparison to Nepal (2013), the research conducted shows that the Rim Trail tributaries contributed less than 1% of TSS load to Hiller Tunnel during the 2/9/2014 storm event. The Hiller Tunnel measured TSS load can be attributed to sediment from the Malakoff Diggins Pit, not from the Rim Trail tributaries. However, the stream power that the tributaries provide and the erosion caused by this power on, over, or through the pit walls is not well understood or quantified. Reduction of sediment from the Hiller Tunnel discharge would reduce sediment in Humbug Creek.

Hydrologic Modeling: ArcGIS Software

An ArcGIS watershed and drainage delineation by a pour point procedure was used along with LiDAR data to delineate the Rim Trail subwatersheds (R2-R8), the Hiller Tunnel watershed, and three additional non-measured watersheds (A, B, C) (Figure 29). Watersheds were not delineated at the eastern side of the Hiller Tunnel watershed because these watersheds are located within Malakoff Diggins Pit. Larger watersheds tend to have greater volume and peak flows from storm events than smaller watersheds (Brooks et al., 2012). The shape of a watershed can also affect how fast surface and subsurface water reaches the outlet (GPS sample point) of a watershed (Brooks et al., 2012). A more round-shaped watershed can contribute to greater surface water peak flows; surface runoff concentrates more quickly at the watershed outlet than in an elongated watershed (Black, 1972; 1997). In addition, the steeper the hillslope or channel gradient, the faster surface water is likely to runoff and reach peak flow (as less surface water will infiltrate) (Black, 1997). Projected surface water flow paths, also called drainage networks, were generated in ArcGIS using drainage topography (Spatial Analyst Tools: Hydrology).

The computer generation of drainage networks based solely on topography can oversimplify hillslope hydrology and the role of infiltration. Consequently, the drainage delineation process can display streams in locations where in fact there are no visible surface flows; the uptake of water by infiltration and groundwater flow are not incorporated as factors that can limit the drainage of a generated stream. Delineated drainages at the Malakoff Diggins upper watershed are likely affected by in-field hydrologic factors; infiltration and other features associated with relatively complex hillslope hydrology associated with the material that composes the pit walls can alter the contribution towards Hiller Tunnel discharge. Drainages on the pit floor, where there is minimal topography and flat surfaces, may cause storm flow to drain differently than shown in ArcGIS. In addition, man-made features such as drainages with culverts and tunnels are not incorporated into the drainage network and need to be inputted manually or excluded. These features generally divert the flow of water within a watershed and must be considered for hydrologic models and remediation efforts.

Rational Method

A number of referenced runoff coefficients (Hayes and Young, 2006; AMEC Earth & Environmental, Inc., 2008; Natural Resources Conservation Service [NRCS], 2013; CADOT, 2006; Shoblom, 2014) were reviewed as background references. While the study's back-calculated runoff coefficients are slightly lower than referenced runoff coefficients (which range from 0.14-0.34), sample day four (0.11) and sample day five (0.14) c values are used as a representation of Malakoff Diggins. Back-calculated runoff coefficient values are likely low due to the high variability of precipitation and stream runoff. An over estimation of the runoff coefficient value (e.g. using a greater c value for surface runoff calculations) would affect watershed instantaneous discharge and volume results. For example, the selection of a larger (>0.14) runoff coefficient value would increase relative proportions of the subwatershed instantaneous discharge and box model fluxes; however, increased surface runoff from streams may not be a true representation of in-field measurements during storm events. The larger runoff coefficient value may lead to an overestimation of the Rim Trail tributaries instantaneous discharge contribution to Hiller Tunnel. Long-term evaluation of tributary discharge would provide a range of potential Rational Method c values and increase accuracy of the method estimates.

In *Runoff Characteristics of California Streams*, the USGS states that most of the runoff of ephemeral streams occurs in a short amount of time, which causes distributions of daily discharges to be more skewed than those for perennial streams (Rantz, 2009). Except for R6 on sample day five, each extrapolated watershed's peak discharge increased with increased rainfall. Rim Trail tributary R6 may have had discharge during sample day five, yet none was observed during the time of sampling. Due to the direct response of the Rim Trail tributaries to rainfall, intermittent rainfall during storm events can contribute to "spotty" storm runoff. The lack of observable discharge at R3 and R6 may be attributed to such an occurrence. Variations in the width, depth, and velocity of a tributary can also lead to variation in peak discharge.

Non-measured watershed peak discharges were not observed in the field and are only an approximation. These streams were not measured because they were not running off during the study's five storm events. They are assumed to have a negligible discharge contribution towards the Malakoff Diggins Pit and Hiller Tunnel.

Box Modeling

A water-budget approach was used to estimate the sample day storm event volumes (ft^3) for the Rim Trail watershed input of precipitation and outputs of surface runoff, evapotranspiration, and loss to storage.

Precipitation events between November and April, characteristic of the Sierra Nevada region, were observed during sample days 1-5. A precipitation event's timing, magnitude, frequency, duration, and rate are factors that contribute toward the surface water runoff and in this study the input of water to the Hiller Tunnel watershed (Poff et al., 1997; Winkler et al., 2010). According to the Our House Dam rain gage, sample day one had the greatest total precipitation, consistent with the greatest tributary volumes. The box model methodology suggests that a greater catchment size, which captures more precipitation, leads to more runoff.

Watershed and Tributary Discharge

A number of processes and pathways can determine how much and how quickly precipitation will initiate the flow of an ephemeral stream within a watershed (Black, 1972; 1997). Discharge from each Rim Trail tributary, R_{QMi}, and non-measured watershed R_{QNi}, was extrapolated from the Humbug Creek hydrograph and calculated as a volume. Error is inherent in this calculation because each tributary is assumed to follow the Humbug Creek rainfall-runoff pattern. The tributary volumes determined from the extrapolation of a larger annual stream (Humbug Creek) are likely over-estimated since the hydrograph pattern expressed may not be fully representative of smaller tributaries that flow off from storm events. Tributary streams have variability in rainfall-runoff processes, and slight variations in precipitation (timing, duration, magnitude, and frequency) or watershed factors, such as ambient moisture or land cover can greatly influence the response of a stream (Poff et al., 1997; Stanfield and Jackson, 2011; Peirce, 2012). The study's instantaneous discharge measurements show that these tributaries do indeed respond differently to different storm timing, durations, and magnitude. The assumption that all tributaries respond similarly to a given amount of precipitation weakens short-term discharge analyses. This assumption is inherent to box models because they assume a steady state, when in fact the relative contributions of each factor are changing over time. Relative instantaneous volumes can still be established because each tributary's hydrograph follows the same general pattern; each tributary was extrapolated from the Humbug Creek stage-discharge relationship during a respective storm event. Tributary R4 had the greatest volume over all sample days, likely due to its large watershed size, circular-shaped watershed, and sample point location. Watershed R8 has a large, circular-shaped watershed while watershed R2 is both an elongated and bean-shaped basin. The ArcGIS delineation of sample points R3, R5, R6, and R7 illustrates these watersheds as narrower and elongated, which can slow the movement of water down toward its sample point location and result in a smaller instantaneous volume.

The non-measured watershed volumes were, as expected, strongly correlated to watershed size with R^2 values of 0.99. The calculation of non-measured peak discharges and volumes is limited by the Rational Method assumptions such as uniformly distributed precipitation over each watershed, constant precipitation intensity during each storm event, and that basin storage effects are negligible (Hayes and Young, 2006). During actual storm events, factors such as antecedent moisture conditions, rainfall magnitude, rainfall intensity, rainfall duration, rainfall frequency, as well as infiltration, detention, and flow routing throughout the watershed influence the peak discharge and ultimately volume. The saturation of a watershed's topsoil before and throughout a storm event can inhibit infiltration and generate overland flow and eventually peak flow (Zere, 2005). During storm events one, four, and five, ponding of water on sections of the Rim Trail path were observed; the trail soil was likely saturated, contributing to the movement of overland flow downstream. Also, the volumes for non-measured watersheds do not take into account the slope or shape of a watershed. In all, the discrepancy of results between the watershed volumes and non-measured watershed volumes on sample days four and five demonstrates that these factors occur and impact tributary discharges and volumes. An unsaturated topsoil, low rainfall intensity, and short rainfall duration are examples of hydrologic factors that can decrease watershed volumes; conversely, a saturated topsoil, high rainfall intensity, and long rainfall duration can increase watershed volumes.

Evapotranspiration

Each watershed at Malakoff Diggins was assumed to have an equal canopy cover and type (representative of a Ponderosa pine forest). In general, the greater the watershed area, the more evapotranspiration that can occur. The assumption that there is a uniform Ponderosa pine canopy cover does not account for changes of vegetative cover within each watershed that can affect fluxes such as evapo-transpiration, surface runoff from streams, and storage. The presence of a vegetative cover can slow or intercept rain falling from the sky to the soil and limit the amount of ephemeral stream runoff generated (North and Stine, 2012). In contrast, scarce vegetative cover and poorly developed soils (e.g., Malakoff Diggins Pit sediment), can produce greater runoff and erosion per unit area for a given rainfall intensity (Levick et al., 2008). The scarce tree cover within the Malakoff Diggins Pit was a factor that led to greater volumetric discharge at the Hiller Tunnel outlet than at the Rim Trail tributaries (Figure 31). Factors that affect evapotranspiration—relative humidity, wind, soil-moisture, and type of plant—were not directly considered for each watershed. The sample day one calculations of evapotranspiration volumes were greater than sample day three because it was a longer storm event. The calculated evapotranspiration rates for all sample days were likely higher than actual in-field evapotranspiration rates since the study was conducted during drought years; transpiration by plants can decrease in an attempt to conserve water (although transpiration increases during winter months as more moisture exists within a watershed).

Storage

The final watershed flux in the box model equation can be defined as the combination of infiltration from the land surface as well as water that percolated downwards into the saturated zone within the water table (described as groundwater). Since infiltration and groundwater measurements were not conducted at the Rim Trail tributary watershed sites, the term was calculated as the difference between input precipitation and the sum of the outputs ET and stream discharge. The remaining volumetric difference is only a calculation and not a measured quantity. Errors in the estimation of the storage flux come from discharge measurements (Buchanan and Somers, 1969; Olson and Norris, 2007), watershed-precipitation input estimates, and watershed-evapotranspiration output estimates. Potential errors in the storage are also associated with the loss of water between watersheds to deep groundwater systems and quantifying this flux is extremely difficult (Sayama et al., 2011). According to the box model, a large amount of precipitation was lost to an unknown combination of soil water and groundwater storage. At Malakoff Diggins, over five sample days, the estimated loss of rainfall to storage ranged from 91% to 99%. Dr. Peter Black, in *Watershed Functions* (1997), states that the total amount of storage available in an undisturbed soil (such as a forest) can be "prodigious; a three-foot soil profile can store more than a third of a million gallons of water per acre in the 33-percent retention storage alone" (Black, 1997, p. 7). The quantified storage of the Rim Trail watersheds was comparable in magnitude to Black's upper boundary undisturbed soil storage (converted storage equal to ~1.0 acre-foot/acre). Hillslope hydrology suggests that water storage generally decreases with an increase in slope. For comparison, the approximated R2-R8 watershed storage for the study are: sample day one (0.93 acre-foot/acre), sample day two (0.29 acre-foot/acre), sample day three (0.31 acre-foot/acre), sample day four (0.38 acre-foot/acre), and sample day five (0.44 acre-foot/acre).

The National Cooperative Soil Survey (NCSS), run by USDA Natural Resources Conservation Service (NRCS), lists the Malakoff Diggins Rim Trail watersheds R2-R8 soil type as predominantly Cohasset cobbly loam (NRCS, 2015). The soil series horizons from top to bottom are listed as A - 0 to 15 inches: cobbly loam, Bt - 15 to 96 inches: cobbly clay loam, and Cr - 96 to 106 inches: bedrock (NRCS, 2015). The NRCS defines the R2-R8 watershed soil type as a well-drained drainage class, a very-high runoff class, and with moderate (~8.2 inches) available water storage (NRCS, 2015).

Study results of the Rim Trail watershed discharge and storage were generally consistent with these soil type characteristics; variability within and between storm events influenced these results. A larger storm (storm event one) led to discharge at all tributaries whereas a smaller storm (storm event two), which produced less precipitation, resulted in discharge at only five tributaries. In comparison, soil containing fine grain and clay seen within Malakoff Diggins Pit can slow the infiltration of water and lead to greater surface runoff and the mobilization of sediment out of the pit. The Malakoff Diggins Pit soil is a factor that contributes towards greater volumetric discharge at the Hiller Tunnel outlet (Figure 31).

A study of larger yet comparable watersheds in Eureka, California (Sayama et al., 2011) showed similar storage results. Sayama et al. concluded that their study site watersheds stored "significant amounts of rainfall with little corresponding runoff in the beginning of the wet season" (Sayama et al., 2011, abstract). Antecedent moisture conditions could have had an effect on the flow responses of both studies. Antecedent moisture conditions are lower when there has been less rainfall; dry soils will typically uptake water more readily and limit storm event discharge. In this study, storm event one had the least rainfall (2.9 inches) prior to its occurrence (Table 1). While the storm produced the greatest instantaneous and volumetric discharge at the Rim Trail tributaries and Hiller Tunnel, a considerable amount of water may have still been taken up by dry soils. Antecedent moisture conditions were likely greater on storm events two, three, and four; these sample days were conducted after a chain of storm events (Figure 8, Figure 9). Successive rainfall events can produce wetter soils and contribute towards greater rates of runoff. Storm event five occurred after a long period without precipitation, when the watershed soils were likely drier. However, the intensity of storm five (0.11 inch/hr) still led to the second highest discharge at the Rim Trail tributaries and the third highest at Hiller Tunnel. Antecedent moisture conditions are another variable factor in the complex determination of a watershed box model and quantified fluxes. The study showed that storm intensity and magnitude can also be driving factors of surface runoff.

Overall, delineation and hydrologic budgeting of Malakoff Diggins Rim Trail subwatersheds is a complex process. In *A hydrological perspective*, Klemeš describes quantification of the hydrologic water balance as "one of the most challenging Rubik Cubes of nature, one in which the 'squares' change colors, shapes, and sizes as they are being moved around by the different forces, and in which even the structural setup changes with time " (1988, p. 20). Each quantified Rim Trail subwatershed is in a constant state of change and the study's measurements and calculations are only a snapshot of a greater picture.

Sources of Error

Potential sources of error arise from field measurements, lab analyses, ArcGIS measurements and processes, instrument error, and associated calculations. These errors collectively contribute to an overall error in calculated quantities for the study.

Sources of field error during velocity measurements can occur with the direction of the electromagnetic EM950 velocity sensor, human disturbance of streamflow, and instream rocks affecting velocity readings (back eddies can greatly influence velocity readings in small streams with low flow). The width and depth of the stream subsections are approximated to the nearest tenth of a foot. The Hach Portable Velocity Meter FH950 sensor accuracy is ±2% of the reading or ±0.05 ft/s in waters from 0 to 10 ft/s; also, the minimum water depth for the sensor is 3.18 cm (1.25 in) (Hach, 2014). Multiple sample day velocity measurements of the Rim Trail tributaries were measured at 0.1 ft (1.2 inches), the minimum depth for the sensor. The sensor loses accuracy at and below the minimum depth, which brings in field measurement error. Additionally, stream velocity subsection measurements and tape measurement lines were not conducted at the same exact location for each sample day. For the small streams, the subsection measurements are also limited; approximately seven to twelve subsections were possible to measure velocity. Intermittent rainfall was observed during the sample days and may have introduced variability in Rim Trail tributary discharge.

There are ArcGIS errors associated with the delineation of the Malakoff Diggins watershed and the Rim Trail tributary watersheds. While the processed LiDAR data were extremely detailed, with 2-foot contours, topological errors can occur when the data is digitized, resulting in imperfect polygon detail.

Precipitation gage error needs to be considered. Both the HOBO and OHD rain gages have instrumentation error. There are limitations in the data since two distant point precipitation measurements were used to estimate precipitation over the study area. The OHD rain gage measurements are only representative of rainfall at the Malakoff Diggins watershed, four miles away, which creates sampling error since the measurements are not at the Malakoff Diggins site. The OHD gage also had a period of time (5/7/2014 20:30 to 5/15/2014 15:15) when data were not present, perhaps due to instrument recalibration or malfunction.

Evapotranspiration from CIMIS is regionally approximated for the study site. CIMIS states that variability in evapotranspiration can vary up to ±0.02 inches/day during the study region's winter months (December, January, and February in the Northern Hemisphere), which accounts for three out of five study sample days. The estimated watershed-evapotranspiration volumes varied by month and are likely higher than the actual volumes, as the study was conducted during drought years.

The five sample days and corresponding measurements are limited in their study period. The amount and reliability of sample day measurements could be greatly improved with in-field continuous remote monitoring of the tributaries and Hiller Tunnel. Continuously monitored data can produce hydrographs and would be extremely beneficial in understanding how surface water, metal concentration, and TSS vary with storm events. During storm events, a number of non-quantified surface water streams (smaller than the streams measured in the study) were observed flowing north-south of the Rim Trail towards Malakoff Diggins Pit. The measurement of these lesser ephemeral flows can provide a better understanding of the amount of water flowing into the pit, and ultimately the Malakoff Diggins box model. Climate change over time within the Malakoff Diggins region is also a factor that contributes error in parameters such as evapotranspiration rates and the Rational Method rainfall-runoff values; these rates and runoff values are based on past hydrologic records, and in reality are in constant change.

CHAPTER VI

CONCLUSIONS

For the five sample days, which spanned a range of storm events, the total Rim Trail tributary instantaneous discharge ranged from 0.4 to 3.8 ft^3/s (± 10%), while the Hiller Tunnel instantaneous discharge ranged from 2.5 (± 10%) to 47 ft^3/s (± 25%). The field measurements indicate that the Rim Trail tributaries (inputs) contribute 6.5-26% towards the Hiller Tunnel (output) outflow discharge.

The metal concentrations in the surface water that enters Malakoff Diggins Pit, as measured at Rim Trail tributaries R2, R4, R5, R7, and R8 during storm event one, are below the regulatory thresholds for mercury, copper, nickel, and zinc, in surface waters of California set by the Regional Water Quality Control Board (USEPA, 2000). However, the Hiller Tunnel metal concentrations of mercury (500 ng/L), copper (136 µg/L), nickel (109 µg/L), and zinc (158 µg/L) in the discharge from storm event one (2/9/2014) (other storm events were not sampled) were above the California Toxics Rule thresholds. The 2/9/2014 storm event results indicate that the metals are primarily bound to sediment in suspension, demonstrating that suspended sediment in surface water discharge facilitates the transport of these metals downstream.

The total instantaneous tributary TSS load (508 mg/s) on 2/9/2014 contributed less than 1% towards the Hiller Tunnel instantaneous TSS load (3.4 kg/s). This finding indicates that it is primarily surface water within the Malakoff Diggins Pit that mobilizes sediment and transports it downstream towards Hiller Tunnel.

Storm event water budgets for the Rim Trail subwatersheds and the Hiller Tunnel watershed were determined using the hydrologic field measurements, the box model, ArcGIS software, and the Rational Method. The subwatershed-precipitation volumes are directly dependent (linearly) on the watershed areas. However, the output discharge volumes for the subwatersheds were found to less directly related to watershed area. The computed subwatershed-evapotranspiration (CIMIS) volumes are likely higher than actual because the study was conducted during drought years. The hillslope storage above the pit is a dominant factor in the Rim Trail subwatershed box model and the uptake of precipitation, which leads to lower surface runoff at the Rim Trail tributaries compared to Hiller Tunnel.

The non-measured watersheds did not have surface water runoff during the study's five storm events and are presumed to have had a relatively minor discharge contribution towards the Malakoff Diggins Pit and Hiller Tunnel. However, the Rational Method calculations of the non-measured watersheds A, B, and C helped predict instantaneous peak discharges during potential larger storm events. During the study's storm events the Rim Trail watersheds were influenced by interactive factors such as antecedent moisture, soil type, and watershed size, shape, and slope.

CHAPTER VII

RECOMMENDATIONS

The Malakoff Diggins Pit rain gage (HOBO) was not operational for storm events one, two, and three. A secondary gage (OHD) located four miles from HOBO was used to approximate the Malakoff Diggins Pit precipitation data for these storm events. It is recommended that an additional rain gage be installed and operated at Malakoff Diggins Pit as a backup to ensure that accurate precipitation data is consistently available. More accurate storm event hydrographs within the study site will allow for better modeling of the Rational Method discharge and TSS loads at Rim Trail tributaries and Hiller Tunnel.

The instantaneous measurements of surface water discharge at the Rim Trail tributaries and Hiller Tunnel were ‘point-in-time’ measurements that limit hydrologic analysis since they are only a snapshot of a storm event and cannot fully illustrate fluctuations in surface water and sediment loads over time. The installation and continuous operation of stream gages at the Rim Trail tributaries and Hiller Tunnel would produce a more comprehensive data set and allow for better comparison between the Rim Trail subwatersheds and downstream discharge locations. Continuous data would allow researchers to quantify lag times between the beginning of a storm event and the flows at the Rim Trail tributaries, Hiller Tunnel, and Humbug Creek. Furthermore, additional research of subsurface and surface flow is needed to determine the extent to which Diggins Pond contributes to Hiller Tunnel discharge.

Sampling multiple storm events each year would provide a greater understanding of the distribution and concentration of metals, the TSS load, as well as their sources and mobilization to the Hiller Tunnel discharge. Bedload was not considered in the sediment samples and may have a significant contribution to the total sediment load; bedload measurements of the Rim Trail tributaries and Hiller Tunnel during storm events should be considered.

Infiltration measurements (measured with infiltrometers) within the Rim Trail watersheds and Malakoff Diggins Pit soils should be conducted to determine infiltration rates because these rates ultimately influence storm event surface runoff, soil erosion, and sediment transport to downstream watersheds. Measurements at these locations would help fill data gaps. The storage of water above and within the pit, as well as potential groundwater movement, are crucial unknowns that, if known, would provide a better understanding of the Malakoff Diggins watershed. Further quantification of storage can improve the watershed hydrological model and provide insights towards remediation and management solutions. For example, the amount of water that infiltrates into pit soils (and consequently mobilizes sediment) during storm events is important to understand for the construction of a sediment detention and filtration structure at the Malakoff Diggins Pit main outlet north of Hiller Tunnel.

The ArcGIS hydrologic tools have errors associated with them and do not account for man-made underground drainages or tunnels at the Malakoff Diggins site. A manual correction of certain areas of the study site using topographic maps and in-the-field site characterization (mapping tunnels, drainages, and roads) would clearly reduce

ArcGIS delineation errors and produce more accurate watershed drainages. Additional watershed delineation software (e.g. EPA's BASINS) could be used for map comparisons; overlaid watershed delineations can act as a visual aid to highlight areas that might need further stream channelization and watershed boundary mapping.

A pilot study could be conducted at Malakoff Diggins to determine the efficacy of removing particulate-bound mercury in turbid suspension with an *in-situ* coagulation method. The removal of mercury requires the addition of metal-based coagulants (ferric chloride, ferric sulfate, or polyaluminum chloride) to isolated dissolved organic matter in surface water (Henneberry et al., 2010). Henneberry et al. (2010) reported that dissolved organic matter (DOM) from water collected from an agricultural drain in the Sacramento-San Joaquin Delta was laboratory tested with the coagulation method. Lab analysis shows that coagulants removed 97% of IHg and 80% of MeHg, while field (Twitchell Island) results showed a removal of 70% IHg and 60% MeHg (Henneberry et al., 2010). The technique is efficient in the removal of Hg in clay sediment and eroding tailings (Henneberry et al., 2010). Fleck et al. (2010) states that the highest Hg concentration at Malakoff Diggins is found within silts and clays. The method could be an additional way to restore water quality within the Malakoff Diggins Pit.

The selection of effective management solutions to remediate the discharge from this historic mine would be beneficial for downstream vegetation, water quality, and wildlife. The study reported on contaminated discharge and sediment loads at Malakoff Diggins from Hiller Tunnel and can be used to inform potential remediation efforts such as Rim Trail tributary stream diversions and a sediment detention and water filtration structure north of the Hiller Tunnel inlet. The study indicates that the Rim Trail tributaries do not contribute a significant amount of surface water and minimal to no sediment load towards Hiller Tunnel load during storm events. In addition, the metal concentrations in these Rim Trail tributaries are below the regulatory metal thresholds for mercury, copper, nickel, and zinc for surface waters of California set by the Regional Water Quality Control Board (USEPA, 2000). Thus, the diversion of the Rim Trail tributaries around the Malakoff Diggins Pit is not a highly impactful option. Instead, sediment abatement at the Hiller Tunnel inlet by water detention and filtration would seem to be a more effective method to control contaminated surface water and sediment from leaving Malakoff Diggins and affecting downstream watersheds in Humbug Creek and the South Yuba River.

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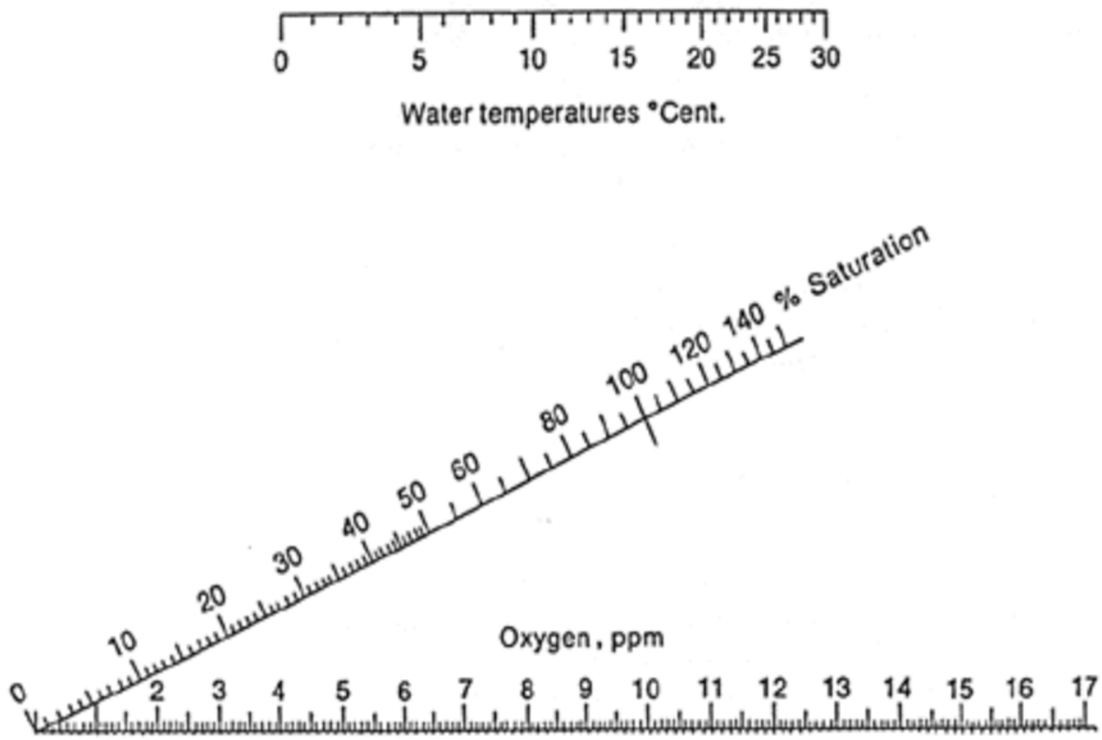
APPENDIX A

Rawson's Nomograph for Obtaining Oxygen Saturation Values (1 ppm = 1 mg/L) (Welch 1948).



APPENDIX B

MALAKOFF DIGGINS RIM TRAIL TRIBUTARY HYDROLOGICAL BUDGET: SAMPLE DAYS 1-5

Sample Day 1 2/9/14	$R_{Qi\ (measured)}$	$A_{Rwshed}\ P_i$	R_{QMi} (measured)	A_{Rwshed} ET	ΔS
Site ID	Extrapolated Peak Instantaneous Runoff (ft^3/s)	Area * Precipitation (ft^3)	Storm Event Tributary Runoff (ft^3)	Area * Evapotranspiration (ft^3)	Change in Storage (ft^3)
R2 Watershed	0.10	3,841,500	17	65,850	3,775,633
R3 Watershed	0.077	1,412,222	13	24,208	1,388,001
R4 Watershed	2.0	6,195,667	341	106,205	6,089,121
R5 Watershed	0.16	1,258,657	27	21,576	1,237,054
R6 Watershed	0.46	727,349	84	12,468	714,797
R7 Watershed	0.32	1,540,869	59	26,413	1,514,397
R8 Watershed	0.72	3,985,888	135	68,325	3,917,428

Footnote: Storm event precipitation is an *Adjusted* amount.

Sample Day 2 3/2/14	$R_{Qi\ (measured)}$	$A_{Rwshed}\ P_i$	R_{QMi} (measured)	A_{Rwshed} ET	ΔS
Site ID	Extrapolated Peak Instantaneous Runoff (ft^3/s)	Area * Precipitation (ft^3)	Storm Event Tributary Runoff (ft^3)	Area * Evapotranspiration (ft^3)	Change in Storage (ft^3)
R2 Watershed	--	1,293,979	--	126,365	1,167,614
R3 Watershed	--	475,696	--	46,455	429,241
R4 Watershed	0.22	2,086,962	84	203,805	1,883,073
R5 Watershed	0.059	423,969	23	41,403	382,543
R6 Watershed	0.031	245,002	11	23,926	221,065
R7 Watershed	0.024	519,029	8	50,686	468,335
R8 Watershed	0.060	1,342,615	23	131,115	1,211,477

Footnote: Storm event precipitation is an *Adjusted* amount.

Sample Day 3 3/30/14	$R_{Qi\ (measured)}$	$A_{Rwshed}\ P_i$	R_{QMi} (measured)	A_{Rwshed} ET	ΔS
Site ID	Extrapolated Peak Instantaneous Runoff (ft^3/s)	Area * Precipitation (ft^3)	Storm Event Tributary Runoff (ft^3)	Area * Evapotranspiration (ft^3)	Change in Storage (ft^3)
R2 Watershed	0.0054	1,293,979	2	50,546	1,243,431
R3 Watershed	0.091	475,696	14	18,582	457,100
R4 Watershed	0.34	2,086,962	52	81,522	2,005,388
R5 Watershed	0.069	423,969	11	16,561	407,397
R6 Watershed	0.011	245,002	2	9,570	235,430
R7 Watershed	0.071	519,029	11	20,275	498,743
R8 Watershed	0.072	1,342,615	11	52,446	1,290,158

Footnote: Storm event precipitation is an *Adjusted* amount.

Sample Day 4 12/13/14	$R_{Qi\ (measured)}$	$A_{Rwshed}\,P_i$	R_{QMi} (measured)	A_{Rwshed} ET	ΔS
Site ID	Extrapolated Peak Instantaneous Runoff (ft^3/s)	Area * Precipitation (ft^3)	Storm Event Tributary Runoff (ft^3)	Area * Evapotranspiration (ft^3)	Change in Storage (ft^3)
R2 Watershed	0.0082	1,550,078	3	23,588	1,526,487
R3 Watershed	--	569,843	--	8,672	561,171
R4 Watershed	0.36	2,500,004	104	38,044	2,461,856
R5 Watershed	0.044	507,879	12	7,729	500,139
R6 Watershed	0.086	293,492	26	4,466	289,000
R7 Watershed	0.0048	621,754	3	9,461	612,290
R8 Watershed	0.046	1,608,340	15	24,475	1,583,850

Sample Day 4 12/13/14	$R_{Qi\ (calculated)}$	$A_{Rwshed}\,P_i$	R_{QNi} (calculated)	A_{Rwshed} ET	ΔS
Site ID	Rational Method Peak Runoff (ft^3/s)	Area * Precipitation (ft^3)	Storm Event Tributary Runoff (ft^3)	Area * Evapotranspiration (ft^3)	Change in Storage (ft^3)
Non-measured Watershed A	0.44	796,021	69	12,113	783,839
Non-measured Watershed B	0.28	504,582	43	7,678	496,861
Non-measured Watershed C	0.14	252,393	22	3,841	248,530

Sample Day 5 2/8/15	$R_{Qi\ (measured)}$	$A_{Rwshed}\ P_i$	R_{QMi} (measured)	A_{Rwshed} ET	ΔS
Site ID	Extrapolated Peak Instantaneous Runoff (ft^3/s)	Area * Precipitation (ft^3)	Storm Event Tributary Runoff (ft^3)	Area * Evapotranspiration (ft^3)	Change in Storage (ft^3)
R2 Watershed	0.20	1,779,221	48	49,142	1,730,031
R3 Watershed	0.29	654,082	67	18,066	635,949
R4 Watershed	0.80	2,869,572	169	79,257	2,790,146
R5 Watershed	0.070	582,957	13	16,101	566,843
R6 Watershed	--	336,878	--	9,305	327,573
R7 Watershed	0.24	713,666	43	19,711	693,912
R8 Watershed	0.070	1,846,096	12	50,989	1,795,095

Sample Day 5 2/8/15	$R_{Qi\ (calculated)}$	$A_{Rwshed}\ P_i$	R_{QNi} (calculated)	A_{Rwshed} ET	ΔS
Site ID	Rational Method Peak Runoff (ft^3/s)	Area * Precipitation (ft^3)	Storm Event Tributary Runoff (ft^3)	Area * Evapotranspiration (ft^3)	Change in Storage (ft^3)
Non-measured Watershed A	0.71	917,156	93	25,237	891,826
Non-measured Watershed B	0.45	581,368	59	15,997	5,653,112
Non-measured Watershed C	0.22	290,802	29	8,002	282,771

APPENDIX C

YSI 556 WATER QUALITY MEASUREMENTS: SAMPLE DAYS 1-5

Sample Day 1 2/9/14	Temperature °C	Conductivity µS/cm	DO mg/L	ORP mV	pH
Hiller Tunnel *10:30 AM*	7.14	770	12.0	108.8	6.55
R1 *11:00 AM*	8.03	49	11.3	105.2	7.14
R2 *11:30 AM*	7.58	65	11.1	105.8	7.06
R3 *12:06 PM*	7.67	65	11.1	87.5	7.17
R4 *12:30 PM*	7.30	49	10.9	100.6	6.83
R5 *1:00 PM*	8.01	65	10.7	97.5	6.80
R6 *1:30 PM*	8.44	76	10.8	97.0	7.10
R7 *2:00 PM*	7.92	49	11.3	98.0	7.18
R8 *4:30 PM*	7.38	51	11.2	86.6	7.20

Sample Day 2 3/2/14	Temperature °C	Conductivity µS/cm	DO mg/L	ORP mV	pH
Hiller Tunnel *10:18 AM*	7.15	146	12.5	-22	7.83
R1	..	..	..	..	..
R2	..	..	..	..	..
R3	..	..	..	..	..
R4 *11:43 AM*	8.19	86	10.2	59.9	7.50
R5 *12:31 PM*	8.55	87	9.5	63.9	7.01
R6 *12:35 PM*	8.07	78	10.7	126.9	7.22
R7 *2:00 PM*	8.59	60	11.2	115.7	7.04
R8 *4:30 PM*	8.23	69	10.9	142	7.15

Footnote: No measurements from R1, R2, and R3 due to lack of surface runoff.

Sample Day 3 3/30/14	Temperature °C	Conductivity µS/cm	DO mg/L	ORP mV	pH
Hiller Tunnel *10:10 AM*	6.18	104	12.3	67.1	6.74
R1 *10:57 AM*	8.31	69	10.9	77.9	6.92
R2 *11:24 AM*	7.98	89	10.4	94.8	6.73
R3 *11:55 AM*	8.88	91	10.7	48.1	7.11
R4 *12:26 PM*	8.29	78	10.4	76.3	6.46
R5 *12:53 PM*	8.85	88	9.5	51.2	6.41
R6 *1:20 PM*	7.32	72	10.5	49.8	6.92
R7 *1:30 PM*	8.24	56	11.0	55.0	6.74
R8 *1:55 PM*	9.41	75	10.7	41.8	6.83

Sample Day 4 12/13/14	Temperature °C	Conductivity µS/cm	DO mg/L	ORP mV	pH
Hiller Tunnel *10:40 AM*	5.86	99	12.5	151.6	6.20
R1 *11:44 AM*	8.91	52	10.8	131.2	6.76
R2 *12:14 PM*	8.69	79	9.4	136.8	6.69
R3	..	..	..	..	..
R4 *12:53 PM*	9.31	82	10.3	138.6	6.70
R5 *1:44 PM*	9.81	82	8.4	142.7	6.43
R6 *2:03 PM*	9.38	79	10.1	141.3	6.49
R7 *2:20 PM*	8.80	54	10.5	146.2	6.52
R8 *2:36 PM*	9.05	64	10.7	134.5	6.68

Footnote: No measurements from R3 due to lack of surface runoff.

Sample Day 5 2/8/15	Temperature °C	Conductivity µS/cm	DO mg/L	ORP mV	pH
Hiller Tunnel *12:00 PM*	8.8	144	10.5	87.7	6.95
R1	..	..	..	..	..
R2 *1:40 PM*	8.91	65	10.7	131.2	6.76
R3 *2:00 PM*	8.50	90	9.3	124.6	6.79
R4 *2:30 PM*	9.36	66	9.6	94.8	6.56
R5 *3:00 PM*	9.89	70	8.7	101	6.68
R6 *3:40 PM*	..	..	..	..	..
R7 *4:00 PM*	9.80	58	9.8	85.7	5.80
R8 *4:30 PM*	9.39	84	10.3	91.6	6.56

Footnote: No measurements from R1 and R6 due to lack of surface runoff.