Appendix G4
Groundwater Modeling Analysis

Groundwater Modeling Analysis of Proposed Wastewater Dispersal -- City of Malibu Malibu, California

Prepared for

City of Malibu, California

by

McDonald Morrissey ASSOCIATES, Inc.

280 Pleasant Street
Concord, New Hampshire
03301
603-228-2280

April 3, 2014

TABLE OF CONTENTS

FIGURES:

FIGURES (continued):

FIGURES (continued):

FIGURES (continued):

FIGURES (continued):

TABLES (in text):

APPENDIX A

1.0 INTRODUCTION

The purpose of this report is to describe groundwater modeling analyses conducted that simulate underground injection of disinfected wastewater (recycled water) in the Civic Center area of the City of Malibu. The groundwater model used for these analyses is an enhanced version of MODFLOW based models prepared for the City of Malibu in 2012 and in 2010. The 2012 model was described in the technical memorandum entitled "Groundwater Injection Feasibility Study, City of Malibu -- Task 2.3: Preliminary Modeling Simulations, June 21, 2012" (RMC, 2012). The 2010 model was described in the report entitled "Hydrology Study of Cumulative Impacts for the Civic Center Area, Malibu, California" (Stone Environmental, Inc., 2010)

The groundwater flow model presented in this study utilizes additional hydrogeologic data collected since the 2010 model was completed. During that period, data collection activities have included installation of several additional deep borings, observation well installation, surface geophysical investigations, groundwater and surface water level monitoring, hydraulic injection testing of deep boreholes, and collection of up-to-date information on precipitation, tide stage, Malibu Lagoon stage, Malibu Creek flow, and water use in the Civic Center area. The recent data collection activities are summarized in reports by Pueblo Water Resources (2014), Cardno Entrix (2012, 2013), Sea Surveyor, Inc. (2012) and RMC (2012).

Modeling analyses conducted for this study evaluate the impacts of proposed subsurface injection of treated disinfected wastewater into deep coarse-grained alluvial deposits on groundwater levels and directions of groundwater flow in the alluvial aquifer that lies along Malibu Creek and Lagoon in the Civic Center area of Malibu. The analyses evaluate three proposed phases of subsurface injection as described in a report by RMC Water and Environment (2014).

The study area, which is shown on Figure 1.1, extends from Winter Canyon on the west to Sweetwater Canyon on the east, and includes upland areas that drain toward the alluvial deposits. The extent of mapped alluvial deposits in the Civic Center area and Winter Canyon are shown in Figure 1.2. The active model area covers the alluvial and beach deposits shown in Figure 1.2.

1.1 Previous Modeling Investigations

Previous groundwater modeling studies include the following.

Earth Consultants International, Inc (2000a) prepared a three-dimensional steady-state groundwater flow model for the Malibu Bay Company. The purpose of the model was to evaluate the effects of additional wastewater dispersal at the Malibu Bay Company site in Winter Canyon. The model covered an area of about 40 acres and simulated flow in alluvial deposits within Winter Canyon, between Malibu Canyon Road and the Pacific Ocean.

Stone Environmental, Inc. and McDonald Morrissey Associates, Inc.(2004) prepared three-dimensional steady-state groundwater flow models for the City of Malibu. The purpose of that modeling was to evaluate groundwater quality impacts of on-site waste-water dispersal on groundwater and receiving waters in the Civic Center area. The model covered an area of about 560 acres, including mapped alluvial areas in the Civic Center and Winter Canyon. In 2005, Questa Engineering, Inc. and McDonald Morrissey Associates, Inc. evaluated the impacts of nitrogen loading on Malibu Lagoon using the 2004 groundwater flow model (Questa, 2005).

Fugro West, Inc. (2005) prepared a three-dimensional steady-state groundwater model for Sterling Capital. The purpose of the modeling was to evaluate the hydraulic effects of wastewater dispersal at the proposed Malibu-La Paz Ranch development. The Fugro model domain covers about 100 acres, centered on the La Paz site, and falls entirely within the area covered by the 2004 Stone/McDonald Morrissey model.

Stone Environmental, Inc. and McDonald Morrissey Associates, Inc. (2010) prepared a three-dimensional transient groundwater flow model for the City of Malibu which incorporated data collected during the period from 2004 through 2009. The model was used to evaluate the hydrologic effects of wastewater dispersal in Winter Canyon and on the west side of the main body of alluvium.

McDonald Morrissey Associates, Inc. (RMC, 2012) refined and recalibrated the 2010 model using data from three deep wells, hydraulic testing of the three new test wells, data from an off-shore marine reflection and sub-bottom profiling survey by Sea Surveyor, Inc (2012) and reinterpreted seismic refraction survey by Cardno Entrix (2012). The new data were used to modify elevation of the bedrock surface, model layer thicknesses, extent of alluvial deposits offshore, ocean bottom elevations, and boundary conditions offshore. New estimates of aquifer hydraulic properties were calculated using results of aquifer testing of the three new test wells along with a combination of manual and automated parameter estimation modeling techniques. Model results showed potential impacts of planned injection of treated wastewater on groundwater levels and directions of groundwater flow. Maximum injection rates for several potential injection sites were estimated using an optimization technique.

2.0 CONCEPTUAL MODEL

The conceptual model of the groundwater flow system includes a description of the hydrogeologic setting, extent of the subsurface system, hydrologic conditions along the boundaries of the flow system, hydraulic properties of the flow system and a generalized water budget that describes sources of groundwater recharge and discharge. The conceptual model is used to guide construction of the numerical model.

2.1 Hydrogeologic Setting

The Malibu Valley Groundwater Basin is a small alluvial basin, approximately 613 acres in size, located along the Los Angeles County coastline. The basin is bounded by the Pacific Ocean on the south, and by the Santa Monica Mountains, composed of non-water-bearing Tertiary age rocks, on all remaining sides. The valley is typified by steep canyons that generally run north to south, and is drained by Malibu Creek to the Pacific Ocean (DWR, 2003).

The Malibu Valley Groundwater Basin is located in a Mediterranean climate, characterized by cool wet winters and warm dry summers, with the majority of precipitation occurs between November and April. This area lies in the semi-permanent high-pressure zone of the Eastern Pacific. As a result, the climate is mild, tempered by cool sea breezes occasionally interrupted by infrequent periods of extremely hot weather, winter storms or Santa Ana winds. Average annual rainfall is approximately 12 inches (Jones and Stokes, 2009).

Figure 1.1 shows the study area, and the lower portion of the Malibu Creek Watershed. The basin is flanked on both sides by canyons - the Sweetwater Canyon to the east, and the Winter Canyon to the west. The Malibu Coast Fault is mapped across the basin in an east-west direction and is aligned approximately along Civic Center Way (Leighton, 1994); however, this fault is not a groundwater barrier (DWR 1975). North of the Malibu Coast Fault, the near-surface bedrock is described as Tertiary marine and non-marine sandstone and siltstone and Miocene volcanics. The sandstones and siltstones are assigned to the Lower Topanga and Sespe Formations. South of the Malibu Coast Fault, the near surface rocks consist of Tertiary marine shales, mudstones and diatomaceous rocks assigned to the Monterey Formation (Earth Consultants International, 2009). The near-surface rocks are assumed to have some permeability due to fracturing and weathering.

There are two primary hydrostratigraphic units within the Malibu Valley Groundwater Basin: bedrock and alluvium. Bedrock is at or near land surface in the upland areas, and beneath the unconsolidated sediments that are present in the Civic Center area along Malibu Creek and Lagoon. For the purposes of this study, the alluvium has been loosely divided into two units including a shallow, relatively fine grained upper unit and a deeper, coarse grained-deposit that has been referred to as Civic Center Gravels. These units are briefly described below.

2.1.1 Bedrock

A large bedrock valley lies beneath the City of Malibu. The interpreted elevation of the top of bedrock, shown in Figure 2.1, is based upon data available as of July 2013. Data used to construct the bedrock surface are presented in previous modeling efforts (Stone Environmental, Inc., 2004 and 2010; RMC 2012) and include data from drill holes, borings, and several geophysical surveys. The most recent data collection program includes several deep drill holes competed for this investigation, and a resistivity geophysical survey (Cardno Entrix, 2013; Pueblo Water Resources, Inc., 2014). Unconsolidated materials containing zones of permeable sand and gravel deposits overlie the bedrock. These aquifer units provide pathways for groundwater to flow from inland recharge areas to discharge areas beneath the sea floor.

Examination of the bedrock surface shown in Figure 2.1 shows that the lowest bedrock elevations occur in the western and central part of the basin, to the west of the current location of Malibu Creek and Lagoon. Onshore seismic geophysical surveys (Cardno Entrix, 2009, 2013), along with data from test borings, show the bedrock surface dropping in elevation from -10 feet below the ground surface level at the foot of the hills on the north side of the Civic Center area, to an elevation of -130 to -140 feet NAVD88 from Legacy Park to Malibu Road. The shape and characteristics of the bedrock layer are consistent with two ancient water courses eroded by Malibu Creek leading to the ocean. The estimated location of the ancient courses, which occurred approximately 20,000 and 60,000 years ago, are shown in Figure 2.2 (written communication, Earth Consultants Inc., 2012).

An offshore seismic reflection survey was conducted to map offshore bathymetry, top of bedrock, and to determine whether the deep gravel/sand layer (now referred to as the Civic Center Gravels) observed in recently installed deep wells continued offshore (Sea Surveyor, Inc, 2012). The reflection survey did not clearly show the thickness of alluvial sediments above bedrock in the offshore area, but it is interpreted to show the top of coarse grained sands and gravel where they exist. This survey was followed by an electrical resistivity survey (CardnoEntrix, 2013) to evaluate the thickness and extent of fresh water-bearing alluvial deposits directly along the shoreline. The results of the reflection survey and resistivity surveys, together with the results of deep test borings done along the coast, strongly suggest that fresh water-bearing alluvial deposits extend offshore from the present day coastline along the western shoreline of the alluvial deposits.

2.1.2 Alluvium

Water-bearing formations in the Malibu Valley Groundwater Basin are composed of Holocene alluvium consisting of clays, silts, sands and gravels. Alluvial sediments deposited in the Civic Center area by Malibu Creek and other small drainages are estimated to range in thickness from a feather edge near the valley walls to around 175 feet in the central part of the main body of alluvium. The alluvial materials can generally be subdivided into two categories or strata: a shallow sequence of fine-grained estuarine deposits, and an underlying coarse-grained strata commonly referred to as the "Civic Center Gravels" (GeoSoils, 1989; Leighton, 1994; ECI, 2000a and 2000b; Ambrose and Orme, 2000; Fugro West, Inc., 2005; Geosyntec Consultants, 2007). The Civic Center Gravels are described below. The basin hydrogeology is depicted in cross-sections A-A' through F-F' shown in Figures 2.3 through 2.5. Locations of the cross-sections and data used to construct the cross-sections are shown in Figure 2.6 (written communication., Earth Forensics, Inc., 2013).

The shallow alluvial zone is capped by modern floodplain deposits and, in some locations, with artificial fill. This zone generally consists of silts and sands, and is underlain by a very fine grained, low-permeability zone containing clay and silt layers, especially in the central part of the alluvium as depicted in north-south trending cross-sections (Figure 2.3 A-A', Figure 2.4 B-B', Figure 2.5 E-E'). These fine grained deposits are interpreted to extend from just north of Civic Center Way, south to Malibu Colony Road, and from the western edge of the main body of the alluvium near the Racquet Club, to the west side of Cross Creek Plaza. The shallow deposits tend to be coarser grained near the valley walls, along the northern edge of the alluvium, and to the east along the present day course of Malibu Creek and Lagoon.

As part of this study Earth Forensics, Inc. (2013) reviewed boring logs included in the project data base and developed a three-dimensional representation of the low permeability zone included within the alluvial deposit. The extent of the low permeability zone is depicted on each of the cross-sections included in Figures 2.3 to 2.5 based upon USCS soil classifications that include clay, silt, and silty and clayey sands. A plan view map showing the interpreted thickness of low permeability deposits is included in Figure 2.7.

The Civic Center Gravels underlie the shallow, low-permeability estuarine deposits throughout much of the Civic Center area. These deposits are described by Leighton (1994), and confirmed with subsequent borings in 2011 and 2013, as consisting of predominantly sands with gravel and cobbles. The top of the Civic Center Gravels is relatively flat, dipping slightly to the south and west. The elevation of the top of the gravels is at approximately -30 feet NAVD88 (North American Vertical Datum 1988). The Civic Center Gravels are interpreted to extend from just north of Civic Center Way, south to Malibu Road on the west side of the alluvium, and from just north of Civic Center Way to the Pacific Coast Highway near the eastern edge of Legacy Park.

The resistivity survey (CardnoEntrix, 2013), conducted along the Malibu shoreline and immediately offshore, identified the Civic Center Gravels as a zone with high resistivity below a shallow zone consisting of low resistivity material. This low resistivity material layer is thought to consist of clay-rich unconsolidated material, similar to materials identified in onshore borings, and correlates with the low permeability zone previously identified. The resistivity of the Civic Center Gravels was higher on the west side of the groundwater basin than on the east, suggesting that the aquifer contains fresher water and is comprised of coarse grained deposits on the west side of the basin, correlating with one of the identified ancient Malibu Creek channels (Figure 2.2).

The electrical resistivity of the Civic Center Gravels zone was lower by about an order of magnitude along the east side of the survey line, suggesting that the groundwater in this area is brackish, or the aquifer contains more silt and clay, or both. Based on the survey results, the fresh to brackish water zone appears to rise towards the sea floor offshore and south of the beach on the western side of the groundwater basin, suggesting that groundwater is discharging through the sea floor offshore and that the Civic Center Gravels continue offshore beneath the sea floor.

2.1.3 Hydraulic Properties of the Alluvium

Hydraulic properties of the saturated alluvium have been estimated by a variety of techniques at several different locations in the study area. Slug tests conducted on three wells completed in alluvium in Winter Canyon yielded hydraulic conductivities that ranged from 13 to 53 feet per day (ft/d) (Earth Consultants International, 2000a). A groundwater model of the Winter Canyon alluvium used hydraulic conductivities ranging from 22 to 66 ft/d (Earth Consultants International, 2000a).

Laboratory testing of clay samples collected from borings near the City of Malibu offices along Civic Center Way reported hydraulic conductivity estimates of 0.00014 and 0.00076 ft/d (Earth Consultants International, June, 2000b). Slug tests conducted on five shallow wells, located near a wastewater dispersal system in Cross Creek Plaza, gave hydraulic conductivity estimates that range from 0.6 to 4 ft/d (URS Greiner Woodward Clyde, 1999). The same study estimated hydraulic conductivities of 200 to 400 ft/d for coarse grained deposits along Malibu Lagoon in the Cross Creek Plaza area based upon results of bromide tracer and coliphage seeding tests.

Slug tests conducted on observation wells completed for a study by Stone Environmental, Inc. (2004) range from less than 1 ft/d to 123 ft/d with an average value of 13 ft/d. These wells are generally less than 50 feet deep and are screened across the water table. The highest hydraulic conductivity (123 ft/d) was at well SMBRP-3c which is located in the coarse deposits along upper Malibu Creek.

The groundwater flow model that was developed as part of the Stone Environmental, Inc. report (2004) used hydraulic conductivity values in the vicinity of the Malibu Sycamore Village property (previously called the IOKI site) immediately east of Stuart Ranch Road and north of Civic Center Way, that ranged from about 5 ft/d for interbedded fine to medium grained materials to 100 to 400 ft/d for the coarse grained Civic Center gravels and alluvium along Malibu Creek.

Water supply in the Malibu Civic Center was originally provided by the Marblehead Land Company, and then by the Malibu Water Company, from wells drilled into alluvial deposits and shallow bedrock along Malibu Creek. The first of these wells was drilled in 1902, and the final well was installed in about 1959. Specific capacity data from the wells were used to estimate transmissivity with a method described by Driscoll (1986). Estimated transmissivities for the old production wells range from approximately 10,000 ft^2/d to 23,000 ft^2/d, which translates to hydraulic conductivities of approximately 200 to 500 ft/d (Stone Environmental, Inc., 2004).

Hydraulic testing of six observation wells reported by Fugro West Inc. (2005) during a hydrogeologic investigation of the proposed La Paz Ranch development reported hydraulic conductivities ranging from 0.5 to 13 ft/d. Materials described as silt had reported hydraulic conductivities of 0.4 to 1.2 ft/d. Silty sands had reported conductivities of 8 to 9 ft/d, and conductivity of sand was reported to range 0.5 to 13 ft/d.

A model constructed as part of the Fugro (Fugro West Inc., 2005) investigation used hydraulic conductivities ranging from 0.5 to 100 ft/d.

Table 2.1: Reported Hydraulic Conductivities for Subsurface Soils in the Malibu Civic Center Area

Hydraulic Conductivity (K)	Aquifer or Soil Type	Source	Notes
0.00014 – 0.00076 ft/day	Clay aquitard above Civic Center Gravels	ECI, 2000b	Laboratory permeameter readings from Civic Center area
0.6 – 4 ft/day	Shallow alluvium	URS, 1999	Slug testing near Cross Creek Plaza
200 – 400 ft/day	Alluvium	URS, 1999	Bromide tracer and coliphage seeding tests near Cross Creek Plaza
<1.0 – 123 ft/day; average of 13 ft/day	Most wells in alluvium; the 123 ft/day K was located in coarse-grained deposits along upper Malibu Creek	Stone Environmental, Inc., 2004	Slug testing of wells in the downtown area
5 – 16 ft/day	Shallow aquifer; fine-medium grained alluvium	Stone Environmental, Inc., 2004	Groundwater flow model of downtown area
100 ft/day	Civic Center Gravels	Stone Environmental, Inc., 2004	Groundwater flow model of downtown area
200 – 500 ft/day	Civic Center Gravels	Stone Environmental, Inc., 2004	Estimate based on historic production well
0.5 – 13 ft/day	Shallow aquifer; sand	Fugro West, 2005	Slug test, La Paz Ranch
0.4 – 1.2 ft/day	Shallow aquifer; silt	Fugro West, 2005	Slug test, La Paz Ranch
9 ft/day	Shallow aquifer; sand/silt	Fugro West, 2005	Slug test, La Paz Ranch
8 – 9 ft/day	Deep aquifer; silty sands	Fugro West, 2005	Slug test, La Paz Ranch
0.5 – 100 ft/day	Alluvium	Fugro West, 2005	Field data and modeled K values
8 – 9 ft/day	Upper alluvium on MSV site, vicinity proposed drainfields	ECI, 2009	Estimated from results of site-specific percolation tests
83-436 ft/d	Civic Center Gravels	Pueblo Water Resources, Inc., 2014	Values from analysis of 7-day injection tests

Data collection activities during the period 2010 through 2013 included hydraulic testing of three deep boreholes in the Civic Center area. The most recent work included analysis of pumping and injection tests at each of the three deep boreholes. Results of the testing are summarized in a report by Pueblo Water Resources (2014).

The hydraulic conductivity values in Table 2.1 were used as a guide in specifying hydraulic properties in the model. Values of hydraulic conductivity in the model vary from a fraction of a foot per day to several feet per day for relatively fine grained materials to approximately 1,000 feet per day for coarse grained deposits.

2.2 Sources of Groundwater

Groundwater recharge to alluvial deposits in the study area occurs by several different processes as follows:

1) Groundwater and surface water runoff from upland areas recharges alluvial deposits as it flows from the upland to the edges of the alluvial deposits on the valley floor. Surface water infiltration is especially evident in the western part of the alluvium at the artificial wetland near the intersection of Civic Center Way and Stuart Ranch Road, on what is referred to in this report as the Smith Parcel.

2) Direct recharge of groundwater from subsurface wastewater dispersal occurs within the main body of alluvium at each dispersal bed. Dispersal systems in upland areas adjacent to the alluvium can also provide indirect recharge to alluvial deposits in the form of groundwater runoff.

3) Infiltration of precipitation directly into the alluvium can occur where land is not covered with impervious surfaces.

4) Recharge from infiltration of Malibu Creek into alluvial deposits occurs when surface water flow infiltrates into permeable alluvium in the upper reaches of the creek.

5) Excess irrigation required to flush root zones on the main body of alluvium for maintenance of turf and other vegetation results in groundwater recharge. Irrigation in upland areas also can cause groundwater recharge to the alluvium via ground and surface water runoff.

The degree to which each of these various mechanisms of recharge can be quantified is variable. Recharge caused by the infiltration of subsurface wastewater dispersal may be easiest to quantify because recharge rates are directly related to water use and water use data are available for the study area. Recharge from infiltration of Malibu Creek along the upper reaches of alluvial deposits may be estimated from stream gaging data. Recharge from infiltration of precipitation and upland runoff cannot be directly measured and therefore must be estimated.

Information from water budget analyses that provide some guidance for these estimates come from data collection and reporting done for the Pepperdine University campus, which is adjacent to this study area (Daniel B. Stephens & Associates, Inc., 2007a, 2007b, 2008a, 2008b, 2009, 2010, 2011, 2012, 2013). Pepperdine calculates an annual soil-water balance for the campus based upon an extensive data collection network that includes measurement of precipitation, soil moisture, irrigation water use, surface runoff, and estimates of evapotranspiration. A summary of annual, campus-wide water balances from Pepperdine for the period from 2003 through 2012 is included in Table 2.2.

Table 2.2 -- Summary of annual soil water budget calculations for irrigated areas of the Pepperdine Campus, in inches per water year.

Water Year	Irrigation (I)	Precipitation (P)	Surface Runoff (RO)	Infiltration (Inf) [I + P - RO]	ET (AET)	Storage Change (ΔS)	Deep Percolation (DP) [Inf-AET- ΔS]
2002-03	27.26	13.22	8.42	32.07	29.12	0.87	2.08
2003-04	30.23	7.95	2.40	35.68	35.74	-0.93	0.97
2004-05	20.96	32.03	16.68	36.30	34.31	-0.03	2.01
2005-06	24.86	20.40	10.20	35.06	34.99	-0.19	0.26
2006-07	27.37	6.75	1.05	33.07	32.85	0.11	0.11
2007-08	25.46	12.47	3.15	34.77	32.90	0.64	1.23
2008-09	27.33	11.03	3.99	34.37	32.33	0.08	1.96
2009-10	24.92	16.93	6.79	35.07	31.53	0.57	2.96
2010-11	23.53	20.15	8.11	35.57	32.32	-0.09	3.34
2011-12	26.14	12.22	6.44	31.92	28.63	-0.95	4.24

The information in Table 2.2 corresponds only to irrigated areas on the Pepperdine campus; hardscape and non-irrigated naturally vegetated areas are not included. Examination of Table 2.2 illustrates that precipitation is highly variable from year to year, evapotranspiration rates are consistently greater than available precipitation and therefore irrigation is required. The estimated deep percolation in Table 2.2, which gives a general indication of groundwater recharge, varies considerably from year to year ranging from a fraction of an inch to several inches. Deep percolation can occur despite the high annual evapotranspiration rates, because most of the precipitation falls in winter months when evapotranspiration rates are lowest.

2.2.1 Recharge from Upland Runoff

Upland areas adjacent to the alluvium provide recharge to the groundwater flow system. The upland recharge can occur as groundwater and/or surfacewater runoff. Estimates of the amount of recharge from uplands are made by delineating the drainage areas of contributing uplands along with an estimate of available runoff. A map showing the upland areas that contribute recharge to groundwater in the alluvium is shown in Figure 2.8. The size of each contributing area is summarized in Table 2.3.

Only a small fraction of the total precipitation in upland areas can become recharge to the alluvium because of runoff and evapotranspiration (Table 2.2). Some precipitation will infiltrate in upland areas, flow through shallow overburden and bedrock, and recharge the alluvium. Based upon estimated deep percolation calculated for the Pepperdine campus it was assumed that the average annual rate of recharge from upland runoff during the period 2003-2012 ranges from less than an inch per year to several inches per year.

Table 2.3. -- Extent of upland sub-drainage areas.

Sub-Basin	Area (ft^2)
Winter Canyon	9,619,226
West Alluvium	3,645,542
Northwest Alluvium	4,482,120
North Alluvium	1,919,216
Malibu Tributary	9,955,536
Serra	1,028,450
East Alluvium	5,446,559
East Shore	771,059
Sweetwater Canyon	17,696,143
West Shore 1	1,466,626
West Shore 2	3,874,105
TOTAL UPLAND	59,904,582

2.2.2 Soil Absorption System Recharge

Wastewater dispersal through onsite septic systems for the period from 2003-2009 was estimated from water use data provided by Los Angeles County Water Works District 29 (County of LA, written communication, 2009). The data used for those estimates were derived from bimonthly water use by user over the period from 2003-2009. A description of the water use 2003-2009 database is included in the report by Stone Environmental, Inc. (2010).

As part of this study, water use data were obtained from District 29 (County of LA, written communication, 2013) for the period 2010-2012. The 2010-2012 water use data provided by the County were aggregated into zones that correspond to meter books. Recharge to groundwater from wastewater dispersal for the period 2003-2009 is the same as that used in previous modeling efforts. For the period 2010-2012, recharge from wastewater dispersal at individual properties was estimated by comparing total water use during 2010-2012 with previous years, and then distributing the total water use proportionally, by meter book area, based upon the use observed in 2003-2009 (written communication, Stone Environmental Inc., 2013).

The water use information is summarized by group based upon specific geographic areas as shown in Figure 2.9. The Malibu Colony Shoreline group includes all of the Malibu Colony residences and residences along adjacent shorelines east and west of the Colony. This group is characterized by relatively small lot sizes, and therefore by relatively small areas that require irrigation. The average water use for the residences in this group, over the period from 2003-2009, was 490 gpd (gallons per day). During the low-irrigation season, which is assumed to occur in February and March, the average water use was approximately 397 gpd. Based upon these data, it was assumed that the average wastewater dispersal from each of the residences in this group was 400 gpd.

The Serra Vicinity group is characterized by large lot sizes with relatively large irrigated areas. The average 2003-2009 water use in this group is 2,524 gpd and, in the low irrigation season, average water use is 1,705 gpd. For the purpose of this study, it was assumed that each of the residences in this group has on-site wastewater dispersal of 400 gpd if the total water use was equal to or greater than 400 gpd. If the water use at a parcel in this group was less than 400 gpd, all of the water was assumed to be wastewater dispersal. Any water use greater than 400 gpd is assumed to be used for irrigation.

Upland areas adjacent to the alluvium have lot sizes that are generally larger than the Colony and smaller than those in the Serra area. Average 2003-2009 water use for these areas is approximately 1,152 gpd. For the purpose of this study, it was assumed that each of the residences in this group has on-site wastewater dispersal of 400 gpd if the total water use was equal to or greater than 400 gpd. If the water use at a parcel in this group was less than 400 gpd, all of the water was assumed to be wastewater. Any water use greater than 400 gpd is assumed to be used for irrigation.

Commercial water users are predominantly located in the Civic Center area in Cross Creek Plaza and Malibu Colony Plaza. There are also a few commercial users along the eastern shoreline and in Winter Canyon. Two of the largest commercial wastewater dispersals occur in Winter Canyon at the County of Los Angeles treatment plant, which serves the condominium development along DeVille Way, and the Malibu Company treatment plant, which serves Malibu Colony Plaza. Wastewater dispersal at all of the commercial properties is assumed to be equal to the reported water use.

Several locations in the area have extensive irrigation of turf and other plantings. These locations include nurseries, a small golf park with extensive turf areas, and a horse farm/estate. At each of these locations, the majority of the reported water use is assumed to be for irrigation. If specific parcels in this group include a residence, the wastewater dispersal at the residence is assumed to be 400 gpd. If the parcel doesn't include a residence, all of the water is assumed to be used for irrigation.

Table 2.4 – Summary of water use in the study area for the period 2003-2009, in gallons per day.

	All Months			Feb/Mar		
Group	Average	Min	Max	Average	Min	Max
Malibu Colony Shoreline	490	43	3,462	397	22	2,256
Upland Areas	1,152	171	2,966	1,062	63	11,800
Serra Vicinity	2,524	99	15,358	1,705	25	9,118
Commercial	5,997	182	52,596	5,154	116	51,449
Nurseries/Golf Courses	3,408	258	5,019	1,996	123	3,411

2.2.3 Infiltration of Precipitation

Daily precipitation data are collected at two gauges located on the Pepperdine campus which is along the western edge of the study area (Daniel B. Stephens & Associates, Inc., 2007a, 2007b, 2008a, 2008b, 2009, 2010, 2011, 2012, 2013). The locations are named the Meadows (lower) and Stables (upper). Monthly precipitation data during 2003 to 2012, shown in Figure 2.10, are typically the average of two Pepperdine gages, except for several months when only the Stables (upper) gage was operational and, for four months when both Pepperdine gages were down and data from a County of Los Angeles gage was utilized. Examination of Figure 2.10 illustrates the fact that most of the precipitation in the study area occurs during the winter months. During the period from 2003 to 2012, the total annual precipitation shown on Figure 2.10 varied from 8.39 inches in 2003 to 24.57 inches in 2005.

Meteorological conditions during 2003-2012 can be evaluated within the context of long term precipitation data (1937-2009) from Santa Monica Pier (California ID 047953). The long term data indicate that average annual precipitation is 11.88 inches, and the maximum annual precipitation over the same period is 25.4 inches. During 2005, precipitation at Santa Monica was 25.19 inches, one of the wettest years on record for that site. Based upon this information, it is assumed that the 2003-2012 period considered in this study includes a year (2005) which can be characterized as being representative of very wet conditions.

Some of the precipitation that falls directly on the alluvium becomes groundwater recharge. This recharge is assumed to be small because most rain comes as intense winter storms with considerable runoff, and much of the runoff is diverted to surface water via storm sewers. There are several areas atop the alluvium that are paved, through which there is no infiltration. In unpaved areas, some of the precipitation will run off and some will be lost to evapotranspiration. For the proposes of this study, it was assumed that average annual recharge from direct infiltration of precipitation would generally be less than 5% of annual precipitation.

2.2.4 Malibu Creek Infiltration

Infiltration of stream flow is a common source of recharge to alluvial aquifers. Recharge occurs as streams flow from steep upland areas, which are predominantly bedrock, onto more permeable, relatively flat alluvial deposits. The rate of recharge is controlled by the difference in head between the stream and the underlying groundwater and the permeability of the streambed and underlying alluvial deposits.

Infiltration of stream flow has been observed as Malibu Creek exits the canyon and crosses onto the alluvial deposits along the coastal plain. Some of this water is lost to evapotranspiration and to infiltration along the stream channel above the main body of alluvium but, based upon available data, a significant amount recharges the alluvial deposits in the Civic Center area. These recharge rates are estimated to be on the order of 0.5 to 2 cfs (ft^3/s) during low flows and may be higher during flood conditions (Stone Environmental, Inc., 2004).

Malibu Creek stream flow data are collected at the County of Los Angeles Flood Control District continuous recording gage F130R, (formerly USGS gaging station 111055500), located 0.3 mi downstream of Cold Creek and approximately 3.5 miles upstream from Arizona Crossing. The gaging station was installed in 1931 and operated cooperatively by the USGS and the County of Los Angeles until 1978. From 1979 until the present, the gage has been operated by County of Los Angeles. Flows recorded at the gage include releases from the Las Virgenes Municipal Water District (LVMWD) Tapia Water Reclmation Facility which was constructed in 1965.

The U.S. Geological Survey operated a stream gage near the bridge over Malibu Creek on Cross Creek Road from December 2007 through October 2012. Daily flows at the U.S. Geological Survey gage, and the County gage 3.5 miles upstream, are shown in Figure 2.11 for the period December 2007 to October 2012. During winter periods, when most of the precipitation and associated runoff occurs, stream flow is generally greater at the downstream gage. During the summer/fall period when there is very little precipitation, there is a consistent loss of flow between the two gages of about 1-10 cfs (cubic feet per second). During these periods, flow at the upstream gage is mostly from release of treated wastewater at the Tapia Plant. By the time this flow reaches the downstream gage at Cross Creek Road, much of the water has infiltrated into the alluvium along Malibu Creek.

In addition to the stream gage data from 2007-2012, described above, infiltration of stream flow has been observed as Malibu Creek exits the canyon and crosses onto the alluvial deposits along the coastal plain on several earlier occasions. On August 23, 1999, flow at the County gaging station was measured at 1.4 cfs and a similar flow was observed the following day about 4,000 feet above the mouth of the Canyon. Another 2,300 feet downstream, flow had decreased to about 1 cfs, and 3,300 further downstream, just below Cross Creek Road, the stream was dry (Entrix, Inc., 1999). On September 10, 1998, a similar pattern was noticed. Flow near the mouth of the canyon was 8.2 cfs and

600 feet downstream of Cross Creek Road it was 6.4 cfs, a decrease of 1.8 cfs (Entrix, Inc., 1999).

On September 24, 2003, Malibu Creek had an average daily flow of 3.0 cfs at the County gage (written communication, County of LADPW, April 2, 2004). Stream flow in the Creek was measured at 0.6 cfs, 3,200 feet above Cross Creek Road/Arizona Crossing, and the stream channel was dry just above the Cross Creek Road bridge (written communication, McDonald Morrissey Associates, Inc., 2003)

Entrix (1999) also states that LVMWD staff observed that “the stream is almost always dry below Cross Creek Road in the late summer months.” Examination of streamflow records show that average daily flows during the late summer months are typically 2-4 cfs. Some of this water is lost to evapotranspiration and to infiltration along the stream channel above the main body of alluvium, but, based upon available gaging data, a significant amount recharges the alluvial deposits in the Civic Center area. These recharge rates are estimated to be on the order of 0.5 to 2 cfs during low flows and may be higher during flood conditions. Stream flow that infiltrates to groundwater during dry periods may move as hyporheic (sub channel) flow through the coarse alluvium along the Malibu Creek channel and ultimately discharge to the upper reaches of the lagoon.

2.2.5 Excess Irrigation

Recharge to the groundwater basin from infiltration of excess irrigation is likely to occur at locations where turf and landscaping are maintained. Some of the water used for irrigation seeps through the soil zone and becomes round-water recharge. In Malibu, the private golf park, commercial nurseries, horse farms and extensively landscaped properties all use significant quantities of water for irrigation. A map showing locations within the Civic Center alluvium and Winter Canyon alluvium where recharge from excess irrigation is assumed to occur is shown in Figure 2.12.

In the northern part of the study area, along Malibu Creek and near Serra Retreat, the amount of recharge from excess irrigation was estimated by subtracting estimated wastewater disposal (400 gallons per day per residence) from the total reported water use for the area and applying one-half of the remainder as recharge from excess irrigation. The same approach was used in each of the upland areas that are adjacent to the alluvium and at the nursery, located on the west side of the study area. At the properties that make up the golf park, those parcels with no dispersal system are assumed to get 50% of the water use as recharge from excess irrigation, and parcels with dispersal systems are assumed to receive 50% of all water use above 400 gpd as recharge from excess irrigation.

The amount of irrigation that actually becomes groundwater recharge is dependent upon site-specific conditions including soil permeability, irrigation practices, land slope, evapotranspiration and other factors. The assumption made in this study that 50% of water use above 400 gpd becomes groundwater recharge is probably on the high side and would occur as a result of inefficient irrigation practice combined with permeable soils. For the purpose of this study, this assumption was assumed to be reasonable.

2.3 Sinks for Groundwater

Groundwater sinks are areas where groundwater discharges out of the alluvial groundwater flow system. Potential groundwater sinks include natural discharge to surface waters and the ocean, evapotranspiration from riparian vegetation, and pumping wells used for irrigation or other water uses in the study area.

2.3.1 Discharge to Ocean and Malibu Lagoon

Water table maps constructed in order to determine general directions of shallow groundwater flow in the alluvium, and to differentiate between groundwater flow to the ocean and lagoon, were prepared by Stone Environmental, Inc. (2004). Data used to construct those water table maps were collected on September 25, 2003 and on March 9, 2004. During the September 2003 measurement, the barrier beach was intact and the lagoon was flooded. During the March 2004 measurement, the barrier beach was breached and flow in Malibu Creek was discharging to the ocean. In addition, a synoptic water level measurement was conducted on December 8, 2009 during a condition when the lagoon was partially breached (Stone Environmental, Inc., 2010). During each of the three synoptic measurements mentioned above, groundwater levels and lagoon stage were measured during a relatively short period of time to minimize the effects that tidal variations had on groundwater elevations.

Contour maps of observed shallow water levels for the September 2003, March 2004 and December 2009 synoptic measurements are shown in Figures 2.13, 2.14 and 2.15 respectively. During both the flooded and breached lagoon conditions, groundwater from the western side of the alluvial flow system, and from Winter Canyon alluvium discharges to the ocean. Groundwater flow from the eastern side of the alluvial flow system discharges to Malibu Lagoon and Creek. The groundwater flow divide can shift slightly depending upon lagoon conditions, but in general, available groundwater level maps show that groundwater in the alluvial deposits in Winter Canyon and the west side of the alluvial deposits discharges to the Pacific Ocean. Shallow groundwater in the central and eastern parts of the alluvium discharges to the Lagoon, except along the eastern shoreline near Malibu Pier where groundwater discharges to the ocean.

2.3.2 Evapotranspiration

Evapotranspiration from groundwater can occur where the root zone of vegetation is at or below the water table. The most likely place for this to occur in the study area is along Malibu Creek and Lagoon where there is riparian vegetation and shallow depths to water. The Las Virgenes Municipal Water District estimated the water demand of riparian vegetation along Malibu Creek downstream of the Tapia Water Reclamation Facility (Letter from Las Virgenes Municipal Water District to National Marine Fisheries Service, September 2, 1998) using a method that takes into account vegetation species type and density along with microclimatic characteristics. Results of this study estimated that riparian vegetation consumes approximately 1.2 cfs of water in the reach below the treatment plant and Cross Creek Road, a distance of about 4 miles, which is approximately 0.3 cfs per mile.

2.3.3 Pumping

The County of Los Angeles Department of Health Services – Environmental Health Division regulates water supply wells in Malibu. All water wells require permits issued by the County of Los Angeles Environmental Health Division. At present, there is no documentation of any pumping wells in the study area, however, observations made during field studies indicate that there may be a few private domestic wells in the study area that are being used for irrigation. The amount of pumping that occurs from such wells is considered to be negligible.

2.4 Summary of Sources and Sinks for Groundwater

A summary of the average-annual model-calculated groundwater budget for the Malibu and Winter Canyon alluvial deposits during 2003-2012 is shown in Figure 2.16. The same information is also summarized Table 2.5. The major sources of recharge to the alluvium in the model area are stream infiltration and wastewater dispersal. Stream infiltration makes up about 44% of average annual recharge. The total wastewater dispersal, which includes upland and alluvial portions in Figure 2.16 and Table 2.5, comprises about 31% of the estimated average annual recharge to groundwater in the model area. Recharge from upland runoff and direct infiltration of precipitation make up approximately 15% of average-annual recharge. Irrigation return from upland and alluvial areas makes up the remaining 10%. On average, approximately 71% of groundwater in the model area discharges to the ocean, 22% goes to the lagoon and the remaining 7% is lost to groundwater evapotransiration.

Table 2.5 -- Summary of model estimated average annual groundwater budget for the Civic Center alluvium and Winter Canyon 2003-2012.

Groundwater Inflows				Groundwater Outflows			
Recharge	rate in cfs	rate in gpd	Percent of Total	Discharge	rate in cfs	rate in gpd	Percent of Total
Net Stream Infiltration	0.86	552,568	44.1%	Lagoon	0.42	269,579	21.5%
Wastewater Alluvium	0.42	268,554	21.4%	Ocean	1.38	894,434	71.4%
Wastewater Upland	0.18	116,130	9.3%	Evapotranspiration	0.14	89,750	7.2%
Upland Runoff	0.20	131,753	10.5%				
Irrigation Return Upland	0.11	69,752	5.6%				
Irrigation Return Alluvium	0.09	58,117	4.6%				
Precipitation Alluvium	0.09	55,831	4.5%				
TOTAL RECHARGE	1.94	1,252,705	100%	TOTAL DISCHARGE	1.94	1,253,768	100%

2.5 Groundwater Levels

As part of this project, water level data were collected from previous studies and organized into a single database. The data were obtained from a variety of sources, including the LARWQCB, the City of Malibu, studies done by private consultants and from previous modeling efforts completed for the City of Malibu (Stone Environmental, Inc., 2004, 2010; RMC, 2012). Horizontal locations of wells used in this study were surveyed to the California State Plane V NAD1983 datum in units of feet. Vertical elevations of wells used in this study were surveyed to the NAVD1988 datum in units of feet. Locations where groundwater level data were used for this study are shown in Figure 2.17a and 2.17b.

Groundwater in the Civic Center area typically occurs at shallow depths, generally between 2 and 50 feet bgs (below the ground surface) (Geosyntec, 2007; Stone Environmental, 2004, 2010; Subsurface Designs, 2002; Bing Yen and Associates, 2001; ECI, 2000b; GeoConcepts; 1999; Leighton, 1994). Maps showing shallow groundwater elevations for three different times are shown in Figures 2.13, 2.14 and 2.15. A map showing distance from land surface to groundwater in December 2009 is shown in Figure 2.18. Groundwater levels tend to be closest to land surface in the vicinity of Malibu Lagoon and Creek, and the greatest depths to groundwater generally occur along the edges of the alluvium near the transition to upland areas, and in Winter Canyon.

There are a few locations where nested wells allow comparison of shallow and deep groundwater levels. These locations include the following wells pairs, MW-5&6; MW-7&8; MW-9&10; M6-1&2; and M7-1&2. Examination of water levels from these wells shows that here is a downward gradient from the shallow sequence of fine-grained estuarine deposits to the underlying coarse grained Civic Center Gravels. During the December 8, 2009 synoptic water level measurement, the difference between shallow and deep water levels varied from 4.39 feet at the MW5&6 well pair to 0.98 feet at M7-1&2 well pair.

Groundwater levels in the Civic Center area of Malibu fluctuate in response to several factors. These factors include variations in precipitation, runoff into the artificial wetland, lagoon stage, and ocean tide stage. In general, groundwater level variations in Winter Canyon, and on the west side of the alluvium, are most closely related to variations in precipitation. Groundwater levels at wells in the vicinity of the Lagoon, especially east of Cross Creek Road, are closely related to variations in lagoon stage. Groundwater levels in wells completed in the Civic Center Gravel also exhibit water-level variations that are affected by lagoon stage. Groundwater levels in wells closest to the coast, especially those wells south of the Pacific Coast Highway, are most directly influenced by tidal variations.

The relationship between precipitation and groundwater levels within the study area during the period from 2003-2012 is illustrated in Figures 2.19a through 2.19c. Wells SMBRP-9, and SMBRP-10C are located on the west side of the alluvium above the Civic Center Gravel, and Well03 is located in Winter Canyon. All of the wells in Figures 2.19a through 2.19c show a strong correlation between water levels and precipitation. In general, water levels rise wet periods and then recede during dry periods. Well SMBRP-10C, located near the artificial wetland near the intersection of Stuart Ranch Road and Civic Center Way, shows abrupt groundwater level fluctuations that are caused, at least in part, by periodic flooding of the artificial wetland. Water levels in the Winter Canyon well, Well03, shows a distinctive peak during the winter period in 2004-5 when record rainfall occurred.

Conditions in Malibu Lagoon have a significant effect on groundwater levels in the Civic Center area, especially at wells closest to the lagoon. Lagoon conditions are dependent upon the condition of the barrier beach that forms along the interface between the lagoon and ocean. Figure 2.20 shows the lagoon stage and the water level in wells P-1, P-4 and MLW-1 during a period when the lagoon transitions from a flooded to breached condition.

Examination of Figure 2.20 clearly shows that when the barrier beach is intact, which generally occurs during dry weather periods, the lagoon is flooded and groundwater levels in nearby wells are high. When the barrier beach is absent, generally during wet periods when flow in Malibu Creek is highest, the lagoon drains and groundwater levels in nearby wells are lowest. Figure 2.20 also shows that fluctuations in the lagoon stage caused by tidal variations are considerably damped when the lagoon is flooded. When the barrier beach is breached, and lagoon is open to the ocean, the lagoon stage is directly influenced by tidal fluctuations. The same appears to be true for shallow groundwater levels near the lagoon. Examination of the groundwater levels for wells in Figure 2.20 shows that the tide-caused fluctuations in groundwater are damped when the lagoon is flooded, especially at well P-1, and less damped when the lagoon is breached.

3.0 NUMERICAL GROUNDWATER FLOW MODEL

The purpose for groundwater flow modeling is to evaluate the hydrologic effects of proposed subsurface injection of treated wastewater at various injection rates. The model is used to predict groundwater level changes associated with the proposed injection, and to evaluate the ultimate fate of injected wastewater. The groundwater model used for these analyses is an enhanced version of models prepared for the City of Malibu in 2012 and in 2010. The 2012 model was described in the technical memorandum "Groundwater Injection Feasibility Study, City of Malibu -- Task 2.3: Preliminary Modeling Simulations, June 21, 2012". The 2010 model was described in the report entitled "Hydrology Study of Cumulative Impacts for the Civic Center Area, Malibu, California" (Stone Environmental, Inc., 2010). Major modifications made to the groundwater model since the 2010 model was prepared are as follows:

-Modified elevation of the bedrock surface based upon drilling and geophysics

-Modified model layer thicknesses

-Increased model extent into offshore areas

-Incorporated ocean bottom bathymetry from offshore geophysical survey

-Modified zonation of model hydraulic property zones.

- Density-dependent modeling was done to evaluate the position of the offshore salt/fresh interface and inform conceptualization of boundary conditions in the offshore area.

-Increased model simulation period from 2003-2009 to 2003-2012.

-Recalibrated model with groundwater level observations through 2012, including results of hydraulic testing done between 2010 and the present, and also used observed tidal fluctuations as a calibration target.

-Revised model recharge from precipitation

The refined model was used to conduct simulations to assess impacts of proposed injection of treated wastewater on water-table elevations and the separation between the water table and land surface after the onset of injection. Model results show potential impacts of planned injection of treated wastewater on groundwater levels and directions of groundwater flow. Maximum injection rates for several potential injection sites were estimated using an optimization technique.

3.1 Construction

The numerical groundwater model code used for this study is MODFLOW2005 which was developed by the U.S. Geological Survey (Harbaugh, 2005). MODFLOW2005 requires that the groundwater flow domain be subdivided into blocks. Specifications describing aquifer hydraulic properties, recharge, discharge, and other factors that can affect the groundwater flow system are required for each block in the model grid. Specifications must also be made to describe flow conditions along each boundary of the model domain (boundary conditions), and for transient simulations, initial groundwater elevation must be specified for each block at the start of the simulation (initial conditions). The groundwater model calculates a groundwater elevation for each block in the model grid at each discrete time interval specified in the model input files.

3.1.1 Model Grid

The model grid developed for this study covers an area of about 3.4 mi^2, with an active area of about 1.9 mi^2. The extent of the model, shown in Figure 3.1, allows simulation of groundwater flow in alluvial deposits that underlie Winter Canyon, the entire Malibu Civic Center area along Malibu Creek and Lagoon and in offshore areas. The model area shown in Figure 3.1 extends 1,500 feet farther into offshore areas than the 2010 model. This was accomplished by adding 50 rows to the original finite difference grid. In addition, the number of model layers was increased from 5 to 7 to provide more detail in the deeper parts of the alluvial deposits.

The refined model grid consists of 300 rows, 350 columns, and 7 layers with a uniform horizontal spacing of 30 feet. The total number of active cells in the model domain is 264,064. Layer thickness varies from a few feet or less near the edges of the model to a maximum of about 50 feet or more where the alluvial deposits are thickest. The horizontal geographic reference system used for all modeling is California State Plane Region V NAD 83 datum in units of feet. The grid origin is at x-coordinate 6347317.759 feet and y-coordinate 1831990.503 feet. The vertical geographic reference used in modeling is the NAVD 1988 datum in units of feet.

Model layers 1-3 are designed to represent the shallow interbedded sands, silts and clays that exist above the deeper coarse-grained deposits. The bottom of model layer 2 corresponds to the ocean bottom in offshore areas. The bottom of model layer 3 corresponds to the top of coarse-grained deposits on land and, in offshore areas, to the top of the first reflector determined from the marine reflection survey. Model layers 4-7 are designed to represent the deeper alluvium, which is the proposed injection zone. The bottom of model layer 7 is designed to represent the contact between alluvium and bedrock. Cross-sections showing the relationship between model layers and subsurface geology are included in Figures 2.3, 2.4 and 2.5.

3.1.2 Time Discretization

A summary of model time stepping and stress periods is included in Table 3.1. The model simulation includes a total of 153 stress periods. A stress period is defined as a segment of time in which modeled hydraulic stresses and boundary conditions are held constant. The first stress period is a steady-state simulation of average hydraulic conditions in the aquifer during the period from 2003 to 2012. Stress periods 2 through 153 are generally one month long. Some stress periods are shorter than one month in order to more accurately represent conditions (flooded or breached) in the Lagoon. The total simulation time is 10 years or 3,653 days, starting on January 1, 2003 and ending on December 31, 2012. Most stress periods have one time step. However, stress periods that include a changing lagoon condition, i.e. when the lagoon changes from flooded to breached, or vice versa, have three time steps.

Table 3.1 -- Summary of model stress periods and time steps.

Stress Period Number	*Type*	Stress Period Start Time		Stress Period Stop Time		*Stress Period Duration (days)*	*Number of Time Steps per Stress Period*	*Breached Lagoon/Flooded Lagoon*
		Date	*Model Time (days)*	*Date*	*Model Time (days)*			
1	SS	January 1, 2003	0	January 1, 2003	0.00001	0.00001	1	*Breached*
2	TR	January 1, 2003	0.00001	January 31, 2003	31	31	1	*Breached*
3	TR	February 1, 2003	31	February 28, 2003	59	28	1	*Breached*
4	TR	March 1, 2003	59	March 31, 2003	90	31	1	*Breached*
5	TR	April 1, 2003	90	April 30, 2003	120	30	1	*Breached*
6	TR	May 1, 2003	120	May 31, 2003	151	31	1	*Breached*
7	TR	June 1, 2003	151	June 30, 2003	181	30	1	*Breached*
8	TR	July 1, 2003	181	July 8, 2003	189	8	1	*Breached*
9	TR	July 9, 2003	189	July 31, 2003	212	23	3	*Flooded*
10	TR	August 1, 2003	212	August 31, 2003	243	31	1	*Flooded*
11	TR	September 1, 2003	243	September 30, 2003	273	30	1	*Flooded*
12	TR	October 1, 2003	273	October 31, 2003	304	31	1	*Flooded*
13	TR	November 1, 2003	304	November 3, 2003	307	3	3	*Flooded*
14	TR	November 4, 2003	307	November 30, 2003	334	27	1	*Breached*
15	TR	December 1, 2003	334	December 31, 2003	365	31	1	*Breached*
16	TR	January 1, 2004	365	January 31, 2004	396	31	1	*Breached*
17	TR	February 1, 2004	396	February 29, 2004	425	29	1	*Breached*
18	TR	March 1, 2004	425	March 31, 2004	456	31	1	*Breached*
19	TR	April 1, 2004	456	April 30, 2004	486	30	1	*Breached*
20	TR	May 1, 2004	486	May 31, 2004	517	31	3	*Flooded*
21	TR	June 1, 2004	517	June 21, 2004	538	21	3	*Breached*
22	TR	June 22, 2004	538	June 30, 2004	547	9	1	*Flooded*
23	TR	July 1, 2004	547	July 31, 2004	578	31	1	*Flooded*
24	TR	August 1, 2004	578	August 31, 2004	609	31	1	*Flooded*
25	TR	September 1, 2004	609	September 30, 2004	639	30	1	*Flooded*
26	TR	October 1, 2004	639	October 18, 2004	657	18	1	*Flooded*
27	TR	October 19, 2004	657	October 31, 2004	670	13	3	*Breached*
28	TR	November 1, 2004	670	November 30, 2004	700	30	1	*Breached*
29	TR	December 1, 2004	700	December 31, 2004	731	31	1	*Breached*
30	TR	January 1, 2005	731	January 31, 2005	762	31	1	*Breached*
31	TR	February 1, 2005	762	February 28, 2005	790	28	1	*Breached*
32	TR	March 1, 2005	790	March 31, 2005	821	31	1	*Breached*
33	TR	April 1, 2005	821	April 30, 2005	851	30	1	*Breached*
34	TR	May 1, 2005	851	May 31, 2005	882	31	1	*Breached*
35	TR	June 1, 2005	882	June 30, 2005	912	30	1	*Breached*
36	TR	July 1, 2005	912	July 31, 2005	943	31	1	*Breached*
37	TR	August 1, 2005	943	August 15, 2005	958	15	1	*Breached*
38	TR	August 16, 2005	958	August 31, 2005	974	16	3	*Flooded*
39	TR	September 1, 2005	974	September 12, 2005	986	12	1	*Flooded*
40	TR	September 13, 2005	986	September 30, 2005	1,004	18	3	*Breached*
41	TR	October 1, 2005	1,004	October 31, 2005	1,035	31	1	*Breached*
42	TR	November 1, 2005	1,035	November 30, 2005	1,065	30	1	*Breached*

Stress Period Number	Type	Stress Period Start Time		Stress Period Stop Time		Stress Period Duration (days)	Number of Time Steps per Stress Period	Breached Lagoon/Flooded Lagoon
		Date	Model Time (days)	Date	Model Time (days)			
43	TR	December 1, 2005	1,065	December 31, 2005	1,096	31	1	*Breached*
44	TR	January 1, 2006	1,096	January 31, 2006	1,127	31	1	*Breached*
45	TR	February 1, 2006	1,127	February 28, 2006	1,155	28	1	*Breached*
46	TR	March 1, 2006	1,155	March 31, 2006	1,186	31	1	*Breached*
47	TR	April 1, 2006	1,186	April 30, 2006	1,216	30	1	*Breached*
48	TR	May 1, 2006	1,216	May 31, 2006	1,247	31	1	*Breached*
49	TR	June 1, 2006	1,247	June 10, 2006	1,257	10	1	*Breached*
50	TR	June 11, 2006	1,257	June 30, 2006	1,277	20	3	*Flooded*
51	TR	July 1, 2006	1,277	July 31, 2006	1,308	31	1	*Flooded*
52	TR	August 1, 2006	1,308	August 22, 2006	1,330	22	1	*Flooded*
53	TR	August 23, 2006	1,330	August 31, 2006	1,339	9	3	*Breached*
54	TR	September 1, 2006	1,339	September 30, 2006	1,369	30	1	*Breached*
55	TR	October 1, 2006	1,369	October 28, 2006	1,397	28	1	*Breached*
56	TR	October 29, 2006	1,397	October 31, 2006	1,400	3	3	*Flooded*
57	TR	November 1, 2006	1,400	November 30, 2006	1,430	30	1	*Flooded*
58	TR	December 1, 2006	1,430	December 31, 2006	1,461	31	3	*Breached*
59	TR	January 1, 2007	1,461	January 31, 2007	1,492	31	1	*Breached*
60	TR	February 1, 2007	1,492	February 28, 2007	1,520	28	1	*Breached*
61	TR	March 1, 2007	1,520	March 31, 2007	1,551	31	1	*Breached*
62	TR	April 1, 2007	1,551	April 28, 2007	1,579	28	1	*Breached*
63	TR	April 29, 2007	1,579	April 30, 2007	1,581	2	3	*Flooded*
64	TR	May 1, 2007	1,581	May 31, 2007	1,612	31	1	*Flooded*
65	TR	June 1, 2007	1,612	June 30, 2007	1,642	30	1	*Flooded*
66	TR	July 1, 2007	1,642	July 31, 2007	1,673	31	1	*Flooded*
67	TR	August 1, 2007	1,673	August 31, 2007	1,704	31	1	*Flooded*
68	TR	September 1, 2007	1,704	September 30, 2007	1,734	30	1	*Flooded*
69	TR	October 1, 2007	1,734	October 19, 2007	1,753	19	1	*Flooded*
70	TR	October 20, 2007	1,753	October 31, 2007	1,765	12	3	*Breached*
71	TR	November 1, 2007	1,765	November 2, 2007	1,767	2	1	*Breached*
72	TR	November 3, 2007	1,767	November 30, 2007	1,795	28	3	*Flooded*
73	TR	December 1, 2007	1,795	December 31, 2007	1,826	31	3	*Breached*
74	TR	January 1, 2008	1,826	January 31, 2008	1,857	31	1	*Breached*
75	TR	February 1, 2008	1,857	February 29, 2008	1,886	29	1	*Breached*
76	TR	March 1, 2008	1,886	March 31, 2008	1,917	31	1	*Breached*
77	TR	April 1, 2008	1,917	April 30, 2008	1,947	30	1	*Breached*
78	TR	May 1, 2008	1,947	May 17, 2008	1,964	17	1	*Breached*
79	TR	May 18, 2008	1,964	May 28, 2008	1,975	11	3	*Flooded*
80	TR	May 29, 2008	1,975	May 31, 2008	1,978	3	3	*Breached*
81	TR	June 1, 2008	1,978	June 29, 2008	2,007	29	1	*Breached*
82	TR	June 30, 2008	2,007	June 30, 2008	2,008	1	3	*Flooded*
83	TR	July 1, 2008	2,008	July 31, 2008	2,039	31	1	*Flooded*
84	TR	August 1, 2008	2,039	August 31, 2008	2,070	31	1	*Flooded*
85	TR	September 1, 2008	2,070	September 30, 2008	2,100	30	1	*Flooded*

Stress Period Number	Type	Stress Period Start Time		Stress Period Stop Time		Stress Period Duration (days)	Number of Time Steps per Stress Period	Breached Lagoon/Flooded Lagoon
		Date	Model Time (days)	Date	Model Time (days)			
86	TR	October 1, 2008	2,100	October 31, 2008	2,131	31	1	*Flooded*
87	TR	November 1, 2008	2,131	November 25, 2008	2,156	25	1	*Flooded*
88	TR	November 26, 2008	2,156	November 30, 2008	2,161	5	3	*Breached*
89	TR	December 1, 2008	2,161	December 31, 2008	2,192	31	1	*Breached*
90	TR	January 1, 2009	2,192	January 31, 2009	2,223	31	1	*Breached*
91	TR	February 1, 2009	2,223	February 28, 2009	2,251	28	1	*Breached*
92	TR	March 1, 2009	2,251	March 31, 2009	2,282	31	1	*Breached*
93	TR	April 1, 2009	2,282	April 18, 2009	2,300	18	1	*Breached*
94	TR	April 19, 2009	2,300	May 1, 2009	2,313	13	3	*Flooded*
95	TR	May 2, 2009	2,313	May 31, 2009	2,343	30	3	*Breached*
96	TR	June 1, 2009	2,313	June 18, 2009	2,361	18	1	*Breached*
97	TR	June 19, 2009	2,361	June 30, 2009	2,373	12	3	*Flooded*
98	TR	July 1, 2009	2,373	July 31, 2009	2,404	31	1	*Flooded*
99	TR	August 1, 2009	2,404	August 31, 2009	2,435	31	1	*Flooded*
100	TR	September 1, 2009	2,435	September 30, 2009	2,465	30	1	*Flooded*
101	TR	October 1, 2009	2,465	October 14, 2009	2,479	14	1	*Flooded*
102	TR	October 15, 2009	2,479	October 31, 2009	2,496	17	3	*Breached*
103	TR	November 1, 2009	2,496	November 30, 2009	2,526	30	3	*Flooded*
104	TR	December 1, 2009	2,526	December 31, 2009	2,557	31	3	*Breached*
105	TR	January 1, 2010	2,557	January 31, 2010	2,588	31	1	Breached
106	TR	February 1, 2010	2,588	February 28, 2010	2,616	28	1	Breached
107	TR	March 1, 2010	2,616	March 31, 2010	2,647	31	1	Breached
108	TR	April 1, 2010	2,647	April 27, 2010	2,674	27	1	Breached
109	TR	April 28, 2010	2,674	April 30, 2010	2,677	3	3	Flooded
110	TR	May 1, 2010	2,677	May 4, 2010	2,681	4	1	Flooded
111	TR	May 5, 2010	2,681	May 11, 2010	2,688	7	3	Breached
112	TR	May 12, 2010	2,688	May 21, 2010	2,698	10	3	Flooded
113	TR	May 22, 2010	2,698	May 31, 2010	2,708	10	3	Breached
114	TR	June 1, 2010	2,708	June 8, 2010	2,716	8	1	Breached
115	TR	June 9, 2010	2,716	June 30, 2010	2,738	22	3	Flooded
116	TR	July 1, 2010	2,738	July 31, 2010	2,769	31	1	Flooded
117	TR	August 1, 2010	2,769	August 31, 2010	2,800	31	1	Flooded
118	TR	September 1, 2010	2,800	September 30, 2010	2,830	30	1	Flooded
119	TR	October 1, 2010	2,830	October 7, 2010	2,837	7	1	Flooded
120	TR	October 8, 2010	2,837	October 26, 2010	2,856	19	3	Breached
121	TR	October 27, 2010	2,856	October 31, 2010	2,861	5	3	Flooded
122	TR	November 1, 2010	2,861	November 2, 2010	2,863	2	1	Flooded
123	TR	November 3, 2010	2,863	November 30, 2010	2,891	28	3	Breached
124	TR	December 1, 2010	2,891	December 31, 2010	2,922	31	1	Breached
125	TR	January 1, 2011	2,922	January 31, 2011	2,953	31	1	Breached
126	TR	February 1, 2011	2,953	February 28, 2011	2,981	28	1	Breached
127	TR	March 1, 2011	2,981	March 31, 2011	3,012	31	1	Breached
128	TR	April 1, 2011	3,012	April 30, 2011	3,042	30	1	Breached
129	TR	May 1, 2011	3,042	May 31, 2011	3,073	31	1	Breached

Stress Period Number	Type	Stress Period Start Time		Stress Period Stop Time		Stress Period Duration (days)	Number of Time Steps per Stress Period	Breached Lagoon/Flooded Lagoon
		Date	Model Time (days)	Date	Model Time (days)			
130	TR	June 1, 2011	3,073	June 26, 2011	3,099	26	1	Breached
131	TR	June 27, 2011	3,099	June 30, 2011	3,103	4	3	Flooded
132	TR	July 1, 2011	3,103	July 31, 2011	3,134	31	1	Flooded
133	TR	August 1, 2011	3,134	August 31, 2011	3,165	31	1	Flooded
134	TR	September 1, 2011	3,165	September 30, 2011	3,195	30	1	Flooded
135	TR	October 1, 2011	3,195	October 6, 2011	3,201	6	1	Flooded
136	TR	October 7, 2011	3,201	October 31, 2011	3,226	25	3	Breached
137	TR	November 1, 2011	3,226	November 30, 2011	3,256	30	1	Breached
138	TR	December 1, 2011	3,256	December 31, 2011	3,287	31	1	Breached
139	TR	January 1, 2012	3,287	January 31, 2012	3,318	31	1	Breached
140	TR	February 1, 2012	3,318	February 29, 2012	3,347	29	1	Breached
141	TR	March 1, 2012	3,347	March 31, 2012	3,378	31	1	Breached
142	TR	April 1, 2012	3,378	April 30, 2012	3,408	30	1	Breached
143	TR	May 1, 2012	3,408	May 14, 2012	3,422	14	1	Breached
144	TR	May 15, 2012	3,422	May 31, 2012	3,439	17	3	Flooded
145	TR	June 1, 2012	3,439	June 9, 2012	3,448	9	1	Flooded
146	TR	June 10, 2012	3,448	June 22, 2012	3,461	13	3	Breached
147	TR	June 23, 2012	3,461	June 30, 2012	3,469	8	3	Flooded
148	TR	July 1, 2012	3,469	July 31, 2012	3,500	31	1	Flooded
149	TR	August 1, 2012	3,500	August 31, 2012	3,531	31	1	Flooded
150	TR	September 1, 2012	3,531	September 30, 2012	3,561	30	1	Flooded
151	TR	October 1, 2012	3,561	October 31, 2012	3,592	31	1	Flooded
152	TR	November 1, 2012	3,592	November 30, 2012	3,622	30	1	Flooded
153	TR	December 1, 2012	3,622	December 31, 2012	3,653	31	3	Breached

3.1.3 Boundary Conditions

Model boundary conditions are shown in Figure 3.1 and were specified as follows. The bottom model boundary, which is at the contact between alluvium and underlying bedrock, was assumed to be impermeable. The top boundary, represented by the water table, receives flow from infiltration of precipitation, excess irrigation, stream leakage and from wastewater dispersal that varies by stress period. Specified flux boundaries were used along the edges of the active model grid and upland areas to simulate recharge from uplands adjacent to the alluvium. Recharge from the uplands includes contributions from precipitation runoff, wastewater dispersal and excess irrigation.

A specified-head boundary condition was assigned to the contact between the alluvial deposits and the Pacific Ocean in model layers 1 and 2. The elevation of the specified head that represents the ocean in model layers 1 and 2 was set based upon average monthly tide elevation at Santa Monica, California Station ID 9410840, as shown in Figure 3.2. The bottom of model layer 2 corresponds to the ocean bottom in offshore areas. The bottom of model layer 3 corresponds to the top of coarse-grained deposits onshore and, in offshore areas, to the top of the first reflector determined from the marine reflection survey. Beneath this, in model layers 4-7, no-flow boundaries represent the interface between fresh and salt water.

The positions of the no-flow boundaries in offshore areas that represent the salt-fresh interface were estimated with a density-dependent flow model. The model used for this purpose is SEAWAT, which was developed by the U.S. Geological Survey (Langevin and others, 2008). The SEAWAT simulation incorporates all refinements made to the original model structure for this investigation.

Malibu Creek and Lagoon were represented as head-dependent boundaries in the model using the GHB package in MODFLOW. Leakage to or from the groundwater system is based upon the difference between Malibu Creek stage and adjacent groundwater elevations, and the hydraulic conductivity of the streambed materials. Stage was determined from measuring points, located on Malibu Creek near Arizona Crossing and at the PCH (Pacific Coast Highway) bridge over Malibu Lagoon, and supplemented with topographic data. Initial estimates of streambed conductance were made using streambed area and a hydraulic conductivity of 1 ft/day. Along the upper reaches of Malibu Creek, the GHB package specifications were set to maintain an infiltration rate of approximately 1.0 cfs (cubic feet per second) when the Lagoon is breached and 0.6 cfs when the lagoon is flooded.

The extent of the Lagoon represented by the GHB package varies depending upon whether the lagoon is flooded or breached as shown in Figure 3.1. When the lagoon is flooded, which usually occurs during the dry summer months, there is a stretch of dry channel between Cross Creek Road and the upper end of the lagoon and the GHB cells are active only above and below the dry stretch. When the lagoon is breached, which usually occurs when Malibu Creek floods in response to winter rains, the channel is continuously wet and GHB cells are specified along the entire reach of channel in the model area. The elevation of the lagoon is set in the GHB package using available stage data and information on conditions in the lagoon (flooded or breached). The lagoon conditions data were provided in daily notes maintained during the period from 2003 to 2012 at the life guard station on Surfrider Beach.

The DRAIN package in MODFLOW was used to simulate the artificial wetland on the Smith parcel. The stage elevation was set in order to control build-up of groundwater levels and to limit levels to the wetland elevation at that location.

3.1.4 Hydraulic Parameters

Specification of hydraulic properties in the model area was guided by delineation of specific hydro-stratigraphic zones in which hydraulic properties were considered to be similar. A summary of hydro-stratigraphic zones used in the model, and the average calibrated hydraulic conductivity value for each zone, are included in Table 3.2. Locations of the hydro-stratigraphic zones for model layers 1-7 are shown in Figures 3.3 through 3.9.

Table 3.2 -- Summary of model hydro-stratigraphic zones

Hydro Stratigraphy Zone	Material Type	Average Zone K (ft/d)	Average Zone Kh/Kz
1	Shallow Alluvium	78	100
2	Low Permeability	45	1000
3	Deep Alluvium	104	42
4	Winter Canyon	71	30
5	Ocean Bed Deposits	1	5
6	Malibu Creek Alluvium	509	50
7	Deep Ancient Channel	684	500
8	Chevron Zone	0.05	500
9	Bedrock	10	1

The low permeability zone was delineated in three-dimensions based upon a review of boring logs in the project database. The low permeability zone included materials that were identified from boring logs with the following USCS soil classifications -- clays (ML/CL, CL-ML, CH, SC-CL), silts (ML, ML-SC, ML-SM) and silty and clayey sands (SM, SM-SC, SC-SM, SC). The top and bottom of the low permeability zone were identified within the borings logs where possible.

The horizontal extent of the low permeability zone was constrained and verified to the west by borings in the terrace deposits and the alluvial contact. To the north, the bedrock/alluvial contact was used as the furthest extent. To the east, Malibu Creek was used as the boundary, and on the south, the shoreline was used. The top surface and bottom surfaces of the low permeability zone were identified and the three-dimensional representation was created. Model cells were intersected with the three-dimensional low-permeability zone to identify locations of low permeability deposits within the model grid.

The highest values of hydraulic conductivity are used to represent the coarse grained sands and gravel along the present course of Malibu Creek (Malibu Creek Alluvium) and in the Civic Center Gravels (Deep Ancient Channel) in model layers 4-7 (Figure 3.6). The lowest values represent fine-grained sediments included in the shallow estuarine deposits represented by model layers 1-3.

3.1.5 Recharge and Discharge

Recharge to alluvium from wastewater dispersal was simulated with the WELL package in MODFLOW. Locations where subsurface wastewater dispersal were simulated in the model are shown in Figure 3.10. On parcels where the exact location of the subsurface dispersal systems were known, they were mapped to the appropriate model cells. On parcels where the location of the subsurface dispersal system was unknown, the dispersal was mapped to the model cell nearest to the centroid of the property. For parcels in upland areas adjacent to the alluvium, subsurface dispersal was aggregated and mapped to the edge of the alluvium as shown on Figure 3.10.

The rate of wastewater dispersal simulated in the model is based upon bimonthly water use data for each parcel provided by County of Los Angeles for the period 2003-2009. For the period from 2010-2012, water use data were not available for individual parcel but only as total water use for specific meter book areas. Wastewater dispersal at individual parcel for 2010-2012 were based upon total water use data and distributed in the same proportions as observed in the 2003-2009 data. The water users, and assumptions about dispersal rates, were grouped into five general areas/categories as shown in Figure 2.9. The dispersal rates were specified in the model as follows:

1) Malibu Colony shoreline area -- 400 gpd (gallons per day), no irrigation.

2) Upland Areas -- If total water use is less than or equal to 400 gpd then the wastewater dispersal rate is the actual reported bimonthly water use. If the reported water use is more than 400 gallons per day, then the dispersal rate is specified as 400 gpd and remaining water is assumed to be used for irrigation

3) Serra Vicinity -- same as for Upland Areas described above.

4) Commercial -- Wastewater dispersal is equal to the total reported bimonthly water use, no irrigation.

5) Nurseries/Golf Park -- Wastewater dispersal is 400 gpd if there is a residence on the property. The remaining water use is assumed to be for irrigation. If there is no residence, the wastewater dispersal rate is zero and all water is assumed to be used for irrigation.

Recharge from excess irrigation was simulated in the model using the RIVER package in MODFLOW at locations shown in Figure 3.11. The rate of recharge from excess irrigation is assumed to be equal to 50% of any bimonthly reported water use in excess of 400 gpd for those properties shown in Figure 3.11 that include a residence.

Recharge from residential properties in upland areas adjacent to the alluvium is also assumed to be equal to 50% of any bimonthly reported water use in excess of 400 gpd, and is aggregated and applied to the edge of the active model areas as shown in Figure 3.11. Recharge from excess irrigation at the Nurseries/Golf Park properties is 50% of bimonthly water use if there is no residence on the property.

Recharge from infiltration of precipitation on the alluvial deposits and from runoff originating in upland areas was simulated in the model with the RECHARGE package in MODFLOW at locations shown in Figure 3.12. Recharge to the alluvium from runoff originating in upland areas, shown in Figure 2.8, is estimated based upon the size of the upland area (Table 2.3) and is applied to the edge of the active model area at the locations shown in Figure 3.12. Recharge from infiltration of precipitation on the alluvium occurs only on unpaved areas as shown in Figure 3.12.

The rate of recharge from infiltration of precipitation on the alluvium is based upon the graph shown in Figure 3.13. The graph was developed during model calibration and relates monthly precipitation to monthly recharge rates. The form of the graph resulted from the need to increase recharge during wet periods such that model calculated water levels would more closely match observed water levels. Examination of Figure 3.13 shows that total monthly precipitation of seven inches would result in a total monthly recharge of approximately 0.9 inches. The maximum monthly precipitation during the model simulation period was 11.24 inches in January 2005, which resulted in a monthly recharge of approximately 1.6 inches. Recharge from precipitation in upland areas that contribute runoff to the modeled area was assumed to be equivalent to recharge to alluvium. The recharge curve in Figure 3.13 is applied to the transient model simulation with a two-month lag.

Evapotranspiration from groundwater was simulated with the ET package in MODFLOW in the model area where phreatophytes exist along the riparian zone adjacent to Malibu Creek and Lagoon as shown in Figure 3.14. The maximum evapotranspiration rate varies by stress period using monthly ET rates calculated for the Pepperdine campus (Daniel B. Stephens & Associates, Inc., 2007a, 2007b, 2008a, 2008b, 2009, 2010, 2011, 2012). The extinction depth was set at 15 feet below land surface.

3.2 Calibration

Calibration of the groundwater flow model was accomplished by adjusting specifications of hydraulic parameters within reasonable ranges to cause the model-calculated heads to agree with observed groundwater levels. Three different sets of groundwater level observations were used as the basis for model calibration. These included 1) groundwater levels measured at observation wells at various locations during the period from 2003-2012; 2) groundwater level changes observed in observation wells at the end of 7-day injection tests done at three deep injection wells done as part of this study (Pueblo Water Resources, 2014); and 3) groundwater level fluctuations caused by ocean tides.

The groundwater level observations from the 2003-2012 period included 3,513 observations at 101 locations in the model area. If multiple observations were available at a given location within a model stress period, the observations were averaged. Water level data from the three 7-day injection tests include water level changes observed in 17 observation wells, 7 shallow and 8 deep, during each injection test. The tidal-induced groundwater fluctuations included hourly data from 5 deep observation wells over a period of 80 hours (May 24-27, 2012). Locations of all wells are shown in Figures 2.17a and 2.17b.

Each of the three sets of observations described above were used as calibration targets in three individual model simulations during the calibration process. The first simulation extended from 2003-2012 with the stress period setup described in Table 3.1. The second simulation included a total of approximately 21 days divided into three 7-day periods that represent the three 7-day injection tests. The third simulation represents an eighty hour period, divided into one hour times steps with hourly tidal fluctuations. The simulation period was from May 24-27, 2012 using tide data from the NOAA tide station in Santa Monica. Each of these three simulations incorporates identical aquifer hydraulic properties and differ only in the hydraulic stresses that are applied and in the way they are discretized in time. During calibration, the three simulations were bundled and run back to back to observe how variations in aquifer hydraulic properties affected the model capability to match each set of targets.

The model calibration process included a combination of trial and error simulations and automated parameter estimation using the PEST numerical code (Watermark Numerical Computing, 1994). During automated calibration, model hydraulic conductivity values and storage properties were adjusted to improve the model-calculated match between computed and observed water levels for each of the three target data sets. The hydraulic conductivity values were modified using a combination of pilot points and zones.

Model calibration involved variation of hydraulic conductivity values for each of the hydro-stratigraphic zones. For some of the zones, one value of hydraulic conductivity was used throughout the model domain during model calibration runs. Zones represented with one uniform value of hydraulic conductivity include Bedrock and the Ocean Bed Deposits. For all of the other hydro-stratigraphic zones, the calibration process allowed hydraulic conductivity to vary spatially within the zone by estimating hydraulic conductivity at discrete horizontal locations that are defined as pilot points.

In the pilot point method, hydraulic property values, in this case values of horizontal hydraulic conductivity, are assigned to a set of points or "pilot points" distributed throughout a model layer rather than directly to model grid cells (Doherty, 2003). Property values are then assigned to model cells through spatial interpolation from the pilot points to the model grid. This results in a smooth variation of hydraulic conductivity over like subsurface materials. Parameter estimation is then performed on the values of the pilot points to minimize the difference between observations and model calculated target values.

Pilot-points were kriged, one two-dimensional array each, for each hydro-stratigraphic zone to provide values for each model cell. Kriged values of hydraulic conductivity, for zones with pilot points, obtained for any particular model row and column were assigned to all model layers where these zones existed. Therefore the hydraulic conductivity distributions for these zones do not vary with depth.

Vertical hydraulic conductivity for each cell in the model grid was estimated using ratios of horizontal to vertical hydraulic conductivity. During calibration, values of the ratio of horizontal to vertical hydraulic conductivity were varied for each of the nine zones. A single ratio value was used for each of the nine zones.

Calibration of aquifer storage properties was accomplished by subdividing the model domain into three general zones. The three zones include shallow alluvium (model layers 1-3), deep alluvium (model layers 4-7) and Winter Canyon. During calibration, specific yield and specific storage were estimated for each of those three zones.

Recharge values were adjusted by modifying the relationship between monthly precipitation and monthly recharge shown in Figure 3.13 and in the time lag between precipitation and the resulting recharge. The process of calibration for recharge was done on a trial and error basis. A summary of final annual recharge rates used in the calibrated model is included in Table 3.3.

Table 3.3 -- Summary of modeled annual recharge rates, in inches per year.

YEAR	Total Precipitation	Precipitation Recharge
2003	8.4	1.2
2004	17.6	1.2
2005	24.6	3.4
2006	17.5	1.9
2007	9.0	0.7
2008	13.6	1.1
2009	12.3	1.2
2010	22.7	1.5
2011	14.4	2.4
2012	11.2	1.0
Average	14.9	1.6

Water level targets used in 2003-2012 model calibration included 3,513 observations at 101 locations. The locations where groundwater levels were used for calibration are included in Figure 2.17a and 2.17b. A scatter diagram showing a comparison of model calculated and observed water levels from the final calibrated model are included in Figure 3.15. The final statistics of calibration are as follows: residual mean 0.19 ft, absolute residual mean 1.47 ft and sum of squares 14,918 ft^2. Given the range of water levels within the model area (72.8 ft), these statistical measures of match are considered to be acceptable. A table of all residuals is included in Appendix A.

A comparison of model-calculated groundwater level changes with observed changes at the end of each 7-day injection test are provided in Tables 3.4, 3.5 and 3.6 for tests at injection wells MCWP-MW01, MCWP-MW02 and MCWP-MW03, respectively. The positive values in observed and computed groundwater level changes in Tables 3.4, 3.5 and 3.6 indicate groundwater level increases observed during injection. Each of the tables below are subdivided into observations made at shallow wells, which are completed in model layers 1 and 2, and deep wells which are located in model layers 4-7. Locations of all of the wells are included in Figures 2.17 a and 2.17b.

Table 3.4 -- Comparison of model calculated and observed groundwater level changes, in feet, at the end of the 7-day injection test at well MCWP-MW-01.

Shallow wells	Model Layer	Observed	Computed	Residual
MCWP-MW04S	2	0.00	0.15	-0.15
SMBRP-11	1	0.00	0.07	-0.07
SMBRP-15B	1	0.00	0.00	0.00
LY-MW04	1	0.00	0.04	-0.04
M7-2	2	0.00	0.16	-0.16
MBCMW-5	1	0.00	0.00	0.00
MBCMW-7	1	0.00	0.00	0.00
MCWP-MW07S	1	0.00	0.02	-0.02
			Average	-0.05

Deep wells	Model Layer	Observed	Computed	Residual
MCWP-MW04D	6	0.70	0.63	0.07
MCWP-MW05	6	0.40	0.39	0.01
MCWP-MW06	7	0.30	0.38	-0.08
MCWP-MW07D	6	0.50	0.40	0.10
MCWP-MW08	5	0.00	0.11	-0.11
MCWP-MW09	6	0.40	0.33	0.07
GH9-M4	4	0.00	0.23	-0.23
MBCMW-10	4	0.35	0.40	-0.05
MBCMW-8	4	0.60	0.54	0.06
			Average	-0.02

Table 3.5 -- Comparison of model calculated and observed groundwater level changes, in feet, at the end of the 7-day injection test at well MCWP-MW-02.

Shallow wells	Model Layer	Observed	Computed	Residual
MCWP-MW04S	2	0.00	0.11	-0.11
SMBRP-11	1	0.00	0.04	-0.04
SMBRP-15B	1	0.00	0.00	0.00
LY-MW04	1	0.00	0.04	-0.04
M7-2	2	0.00	0.12	-0.12
MBCMW-5	1	0.00	0.00	0.00
MBCMW-7	1	0.00	0.00	0.00
MCWP-MW07S	1	0.00	0.01	-0.01
			Average	-0.04

Deep wells	Model Layer	Observed	Computed	Residual
MCWP-MW04D	6	0.30	0.38	-0.08
MCWP-MW05	6	0.30	0.41	-0.11
MCWP-MW06	7	1.30	1.39	-0.09
MCWP-MW07D	6	0.20	0.28	-0.08
MCWP-MW08	5	0.00	0.14	-0.14
MCWP-MW09	6	0.20	0.26	-0.06
GH9-M4	4	0.00	0.18	-0.18
MBCMW-10	4	0.25	0.34	-0.09
MBCMW-8	4	0.30	0.35	-0.05
			Average	-0.09

Table 3.6 -- Comparison of model calculated and observed groundwater level changes, in feet, at the end of the 7-day injection test at well MCWP-MW-03.

Shallow wells	Model Layer	Observed	Computed	Residual
MCWP-MW04S	2	0.00	0.13	-0.13
SMBRP-11	1	0.00	0.14	-0.14
SMBRP-15B	1	0.00	0.00	0.00
LY-MW04	1	0.00	0.03	-0.03
M7-2	2	0.00	0.11	-0.11
MBCMW-5	1	0.00	0.00	0.00
MBCMW-7	1	0.00	0.00	0.00
MCWP-MW07S	1	0.00	0.03	-0.03
			Average	-0.05

Deep wells	Model Layer	Observed	Computed	Residual
MCWP-MW04D	6	0.50	0.36	0.14
MCWP-MW05	6	0.30	0.26	0.04
MCWP-MW06	7	0.20	0.26	-0.06
MCWP-MW07D	6	1.15	1.04	0.11
MCWP-MW08	5	0.00	0.08	-0.08
MCWP-MW09	6	0.40	0.30	0.10
GH9-M4	4	0.00	0.16	-0.16
MBCMW-10	4	0.30	0.26	0.04
MBCMW-8	4	0.40	0.33	0.07
			Average	0.02

Examination of Tables 3.4, 3.5 and 3.6 shows that the model does a reasonably good job of reproducing the groundwater level changes that were observed at the end of the 7-day injection testing. At the end of each of the 7-day injection tests, there was no observable increase in groundwater levels in any of the shallow observation wells. On average, the model over-predicts the groundwater level increases in the shallow wells by approximately 0.05 feet at MCWP-MW01 and MCWP-MW03 and by 0.04 feet at well MCWP-MW-MW02. On average, in the deep observation wells, the model over-predicts groundwater level increases caused by injection at MCWP-MW01 and MCWP-MW02, and slightly over-predicts groundwater level increases at MCWP-MW03.

A comparison of modeled and observed tidally induced groundwater level fluctuations is illustrated in Figure 3.16. Well MCWP-MW03 is located 450 feet from the coast and has a screened interval from 45-134 feet below land surface. Well MBC-MW06 is located 1,900 feet from the coast and has a screened interval from 60-65 feet below land surface. Both well screens are in the Civic Center gravels and both show tidal fluctuations. Examination of Figure 3.16 shows that the calibrated model does a reasonably good job of reproducing the observed phase and amplitude of the tidal fluctuation at both wells.

Hydrographs showing a comparison of model calculated and observed groundwater elevations are shown for representative locations in Figures 3.17a through 3.17g. Figures 3.17a and 3.17b show calculated and observed water levels for Well02 and SMBRP-11, which are both located in Winter Canyon. During 2003-2012, the observed water levels at Well02, in the upper part of the Canyon, range from approximately 47 to 61 ft NAVD88, a 14 foot variation. At SMBRP-11, in the lower part of the Canyon, observed water levels vary from 9.5 to 12 ft NAVD88, a 2.5 foot variation. At both locations, the highest water levels correspond with the record high precipitation that occurred in winter of 2004-05. Examination of Figures 3.17a and 3.17b show that the model reasonably replicates the observed water level fluctuations at both locations.

Figures 3.17c, 3.17d, 3.17e and 3.17f show calculated and observed water levels for selected wells in main body of the alluvium. Wells MBC-MW5 (Figure 3.17c), W-4A (Figure 3.17d) and SMBRP-13 (Figure 3.17e) are shallow wells completed above the Civic Center Gravels. Well MBC-MW6 (Figure 3.17f) is deeper and is completed in the top of the Civic Center Gravels.

Well MBC-MW5 (Figure 3.17c) is in the northwestern part of the alluvium and, like most of the wells in the study area has a gap in available water level data from late 2003 to the middle of 2007. Observed water levels at this location vary from about 12 to 16 ft NAVD88. The timing of model calculated and observed high water levels match closely, and the model predicts that the highest water level at this location would have occurred in response to the very wet winter of 2004-05.

Well W-4A (Figure 3.17d) is located at the gas station near the intersection of Pacific Coast Highway and Malibu Road. Water level data have been collected at this location quarterly since 2007 as part of site remediation activities. Observed low elevations are approximately 9 ft NAVD88 and observed high water levels are about 12 ft NAVD88. The modeled water levels fluctuations at this location closely match observed water levels. The maximum model predicted water level (15.5 ft NAVD88) at this location also occurs in the wet winter of 2004-2005.

Well SMBRP-13 (Figure 3.17e) is on Malibu Colony Road, approximately 300 feet from the Pacific Ocean. The observed water levels at this location vary from approximately 4.5 to 6.5 ft NAVD88 and appear to dominated by tidal fluctuations as opposed to variations in recharge from precipitation. The model does a reasonably good job of reproducing the tidal fluctuations observed at this location.

Well MW-6 (Figure 3.17f) is located in the center of the Malibu Sycamore Village parcel and is completed in the Civic Center gravels which are represented in model layer 4. The groundwater levels in this well are lower than those measured in the nearby shallow unconfined wells. Furthermore, water levels in this well do not vary in response to precipitation and runoff events in the same way that shallow wells do. Water levels in MW-6 well have smaller fluctuations than the shallow unconfined wells and are slightly affected by lagoon stage and tidal fluctuations. The model does a reasonable job of replicating the deep water level and fluctuations related to variations in tide/lagoon stage. Model calculated levels at MW-6 are slightly higher than observed values especially in early time.

Well P-9 (Figure 3.17g) is located in the eastern part of the alluvium close to the lagoon. The observed water levels at this location directly reflect variations in lagoon stage and do not correlate with precipitation events like wells in Winter Canyon and the western part of the alluvium. The model calculated water levels are very close to observed elevations for the periods when data are available.

Final average values of horizontal hydraulic conductivity, and the ratio of horizontal to vertical hydraulic conductivity, resulting from model calibration for each of the hydro-stratigraphic zones, are shown in Table 3.2. The zones are illustrated in Figures 3.3 to 3.9 for model layers 1-7 respectively. The highest hydraulic conductivities occur in the Malibu Creek Alluvium in model layers 1, 2 and 3 and in the Deep Ancient Channel (Civic Center gravels) in model layer 4-7. The resulting ratios of horizontal to vertical hydraulic conductivity vary from about 1000:1 in the Low Permeability zone to 1:1 in bedrock. Specific yield was estimated to be 0.12 in the main body of alluvium and 0.15 in Winter Canyon. Calibrated values of specific storage were 2.79e-5 ft^{-1} in model layers 1-3 and 1.0 e-6 ft^{-1} in model layers 4-7. In Winter Canyon specific storage was 1.0 e-6 ft^{-1} in all layers.

A detailed summary of the model calculated water budget for the calibrated model is included in Table 3.7. Table 3.7 includes a detailed summary of water balance terms by year for the simulation period, including an average for the 2003-2012 period. The average values are also summarized in the block diagram included in Figure 2.16 and in Table 2.5.

Table 3.3. Model calculated annual water budgets for the period 2003-2012, in gallons per day.

Source/Sink	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	Average
Precipitation Recharge											
Alluvium (Exclusive of Winter Canyon)	35,747	44,421	103,676	62,204	25,614	39,130	40,994	54,833	71,718	33,582	51,192
Natural Upland Runoff											
East Shore 1	1,587	1,704	4,601	2,655	1,026	1,573	1,718	2,062	3,281	1,369	2,158
East Alluvium	11,169	11,998	32,380	18,687	7,217	11,071	12,094	14,512	23,093	9,635	15,186
Tributary	9,850	10,579	28,551	16,478	6,365	9,764	10,666	12,799	20,363	8,497	13,391
North Alluvium	4,060	4,361	11,771	6,794	2,624	4,026	4,396	5,276	8,396	3,503	5,521
Serra Retreat	2,329	2,501	6,751	3,896	1,505	2,308	2,522	3,026	4,814	2,009	3,166
Northwest Alluvium	9,245	9,930	26,797	15,466	5,974	9,165	10,008	12,012	19,114	7,975	12,568
West Alluvium	7,386	7,932	21,410	12,356	4,772	7,320	7,996	9,596	15,268	6,372	10,041
West Shore 1	2,924	3,140	8,477	4,891	1,889	2,898	3,166	3,799	6,044	2,522	3,975
East Shore 2	17,484	18,781	50,685	29,254	11,299	17,332	18,931	22,719	36,150	15,086	23,772
West Shore 2	7,682	8,251	22,267	12,853	4,964	7,614	8,317	9,981	15,881	6,627	10,444
Alluvium Irrigation Return											
Serra Retreat	37,594	40,081	38,104	41,500	51,710	51,853	41,581	35,043	43,476	43,945	42,489
Malibu Colony Golf Course	8,874	9,687	5,043	9,073	10,856	10,861	9,399	7,790	8,053	9,139	8,877
Nurseries	2,705	2,496	3,172	2,855	1,929	1,468	1,099	974	1,117	1,205	1,902
Estate	6,023	3,064	2,447	2,901	2,966	3,154	2,715	2,321	2,851	2,911	3,135
Miscellaneous	1,236	1,536	1,479	1,856	1,758	1,564	1,847	1,596	1,956	1,979	1,681
Remaining Alluvium	0	0	0	0	0	0	0	0	0	0	0
Upland Irrigation Return											
East Shore 1	3,928	4,263	3,789	4,326	5,815	5,554	4,428	3,774	4,041	4,450	4,437
East Alluvium	31,404	34,746	28,888	29,680	36,263	33,443	31,146	26,367	31,111	32,530	31,558
Tributary	0	0	0	0	0	0	0	0	0	0	0
North Alluvium	1,349	1,249	1,145	1,218	1,457	1,312	1,131	973	1,199	1,205	1,224
Serra Retreat	777	1,060	1,544	1,529	1,952	1,995	1,386	1,160	1,493	1,500	1,440
Northwest Alluvium	10,296	12,440	11,136	12,553	15,083	14,216	10,791	7,904	8,902	10,708	11,403
West Alluvium	8,847	11,498	9,563	9,244	9,510	9,056	8,332	6,484	7,722	8,576	8,883
West Shore 1	0	0	0	0	0	0	0	0	0	0	0
East Shore 2	8,310	8,731	6,862	7,263	9,236	9,520	7,132	6,055	6,523	7,153	7,678
West Shore 2	0	0	0	0	0	0	0	0	0	0	0
Malibu Creek Leakage											
Upper Creek	619,799	597,473	674,446	621,294	545,401	577,898	586,716	612,481	626,092	559,909	602,151
Lagoon	216,235	274,192	89,980	231,357	353,604	266,439	258,099	218,685	144,744	145,895	219,923
Wastewater Main Alluvium											
West Shore Septic	13,472	14,532	14,414	14,444	14,542	14,367	14,497	14,431	14,414	14,420	14,353
Commercial Septic	110,858	121,356	93,164	103,299	88,083	89,345	76,687	66,623	75,688	80,404	90,551
Colony Septic	52,247	53,569	52,903	53,138	53,000	53,840	54,337	54,337	54,337	54,336	53,604
East Shore Septic	2,400	2,334	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,394
Around Serra Septic	22,884	22,798	22,685	22,405	22,736	22,016	22,155	21,997	22,135	22,187	22,400

Wastewater Upland											
Upland Northwest NN Septic	56,966	53,182	50,879	52,832	54,614	59,309	55,609	44,764	48,886	55,799	53,284
Upland Northwest W Septic	7,459	8,179	8,521	10,660	10,536	7,372	5,979	5,609	5,966	6,004	7,629
Upland Northwest E Septic	9,545	10,055	9,873	9,639	9,900	9,298	9,413	9,066	9,229	9,355	9,538
Upland Northeast	11,982	12,760	12,804	12,610	12,746	12,538	12,591	12,366	12,610	12,639	12,565
Upland East Shore 1	9,017	8,409	8,053	7,977	8,554	8,209	7,051	6,174	6,538	7,106	7,709
Upland East Shore 2	1,849	2,563	2,655	3,446	3,332	3,345	5,407	4,921	5,130	5,496	3,814
Upland West Shore	15,355	19,528	17,370	18,631	22,622	18,166	18,135	15,343	14,653	14,839	17,464
Winter Canyon											
Winter Canyon Upland Recharge	19,411	20,849	56,270	32,474	12,544	19,240	21,016	25,220	40,134	16,745	26,390
Winter Canyon Alluvium Recharge	1,896	2,036	5,495	3,172	1,225	1,879	2,053	2,463	3,919	1,635	2,577
Winter Canyon Irrigation Return	199	291	227	178	206	89	68	41	91	86	148
Winter Canyon Upland Irrigation Return	2,046	7,211	2,334	2,739	2,868	2,579	2,734	2,274	2,879	2,943	3,061
Winter Canyon Upland Septic	4,521	4,845	4,863	5,386	5,138	2,168	3,295	3,024	3,149	3,281	3,967
Winter Canyon Alluvium Septic	11,712	9,641	11,441	11,984	13,617	12,903	10,799	9,471	11,376	11,326	11,427
MBC Wastewater	33,428	36,178	32,827	26,227	29,473	30,322	29,915	25,264	23,731	25,391	29,276
LA County Wastewater	34,535	52,622	59,869	46,210	47,826	45,382	34,687	30,519	35,749	36,978	42,438
Change in Storage	-20,937	46,832	-5,070	-4,322	-8,833	-31,166	5,267	-40,365	16,041	-36,539	-7,909
Flow to Ocean	869,516	930,801	853,658	923,853	999,903	931,295	883,441	849,711	807,727	703,541	875,345
Evapotranspiration	79,702	95,293	97,103	109,342	106,095	80,466	84,625	93,606	61,519	63,675	87,143
Malibu Creek	51,863	42,729	107,770	60,830	31,127	46,547	40,445	41,175	66,001	35,837	52,432
Lagoon	508,526	470,546	597,127	506,471	408,517	486,389	460,399	489,055	552,516	545,030	502,458
Smith Parcel Wetland	0	2,879	0	0	0	1,921	0	5,435	2,668	97	1,300
Total In	1,488,625	1,589,053	1,664,012	1,602,036	1,536,750	1,515,303	1,475,437	1,438,528	1,506,420	1,311,654	1,512,782
Total Out	1,488,671	1,589,081	1,650,589	1,596,173	1,536,810	1,515,453	1,474,178	1,438,617	1,506,471	1,311,640	1,510,768

3.3 Application

The primary objective of the groundwater modeling effort was to evaluate the effects of the proposed treated wastewater injections on groundwater elevations and flow directions and to estimate subsurface injection capacity. The recalibrated model, which simulates groundwater levels in the alluvium during the period 2003-2012, forms the basis for evaluation of injection capacity and directions of groundwater flow.

3.3.1 Optimization Code and Procedure

The approach for evaluating underground injection capacity involves use of the recalibrated transient MODFLOW model and an optimization technique using GWM-VI (Banta and Ahlfeld), a parallel processing version of GWM-2005 (Ahlfeld and others, 2009). GWM-VI uses output from MODFLOW to determine optimal injection rates. In this technique, potential injection locations are identified, and the acceptable amount of groundwater level change is specified at multiple constraints. The optimizing routine then determines the amount of injection that can occur at each of the potential injection sites without causing unacceptable groundwater level increases at any of the constraint locations.

3.3.2 Selection of Potential Injection Well Location and Rate

Locations where the ten potential injection wells were simulated are shown in Figure 3.18. The locations of W-1, W-7 and W-9 shown on Figure 3.18 correspond to the locations of Phase 1 test wells MCWP-MW03, MCWP-MW01, and MCWP-MW02 respectively. Other than W-1, W-7 and W-9, the potential locations for injection wells shown on Figure 3.18 are not based upon any specific drilling or field testing data but rather on the logistics of access. In the optimization routine, the maximum allowable injection rate at any of the wells is limited to 280 gallons per minute. This value is based upon results of injection testing done at wells MCWP-MW01, MCWP-MW02, and MCWP-MW03 (Pueblo Water Resources, 2014). The injected water was distributed equally in model layers 4-7, which represent deep alluvial deposits.

Through the optimization and the subsequent particle tracking process it became clear that limiting injection to wells W-1, W-2, and W-3 would allow increased injection while minimizing flow of treated wastewater to Malibu Lagoon. For this reason, the optimization simulation results presented only consider injection to the W-1, W-2, and W-3 locations.

3.3.3 Selection of Groundwater Level Constraints

Forty-three locations where groundwater level constraints were imposed within the shallowest unit (layer 1 of the model) during the optimization simulations are shown on Figure 3.19. Figure 3.19 also shows the acceptable distance from land surface to groundwater at each of the head constraint locations. For the purpose of this study, acceptable groundwater levels are generally assumed to be at approximately 5 feet below land surface in model layer 1. At some locations where groundwater levels are currently less than 5 feet from land surface, such as in the dedicated wetland area on the west side of the alluvium, the 5 foot depth-to-water constraint is relaxed. Other locations where the head constraints are less than 5 feet include the area under Legacy Park Pond and near Malibu Lagoon.

Long-term precipitation data (1937-2012) from the Santa Monica Pier (California ID 047953) indicate that the average annual precipitation for a water year (October 1, Year 1 to November 30, Year 2) is 10.9 inches per year. During the 2005 water year (October 1, 2004 to November 30, 2005), precipitation at Santa Monica was 32.15 inches which represents one of the wettest water years on record for that site. Based on this information, it is assumed that the 2003-2012 period considered in this study includes a period from which can be characterized as being representative of extremely wet conditions. High precipitation at the site can increase groundwater levels over a long period of time (Figure 3.20). As shown in Figure 3.20, groundwater levels are high for a period of years following the 2005 precipitation event.

For the results presented in this report, optimization constraints were not invoked during the period of time in which groundwater levels were impacted by the high precipitation in the 2005 water year. Figure 3.21 shows groundwater levels at an optimization constraint in model layer 1 located near the Legacy Park Pond. In this figure, simulated groundwater levels for the current condition are plotted over time. The figure also shows the constraint elevation limit at this location which is five feet below the land surface and the land surface elevation. The figure shows that, even historic and current conditions with all existing septic disposal on, generates groundwater levels that are above the constraint limit as a result of the 2005 precipitation event. Since the objective of the optimization is to determine long-term injection rates not subject to extreme events, all groundwater level constraints were limited to the simulation period January 1, 2003 to August 31, 2004 and August 31, 2008 through December 31, 2012 (Figure 3.21).

3.3.4 Septic Disposal Reduction Phases

The optimization model was used to evaluate the effects of treated wastewater injected for each of the three phases of current septic system reduction. The current groundwater septic dispersal systems discharged an average of 382,422 gallons per day for the period 2003 to 2012 per day. For the same simulation period Phase 1, an average of 281,801 gallons per day will continue to be dispersed through existing septic systems until the Phase 2 reduction is initiated. During the same simulation period, for Phase 2, an average of 131,965 gallons per day will continue to be dispersed through existing septic systems. During the same simulation period for Phase 3, an average of 8,879 gallons per day will continue to be dispersed through existing septic systems. The presence of wastewaters entering the groundwater system from septic systems during each of the septic reduction phases limits the amount of water that can be injected into the ground without adverse effects. For this reason, the amount of water that could be injected was optimized separately for each of the three phases.

3.3.5 Particle Tracking Analyses Technique

For each optimized injection phase, the migration of injected wastewater was simulated using particle tracking. The particle tracking analysis was completed using the MODPATH computer code (Pollock, 1994). MODPATH uses output from the MODFLOW transient groundwater flow model to compute "imaginary" particles of water moving through the simulated groundwater flow system. Particles were placed around each of the active injection wells in model layers 4-7 (the zone where injection would occur) and tracked forward toward points of groundwater discharge. For these analyses, particles were released every year during the transient simulation period from 2003 through 2012, and porosity was set at 0.20.

3.3.6 Injection Simulation Results

During Phase 1, the maximum amount of treated wastewater that could be injected without violation of the constraints was 311,135 gallons per day. The optimization technique only identified injection in well W-3 at 216 gpm. The particle tracks for this simulation show that all of the injected water travels offshore and ultimately discharges to the Pacific Ocean rather than to Malibu Lagoon (Figure 3.22).

The Phase 2, optimization application determined that the maximum amount of treated wastewater that could be injected was 497,642 gallons per day. In this simulation, the optimization technique identified injection in wells W-1 (52 gpm) and W-3 (224 gpm). Particle tracking for this condition also shows that all of the injected water travels offshore and ultimately discharges to the Pacific Ocean rather than to Malibu Lagoon (Figure 3.23).

Phase 3, which represents the maximum conversion of septic dispersal to subsurface injection, showed that the optimized rate of injection that meets the groundwater level constraints was 815,540 gallons per day. Particle tracking for this rate of injection indicated that a least some portion of injected groundwater could go to Malibu Lagoon. The optimization technique identified injection for wells W-1, W-2 and W-3. To reduce the possibility that treated wastewater would flow to Malibu Lagoon, injection was reduced to 75% of the optimized rate at each of the injection locations. As a result, the total injection rate was 611,654 gallons per day, with 210 gpm being injected at W-1 and W-3 and 5 gpm being injected at W-2. The resulting particle tracking for this reduced injection rate is shown in Figure 3.24. With the injection rate reduced to 611,654 gallons per day, all of the injected water travels offshore and ultimately discharges to the Pacific Ocean rather than to Malibu Lagoon.

3.3.7 Effect of Distribution of Treated Water to Winter Canyon

In addition to simulations of the injection of treated wastewater into deep units in the main alluvium, simulations were made to evaluate to the potential for percolating a portion of treated water during Phase 3 into Winter Canyon. In these simulations, the conditions of the transient MODFLOW groundwater flow model were used along with specified fixed rate injection in both the main alluvium in model layers 4 to 7 and into model layer 1 in Winter Canyon. Two simulations were completed; the first with 50,000 gallons per day percolated in Winter Canyon and the second with 100,000 gallons per day percolated in Winter Canyon. In both cases, the total combined injection and percolation rate was 611,654 gallons per day as had been determined for Phase 3.

Particle tracking for each of the two simulations is presented in Figures 3.25 and Figure 3.26. These figures show all of the injected and percolated wastewater travels offshore and ultimately discharges to the Pacific Ocean rather than to Malibu Lagoon with percolation of 50,000 gallons per day or 100,000 gallons per day in Winter Canyon. A review of the head constraints used during optimization indicates that groundwater levels did not exceed the specified limits for either of Winter Canyon percolation scenarios.

3.4 Sensitivity Analyses

A series of simulations were completed to evaluate the sensitivity of model predictions to selected model parameters. These model parameters included the conductivity (horizontal and vertical) of deep channel deposits, the vertical conductivity of the low permeability unit that separates shallow and deep deposits, and recharge from precipitation. Specifically, in the sensitivity analysis runs, both the vertical and horizontal conductivity of the deep channel deposits were decreased by 10 percent, the vertical conductivity of the low permeability unit was increased by 50 percent, and precipitation recharge was increased by 10 percent. Each of these changes to model parameter values was reasonable given the expected value ranges.

In each series of sensitivity simulations, the statistical match for groundwater level and injection test groundwater level changes were calculated; and a summary of those results is provided in Table 3.4. The statistics show small absolute differences between base or calibrated historic simulation statistics and the sensitivity simulations. Based on groundwater level statistics, the most sensitive parameter of those tested was the vertical conductivity of the low permeability unit. A positive number in this portion of Table 3.4 represents model calculated values that are lower than observed values. With increased vertical conductivity of the low permeability unit, groundwater levels drop and the residual mean goes from 0.19 feet in the base run to 0.40 feet in the sensitivity run.

Although the results are very similar, the injection test groundwater level change statistics show that the model is most sensitive to the decrease in conductivity of the deep channel deposits. Based on the residual mean values, the base 2003 to 2012 calibrated transient model generally shows that the model is calculating a rise in water level that is greater than that observed during the injection tests. The simulation with a decreased conductivity of the deep channel deposits shows an even greater injection test rise in groundwater levels than the base simulation.

Particle tracking was completed for each of the sensitivity simulations. The methods used for these particle tracking analyses are identical to those described in Section 3.35. Figure 3.27 to Figure 3.35 show the results of this particle tracking analyses. In these figures, the upper panel shows particle tracks for the base 2003 to 2012 calibrated conditions with injection, and the lower panel show the equivalent for the particular sensitivity simulation. As previously noted, particle tracking was completed for each of the injection phases. The results show that for the parameters changes selected, particles tracks are very similar to the base non-sensitivity simulation condition. In all cases, all particles travel offshore and ultimately discharge to the Pacific Ocean rather than to Malibu Lagoon.

Based on these figures, the most sensitive parameter to the direction of flow is deep channel conductivity (Figures 3.27 to 3.29). The changes to vertical conductivity of the low permeability unit (Figure 3.30 to Figure 3.32) and precipitation recharge (Figure 3.33 to Figure 3.35) show very little difference in particle flow paths.

Table 3.4 -- Statistics of match for model sensitivity simulations.

Statistic	Base Run 2003-2012	Decrease Horizontal Conductivity in Deep Channel Deposit by 10%	Increase Vertical Conductivity in Low Permeability Unit by 50%	Increase Precipitation Recharge by 10%
Groundwater Levels				
Residual Mean (ft)	0.19	0.19	0.40	0.07
Absolute Residual Mean (ft)	1.47	1.47	1.53	1.48
Residual Standard Deviation (ft)	2.05	2.05	2.09	2.06
Sum of Squares (ft^2)	14,918	14,924	15,945	14,991
Root Mean Square Error (ft)	2.06	2.06	2.13	2.07
Minimum Residual (ft)	-14.27	-14.27	-14.26	-14.47
Maximum Residual (ft)	9.69	9.69	9.70	9.42
Number of Observations	3513	3513	3513	3513
Range in Observations (ft)	72.77	72.77	72.77	72.77

Injection Test Groundwater Level Change[4]

MCWP-MW01				
Shallow Residual Mean (ft) [1]	-0.05	-0.06	-0.06	Same as Base Run[3]
Deep Residual Mean (ft)[2]	-0.02	-0.04	-0.01	Same as Base Run[3]
MCWP-MW02				
Shallow Residual Mean (ft)1	-0.04	-0.04	-0.04	Same as Base Run3
Deep Residual Mean (ft)2	-0.10	-0.12	-0.09	Same as Base Run3
MCWP-MW03				
Shallow Residual Mean (ft)[1]	-0.06	-0.06	-0.06	Same as Base Run[3]
Deep Residual Mean (ft)[2]	0.02	0.00	0.03	Same as Base Run[3]

Notes:

Statistics based on observed - model calculated values

[1] Shallow represents model layers 1 to 3

[2] Deep represents model layers 4 to 7

[3]Recharge held constant over time in injection test model.

[4]If the value is negative, there is more of a simulated rise in groundwater levels than observed. If the value is positive there is less of a simulated rise in groundwater levels than observed.

4.0 SUMMARY AND CONCLUSIONS

Modeling analyses conducted for this study evaluate the impacts of proposed subsurface injection of treated disinfected wastewater into deep coarse-grained alluvial deposits on groundwater levels and directions of groundwater flow in the alluvial aquifer that lies along Malibu Creek and Lagoon in the Civic Center area of Malibu. The analyses evaluate three proposed phases of subsurface injection as described in a report by RMC Water and Environment (2014).

The groundwater model used for these analyses is an enhanced version of models prepared for the City of Malibu in 2012 and in 2010. Major modifications made to the groundwater model for since the 2010 include the following:

-Modified elevation of the bedrock surface based upon recent drilling and geophysics

-Modified model layer thicknesses

-Increased model extent into offshore areas

-Incorporated ocean bottom bathymetry from offshore geophysical survey

-Modified zonation of model hydraulic property zones.

- Density-dependent modeling was done to evaluate the position of the offshore salt/fresh interface and inform conceptualization of boundary conditions in the offshore area.

-Increased model simulation period from 2003-2009 to 2003-2012.

-Recalibrated model with groundwater level observations through 2012, including results of hydraulic testing done between 2010 and the present, and also used observed tidal fluctuations as a calibration target.

-Revised model recharge from precipitation

Calibration of the groundwater flow model was accomplished by adjusting specifications of hydraulic parameters within reasonable ranges to cause the model-calculated heads to agree with observed groundwater levels. Three different sets of groundwater level observations were used as the basis for model calibration. These included 1) groundwater levels measured at observation wells at various locations during the period from 2003-2012; 2) groundwater level changes observed in monitoring wells at the end of 7-day injection tests done at three deep injection wells; and 3) groundwater level fluctuations caused by ocean tides.

Water level targets used in 2003-2012 model calibration included 3,513 observations at 101 locations. The locations where groundwater levels were used for calibration are included in Figure 2.17a and 2.17b. A scatter diagram showing a comparison of model calculated and observed water levels from the final calibrated model are included in Figure 3.15. The final statistics of calibration are as follows: residual mean 0.19 ft, absolute residual mean 1.47 ft and sum of squares 14,918 ft^2. Given the range of water levels within the model area (72.8 ft), these statistical measures of match are considered to be acceptable.

The model does a reasonably good job of reproducing the groundwater level changes that were observed at the end of the 7-day injection testing. At the end of each of the 7-day injection tests, there was no observable increase in groundwater levels in any of the shallow observation wells. On average, the model over-predicts the groundwater level increases in the shallow wells by approximately 0.05 feet at MCWP-MW01 and MCWP-MW03 and by 0.04 feet at well MCWP-MW-MW02. On average, in the deep observation wells, the model over-predicts groundwater level increases caused by injection at MCWP-MW01 and MCWP-MW02, and slightly over-predicts groundwater level increases at MCWP-MW03. The calibrated model also does a reasonably good job of reproducing the observed phase and amplitude of the tidal fluctuation observed in monitoring wells.

The calibrated model was used to estimate the injection capacity of the Civic Center Gravels. The approach for evaluating underground injection capacity involves use of the recalibrated transient groundwater flow model and an optimization technique which uses output from the calibrated model to determine optimal injection rates. In this technique, potential injection locations are identified, and the acceptable amount of groundwater level change is specified at multiple constraints. The optimizing routine then determines the amount of injection that can occur at each of the potential injection sites without causing unacceptable groundwater level increases at any of the constraint locations. Based upon the optimization results, the approximate model-estimated injection capacities for each of the three proposed phases of development are as follows:

Phase 1 -- 311,000 gallons per day

Phase 2 -- 498,000 gallons per day

Phase 3 -- 612,000 gallons per day

The injection locations for each of the three phases are located on the western side of the alluvial deposits. For each optimized injection phase, the migration of injected wastewater was simulated using particle tracking. Results of the particle tracking indicate that treated wastewater will travel to the Pacific Ocean for each of the proposed phases of injection. The model results also indicate that as much as 100,000 gallons per day of treated wastewater could be percolated in Winter Canyon, with an equivalent reduction in injected wastewater, and wastewater would still discharge to the Pacific Ocean.

A series of simulations were completed to evaluate the sensitivity of model predictions to selected model parameters. These model parameters included the conductivity (horizontal and vertical) of deep channel deposits, the vertical conductivity of the low permeability unit that separates shallow and deep deposits, and recharge from precipitation. Specifically, in the sensitivity analysis runs, both the vertical and horizontal conductivity of the deep channel deposits were decreased by 10 percent, the vertical conductivity of the low permeability unit was increased by 50 percent, and precipitation recharge was increased by 10 percent. Results of the sensitivity analyses indicate that the changes model parameters do not significantly alter model predictions with regard to injection capacity or the fate of injected wastewater.

The modeling analyses presented in this report are based upon existing data. As additional hydrogeologic data become available, they could alter model predictions. The model results indicate that the proposed injection may be feasible, but are not considered to be a guarantee that the planned injection will work. The actual response of the groundwater system to planned injection should be carefully monitored during each phase of development. Monitoring should include observation of groundwater level changes and water quality changes in both deep and shallow observation wells at locations throughout the alluvial deposits. All data collected in the future should be used to update model parameters and to refine estimates of injection capacity and directions of groundwater flow.

5.0 REFERENCES

Ahlfeld, D.P., Baker, K.M., and Barlow, P.M, 2009, GWM-2005 - A Groundwater-Management Process for MODFLOW-2005 with Local Grid Refinement (LGR) Capability: U.S. Geological Survey Techniques and Methods 6-A33.

Ambrose, Richard F. and Orme, Anthony R., 2000, Lower Malibu Creek and Lagoon Resource Enhancement and Management: Final Report to the California Coastal Conservancy.

Anderson, M.P. and W.W. Woessner, 1992, Applied Groundwater Modeling -- Simulation of Flow and Advective Transport, Academic Press Inc., 381 p.

Banta, E.R. and D.P. Ahlfeld, 2013, GWM-VI-Groundwater Management with Parallel Processing for Multiple MODFLOW Versions, U.S. Geological Survey, Chapter 48 of Section A Groundwater Book 6, Modeling Techniques, TM6-A48.

Bing Yen & Associates, Inc., 2001, Report of Malibu Civic Center Groundwater Evaluation, Malibu, California 90265.

California Department of Water Resources (DWR), 1975, Sea-Water Intrusion in California: Inventory of Coastal Ground Water Basins. Bulletin 63-5.

California Department of Water Resources (DWR), 2003, California’s Ground Water. Bulletin 118

Cardno ENTRIX, 2012, Report on the Reinterpretation of the MASW Survey, Prepared for the City of Malibu, April 2012.

Cardno ENTRIX, 2013, The City of Malibu Shoreline Geophysical Survey Report, Prepared for RMC Water and Environment, June 2013.

Daniel B. Stephens & Associates, Inc., 2007a, Hydrologic Monitoring Program Annual Report Water Year October 2003 through September 2004, Pepperdine University

Daniel B. Stephens & Associates, Inc., 2007b, Hydrologic Monitoring Program Annual Report Water Year October 2004 through September 2005, Pepperdine University

Daniel B. Stephens & Associates, Inc., 2008a, Hydrologic Monitoring Program Annual Report Water Year October 2005 through September 2006, Pepperdine University

Daniel B. Stephens & Associates, Inc., 2008b, Hydrologic Monitoring Program Annual Report Water Year October 2006 through September 2007, Pepperdine University

Daniel B. Stephens & Associates, Inc., 2009, Hydrologic Monitoring Program Annual Report Water Year October 2007 through September 2008, Pepperdine University

Daniel B. Stephens & Associates, Inc., 2010, Hydrologic Monitoring Program Annual Report Water Year October 2008 through September 2009, Pepperdine University

Daniel B. Stephens & Associates, Inc., 2011, Hydrologic Monitoring Program Annual Report Water Year October 2009 through September 2010, Pepperdine University

Daniel B. Stephens & Associates, Inc., 2012, Hydrologic Monitoring Program Annual Report Water Year October 2010 through September 2011, Pepperdine University

Daniel B. Stephens & Associates, Inc., 2013, Hydrologic Monitoring Program Annual Report Water Year October 2011 through September 2012, Pepperdine University

Doherty, John, 2003. Groundwater model calibration using pilot points and regularization, Groundwater, Vol. 41, No. 2, pages 170-177.

Driscoll, F.G., 1986, Groundwater and wells, 2nd ed: Johnson Filtration Systems, Inc.

Earth Consultants International, Inc., 2000a, Hydrologic field investigation and modeling Winter Canyon, Malibu, California, Vol. 1 and 2: Prepared for Malibu Bay Company

Earth Consultants International Inc., 2000b, IOKI and Chili Cookoff Parcels Malibu, California: Civic Center Groundwater Report

Earth Consultants International, Inc., 2009, Geologic and Hydrogeologic Report for the 0.15FAR Plan, Malibu Sycamore Village Project (aka IOKI Parcel), Northeast Corner of Civic Center Way and Stuart Ranch Road, City of Malibu, California, unreleased report.

Earth Forensics, Inc., 2013, Geologic Cross-Sections, Malibu Centralized Wastewater Project, Civic Center Area, Malibu, CA. September 30.

Earth Forensics, Inc., 2013, Technical Memorandum - Development of 3D Low Permeability Zone (LPZ), Downtown Malibu, CA, October 21, 2013.

ENTRIX, 2010, Report on the MASW Survey for the City of Malibu, July 2010.

Entrix, Inc., 1999, Minimum Flow Recommendation for Malibu Creek Draft Report; prepared for Las Virgenes Municipal Water District, December 22, 1999

Fugro West Inc., 2005, A steady-state groundwater flow model for the proposed Malibu-LaPaz Ranch development: Prepared for Sterling Capitol.

GeoSoils, 1989, Response to County of Los Angeles Geologic Review of 18.4 Acre Parcel NW of Cross Creek Road and Civic Center Way: GeoSoils, Inc., April 17, 1989.

GeoConcepts, 1999, Geotechnical exploration at 23401 Civic Center Way.

Geosyntec Consultants, 2007, Geotechnical site exploration and interpretation of subsurface conditions Malibu Legacy Park site Malibu, California: July 30, 2007.

Harbaugh, A.W., 2005, MODFLOW-2005, the U.S. Geological Survey modular ground-water model -- the Ground-Water Flow Process: U.S. Geological Survey Techniques and Methods 6-A16.

Izbicki, 2009, Preliminary results of cooperative water-resources study to identify the source of fecal indicator bacteria in the Malibu Lagoon and Ocean beaches near Malibu, California: Letter from U.S. Geological Survey to City of Malibu dated October 29, 2009.

Jones and Stokes. 2009. Malibu Legacy Park Project, Final Environmental Impact Report. State Clearinghouse Number 2007111092. January.

Langevin, C.D., Thorne, D.T., Jr., Dausman, A.M., Sukop, M.C., and Guo, Weixing, 2007, SEAWAT Version 4: A Computer Program for Simulation of Multi-Species Solute and Heat Transport: U.S. Geological Survey Techniques and Methods Book 6, Chapter A22, 39 p.

LawGibb Group, 2001, Hydrogeologic Monitoring Program Annual Report Water Year 1999-00 Pepperdine University.

Leighton and Associates, Inc., 1994, Report for Geotechnical Studies for Planning Purposes in the Civic Center Area, City of Malibu, California, Volumes I and II

Pollock, D.W., 1994, User's Guide for MODPATH/MODPATH-PLOT, Version 3: A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference groundwater flow model: U.S. Geological Survey Open-File Report 94-464, 234 p.

Pueblo Water Resources, Inc., 2014, Malibu Groundwater Injection Feasibility Project – Phase 3; Pilot Injection Testing Summary of Operations and Analysis: Technical Memorandum February 2014.

Questa Engineering, Inc., 2005, Malibu Civic Center Integrated Water Quality Management Feasibility Study

RMC Water and Environment, 2012, Conceptual Groundwater Injection Plan. June 29, 2012; updated February 27.

RMC Water and Environment, 2014, Preliminary Design Concept Report for Malibu Wastewater System; updated February 10, 2014.

Sea Surveyor, Inc., 2012, Survey Conducted for RMC Water and Environment.

Stone Environmental, Inc., 2004, Final Report, Risk Assessment of decentralized wastewater treatment systems in high priority areas in the City of Malibu, California.

Stone, Environmental, Inc., 2010, Hydrology Study of Cumulative Impacts for the Civic Center Area, Malibu, California. Project ID 082026-W, August 27.

SubSurface Designs, 2002, Geologic and soils engineering investigation of the northeastern portion of the IOKI Property, January 23, 2002.

URS Greiner Woodward Clyde, 1999, Study of Potential Water Quality Impacts on Malibu Creek and Lagoon from On-site Septic Systems.

U. S. Geological Survey, 1995, Malibu, California 7.5 min quadrangle map.

Watermark Numerical Computing, 1994, PEST Model-Independent Parameter Estimation.

Yerkes, R.F. and R.H. Campbell, 1980, Geologic Map of East-Central Santa Monica Mountains, County of Los Angeles, California: U.S. Geological Survey Map I-1146.

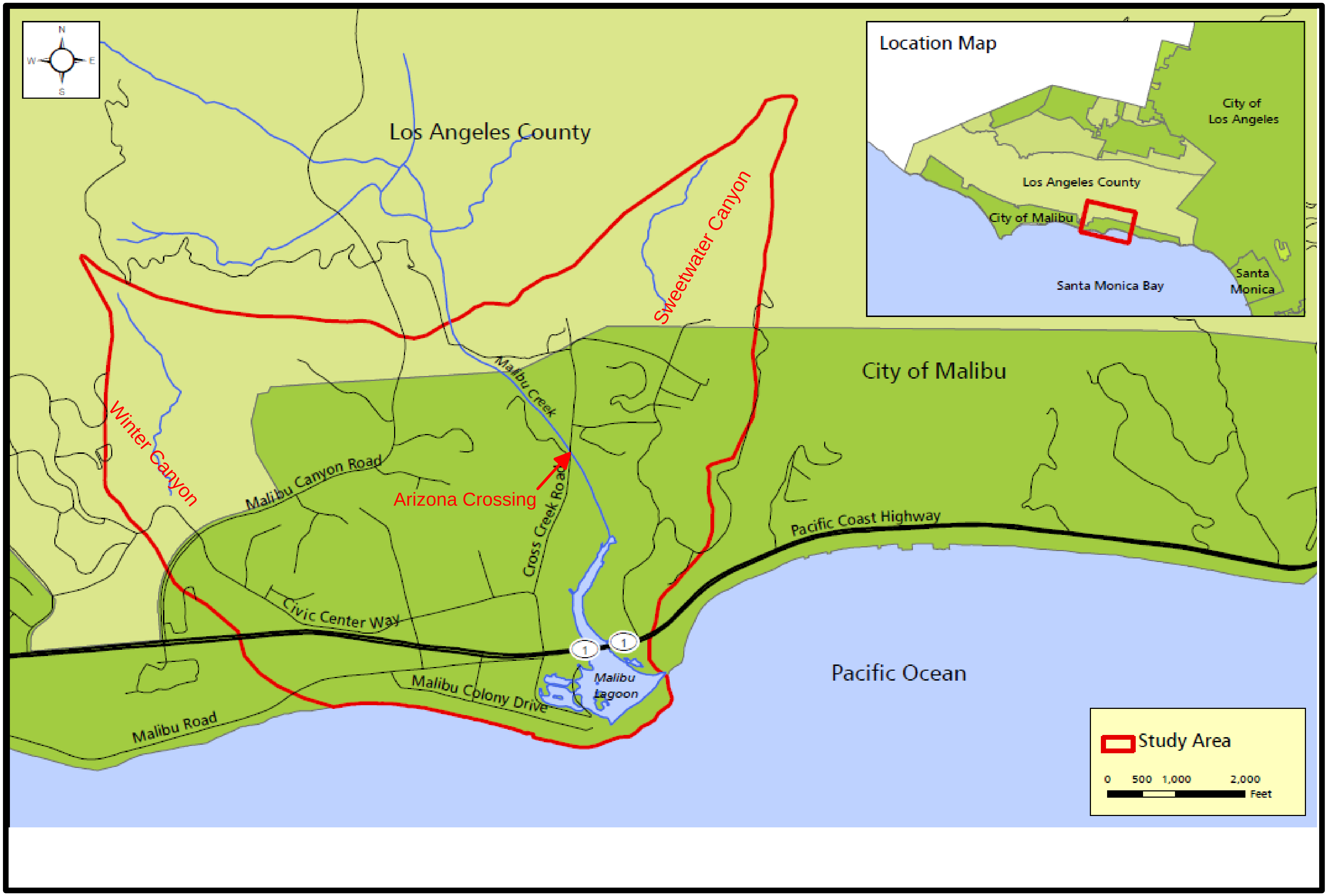


Figure 1.1-- Map showing location of study area (modified from Stone Environmental, Inc., 2010).

McDonald Morrissey ASSOCIATES, Inc.

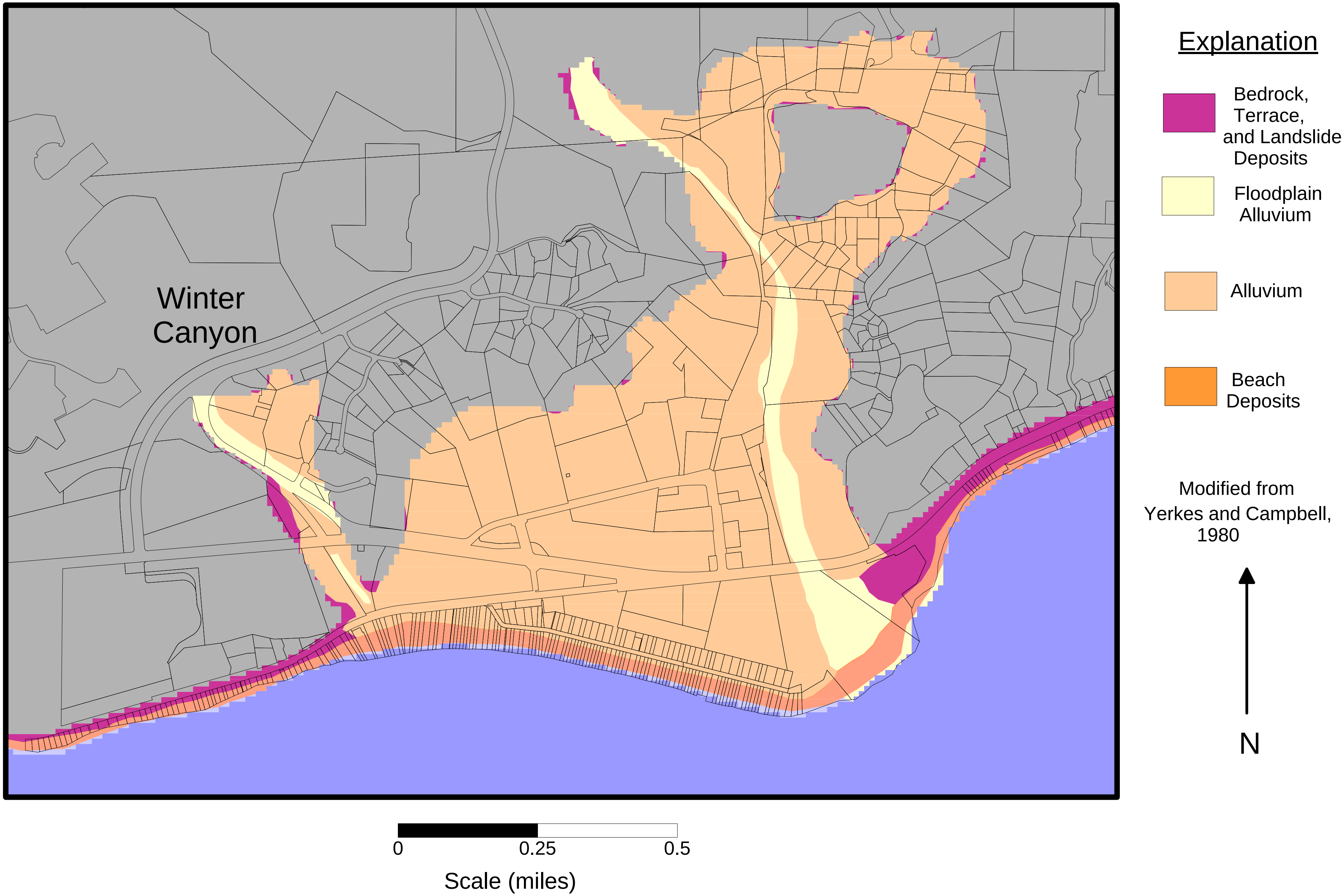


Figure 1.2 -- Map showing the extent of alluvium along Malibu Creek near the Malibu Civic Center area and Winter Canyon.

McDonald Morrissey ASSOCIATES, Inc.

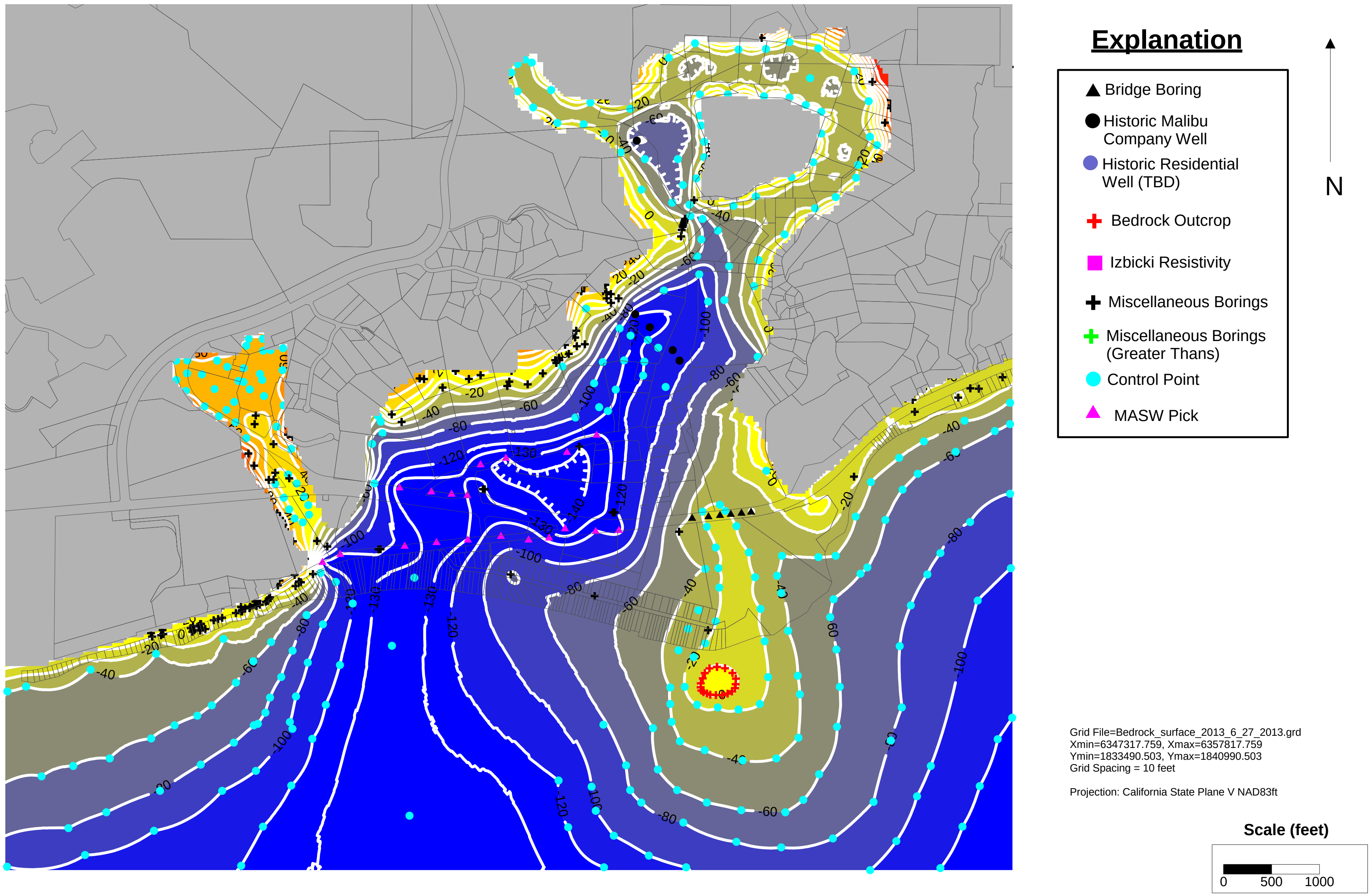


Figure 2.1 -- Map showing top of bedrock elevations.

McDonald Morrissey Associates, Inc.

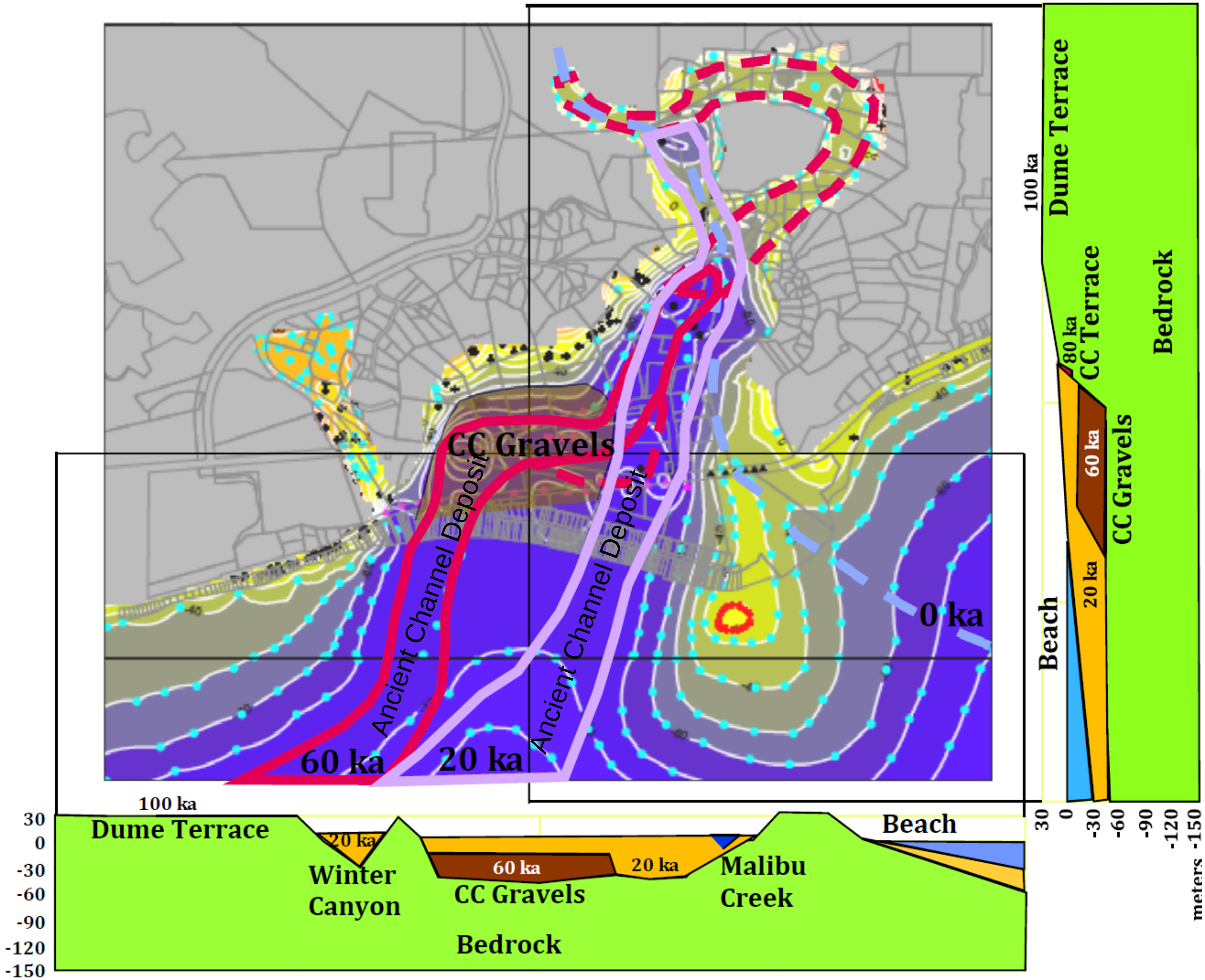


Figure 2.2 -- Map showing fluvial history Malibu Civic Center Area (modified from Earth Consultants Inc., 2012).

McDonald Morrissey ASSOCIATES, Inc.

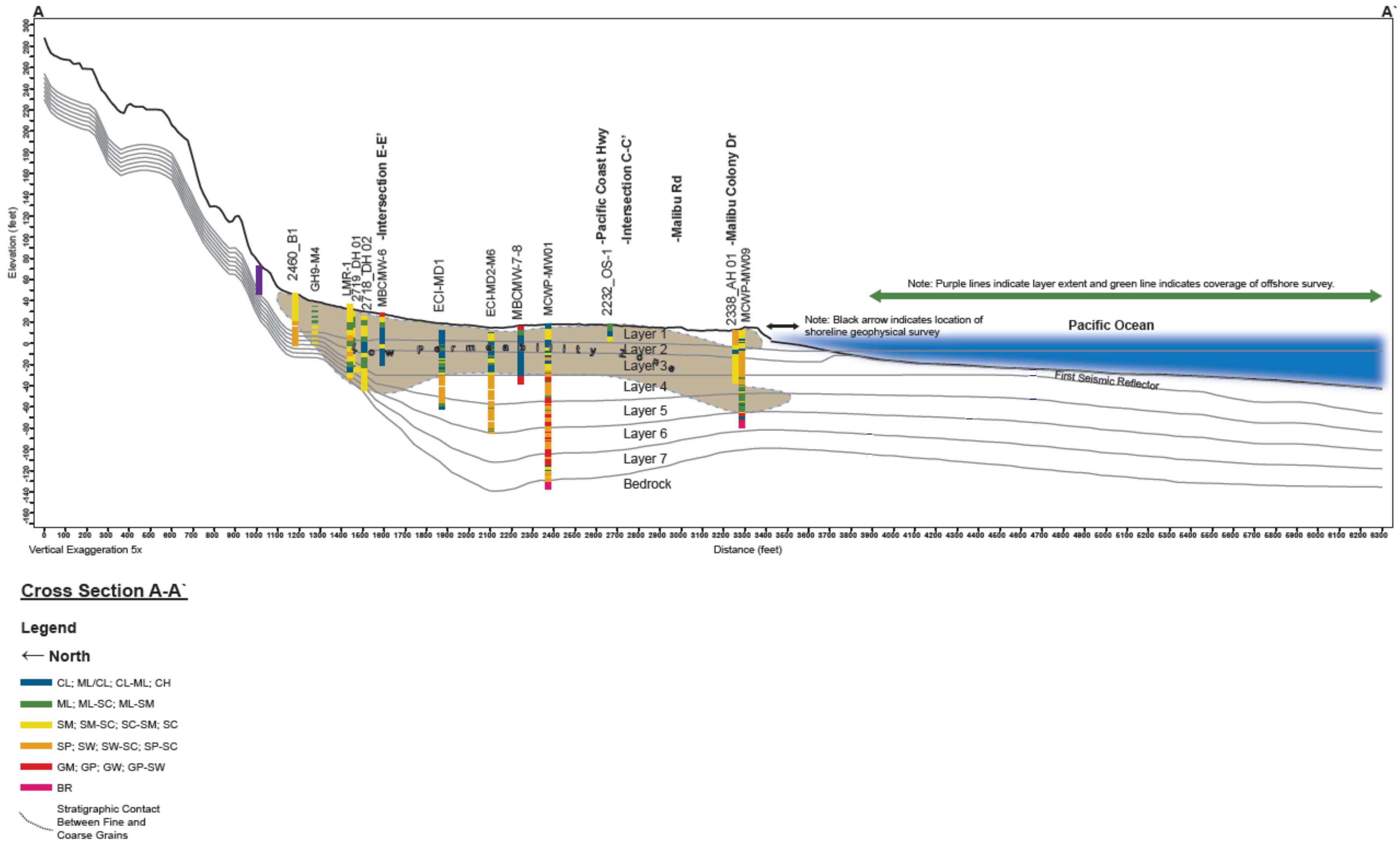


Figure 2.3 -- Geologic cross section A-A' (modified from Earth Forensics Inc., 2013).

McDonald Morrissey ASSOCIATES, Inc.

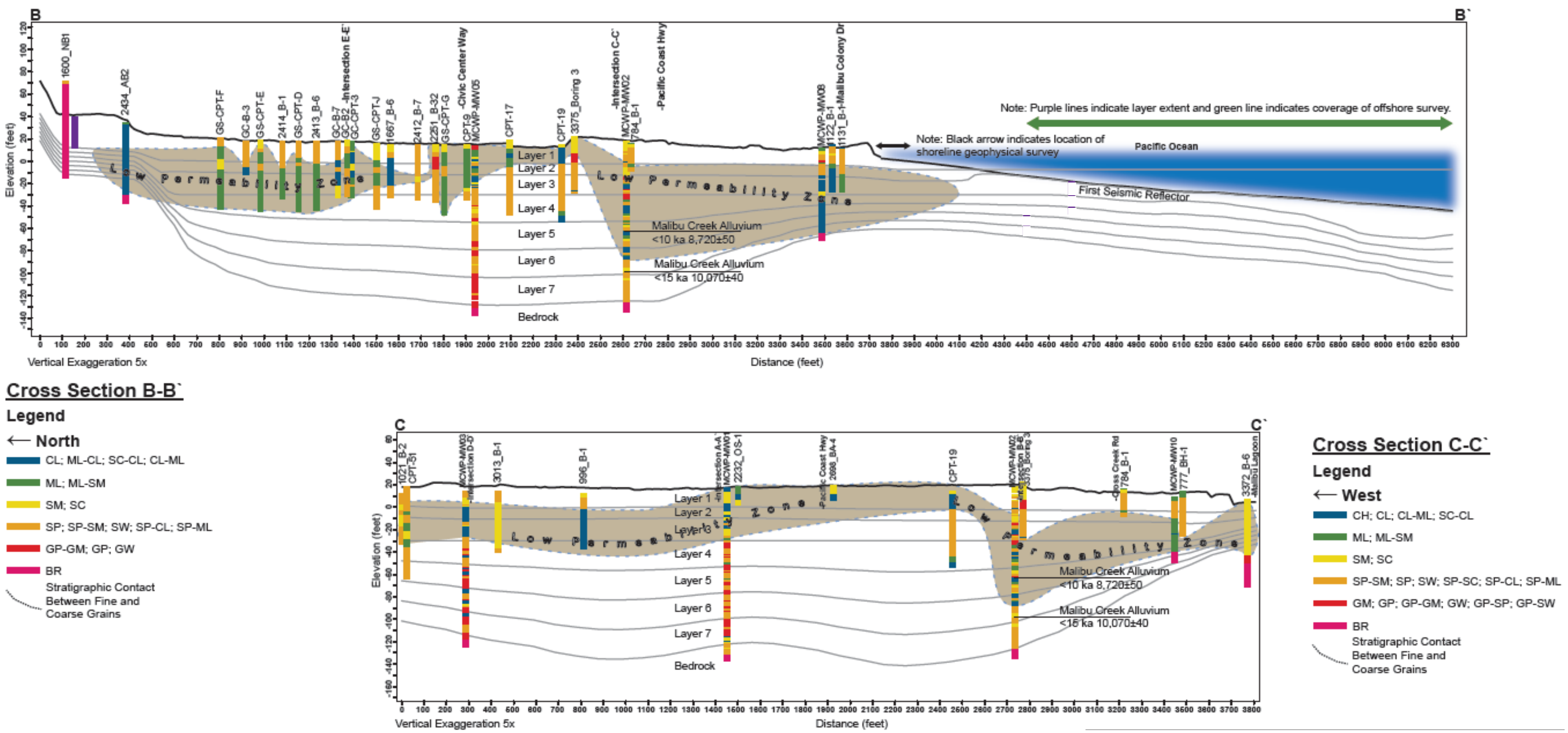


Figure 2.4 -- Geologic cross sections B-B' and C-C' (modified from Earth Forensics Inc., 2013).

McDonald Morrissey ASSOCIATES, Inc.

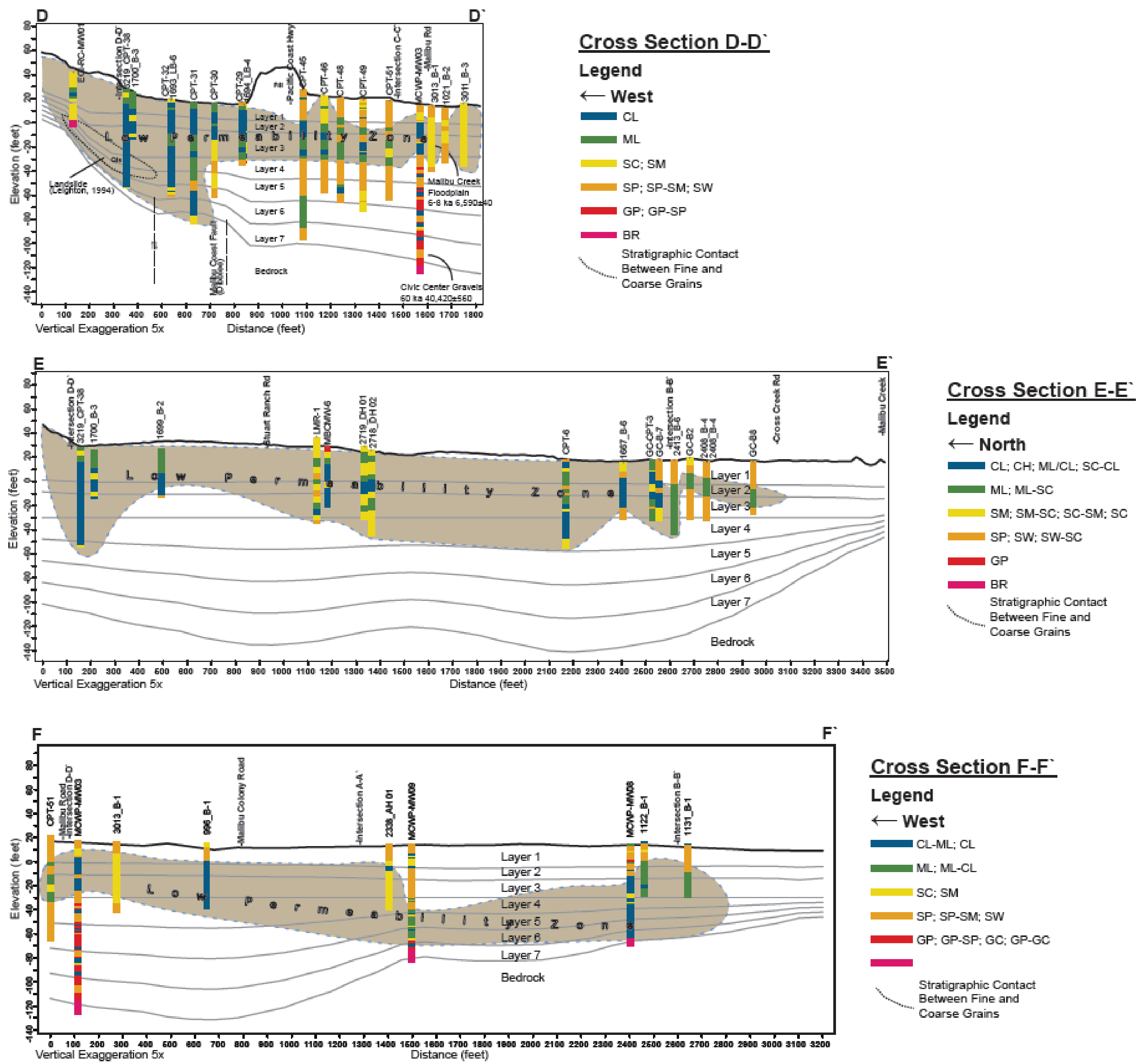


Figure 2.5 -- Geologic cross sections D-D', E-E' and F-F' (modified from Earth Forensics Inc., 2013).

McDonald Morrissey ASSOCIATES, Inc.

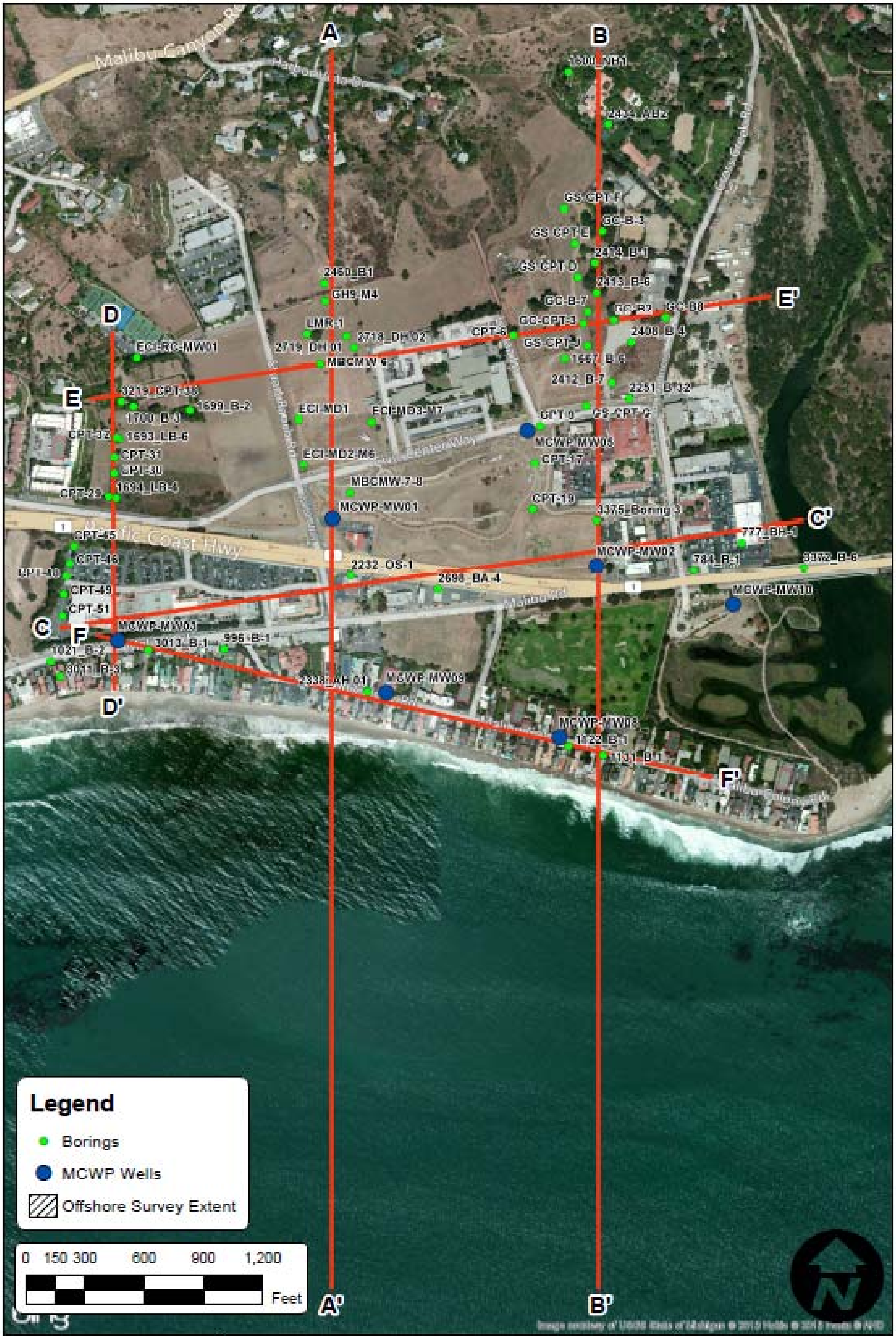


Figure 2.6 -- Locations of geologic cross sections
(modified from Earth Forensics, Inc., 2013)

McDonald Morrissey Associates, Inc.

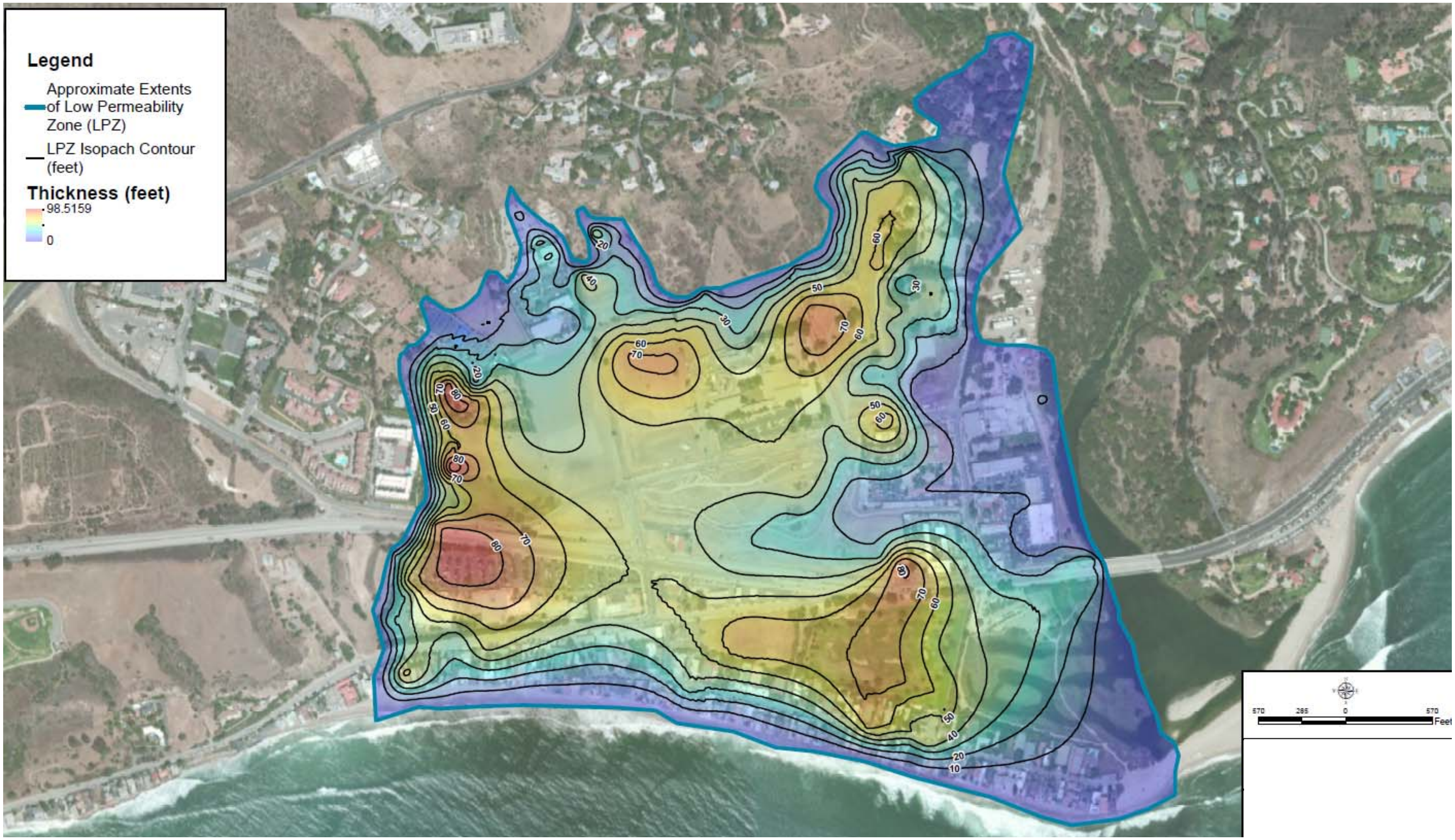


Figure 2.7 -- Map showing thickness of low permeability zone. (modified from Earth Forensic Inc., 2013).

McDonald Morrissey ASSOCIATES, Inc.

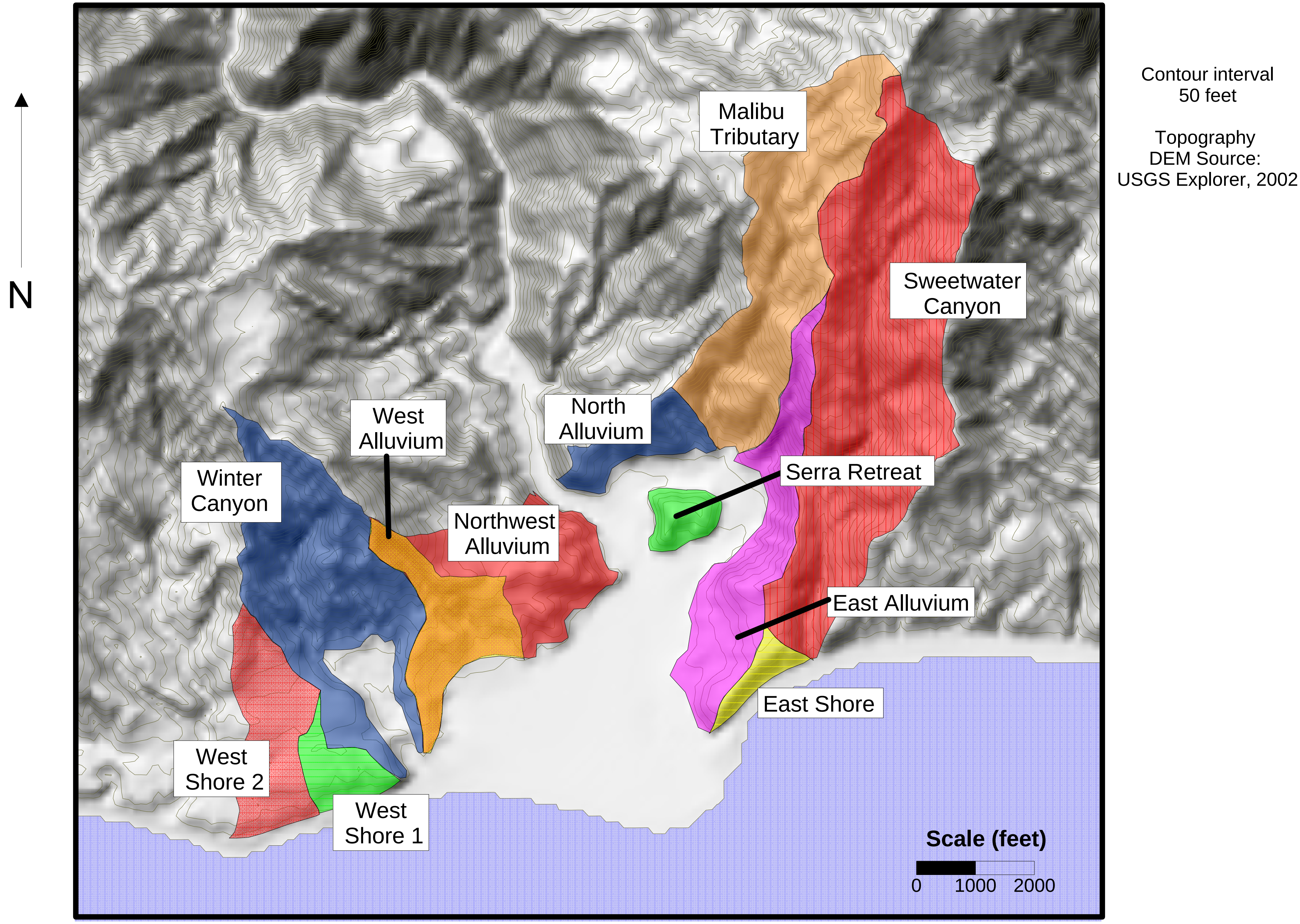


Figure 2.8 -- Map showing upland areas contributing recharge to Malibu alluvium.

McDonald Morrissey ASSOCIATES, Inc.

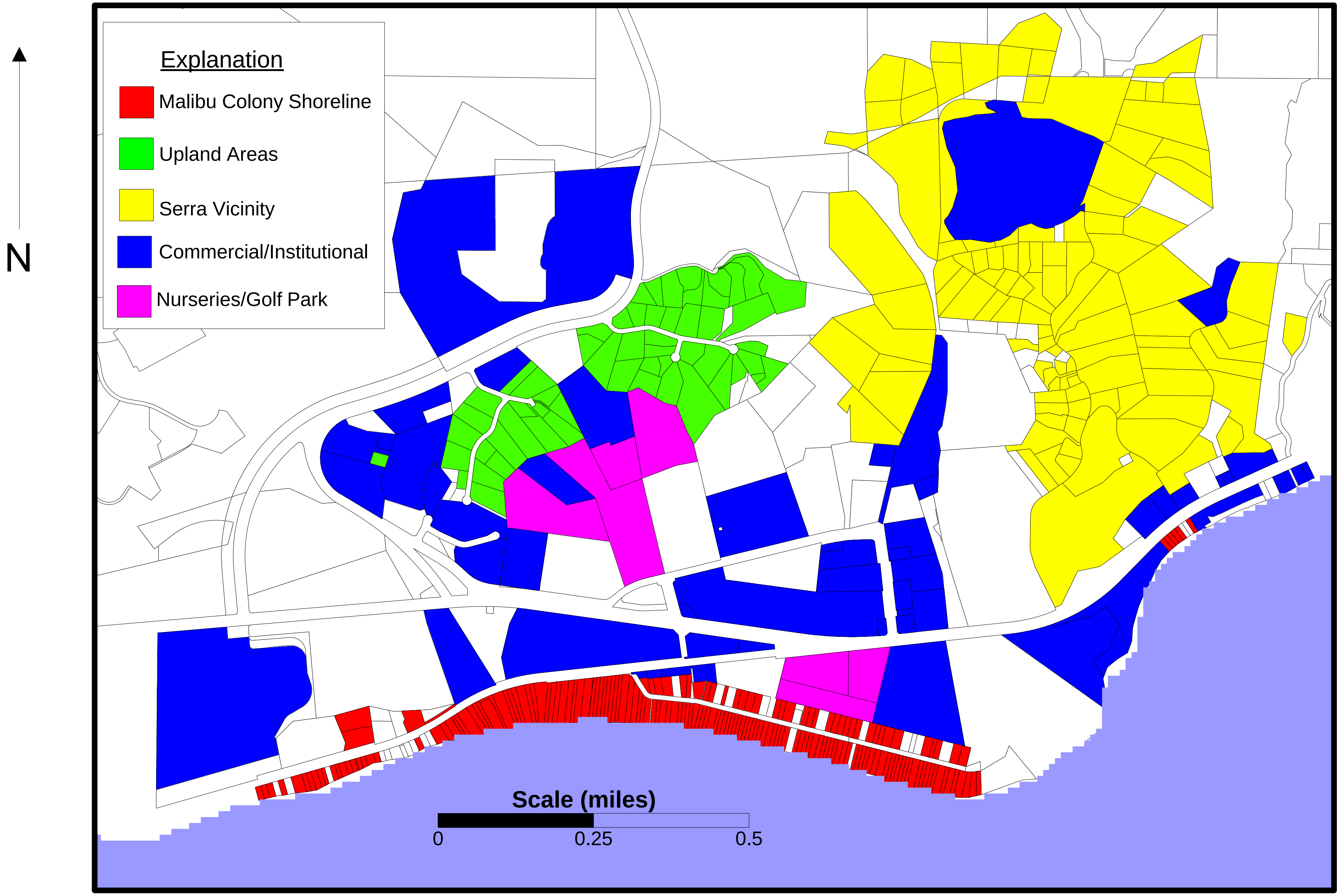


Figure 2.9 -- Map showing locations of areas used for water use summary.

McDonald Morrissey ASSOCIATES, Inc.

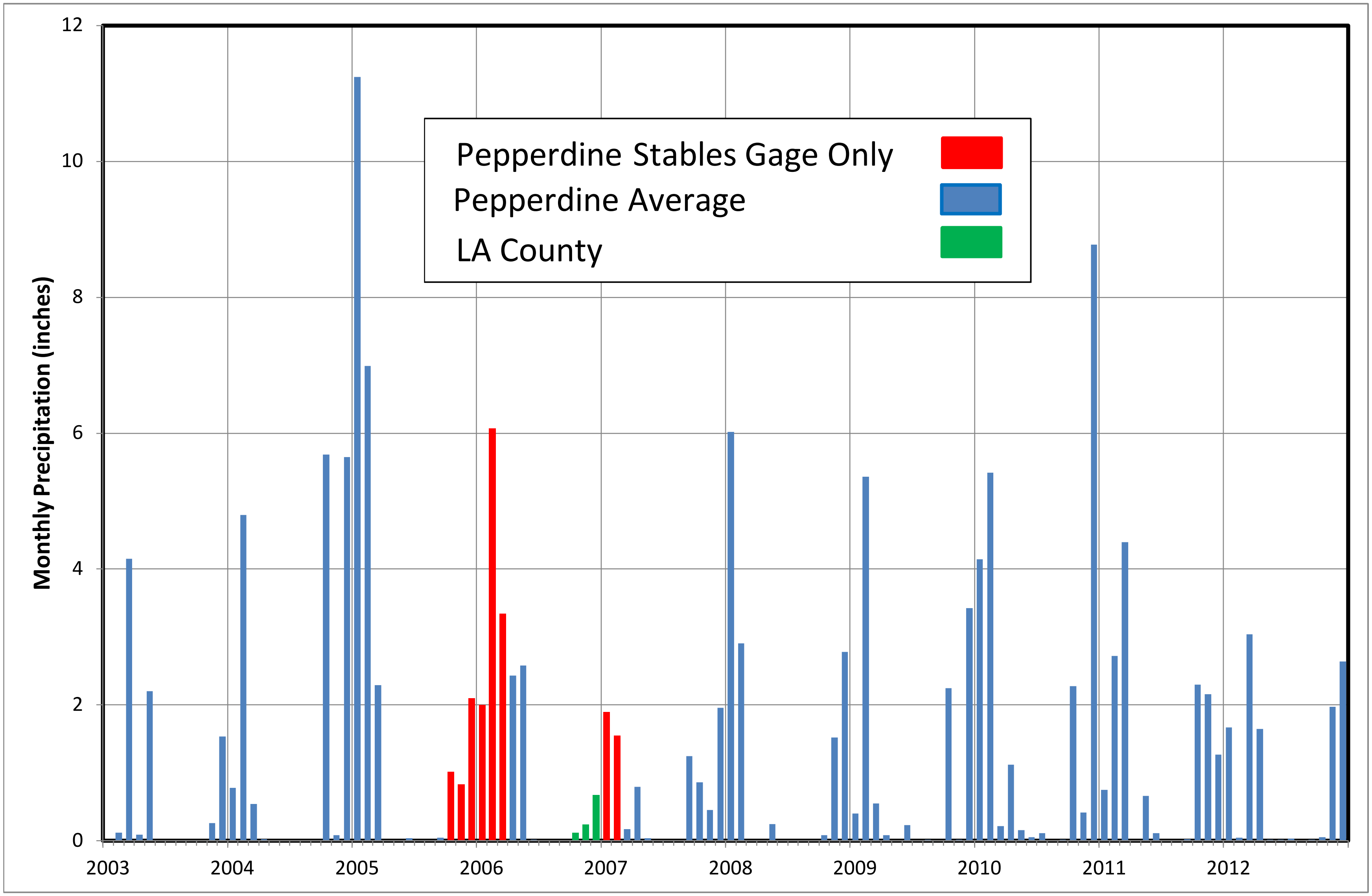


Figure 2.10 -- Graph showing monthly precipitation for the period 2003 to 2012.

McDonald Morrissey ASSOCIATES, Inc.

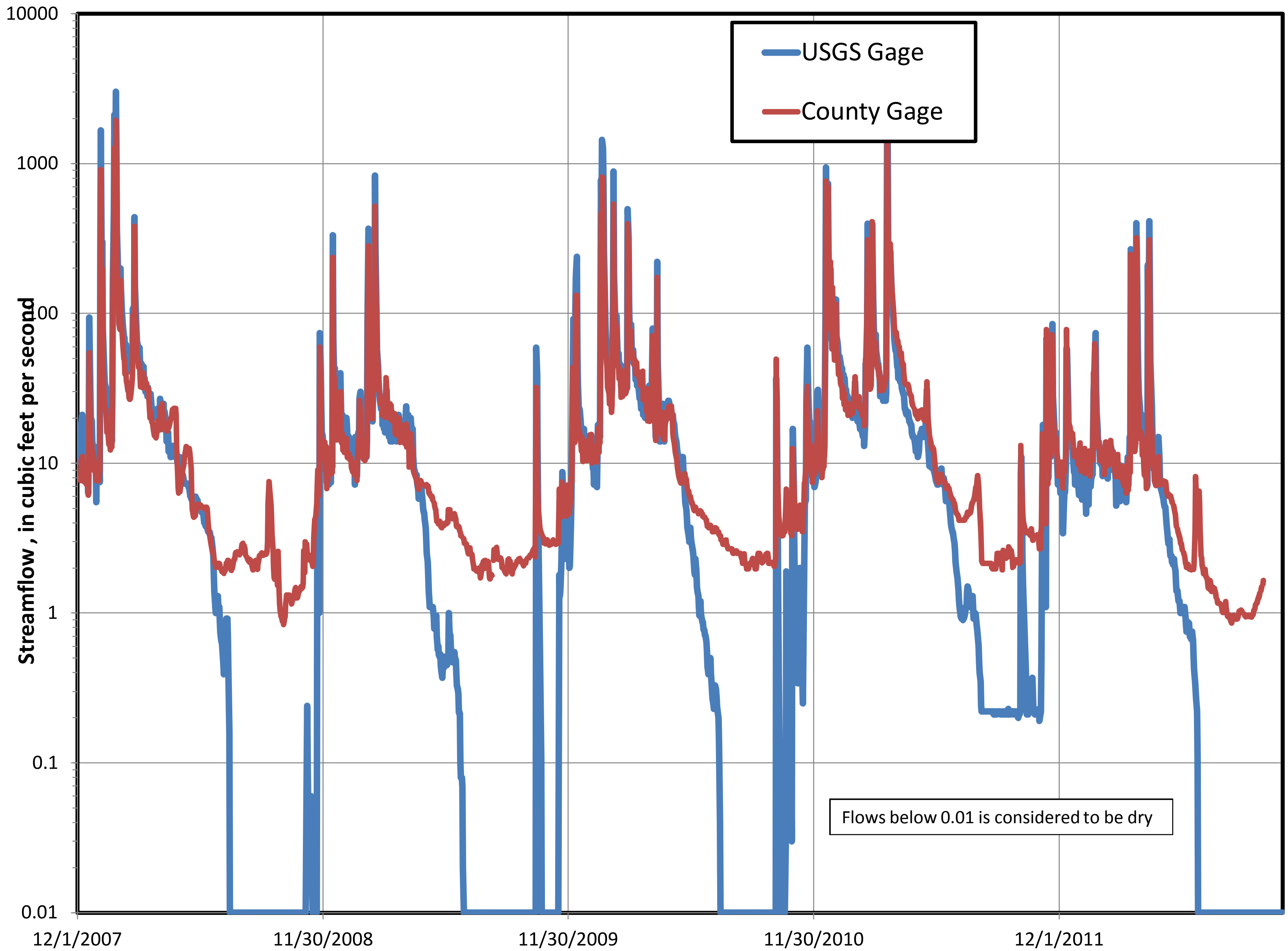


Figure 2.11 -- Graph showing daily stream flow in Malibu Creek at the U.S. Geological Survey and County gages.

McDonald Morrissey Associates, Inc.

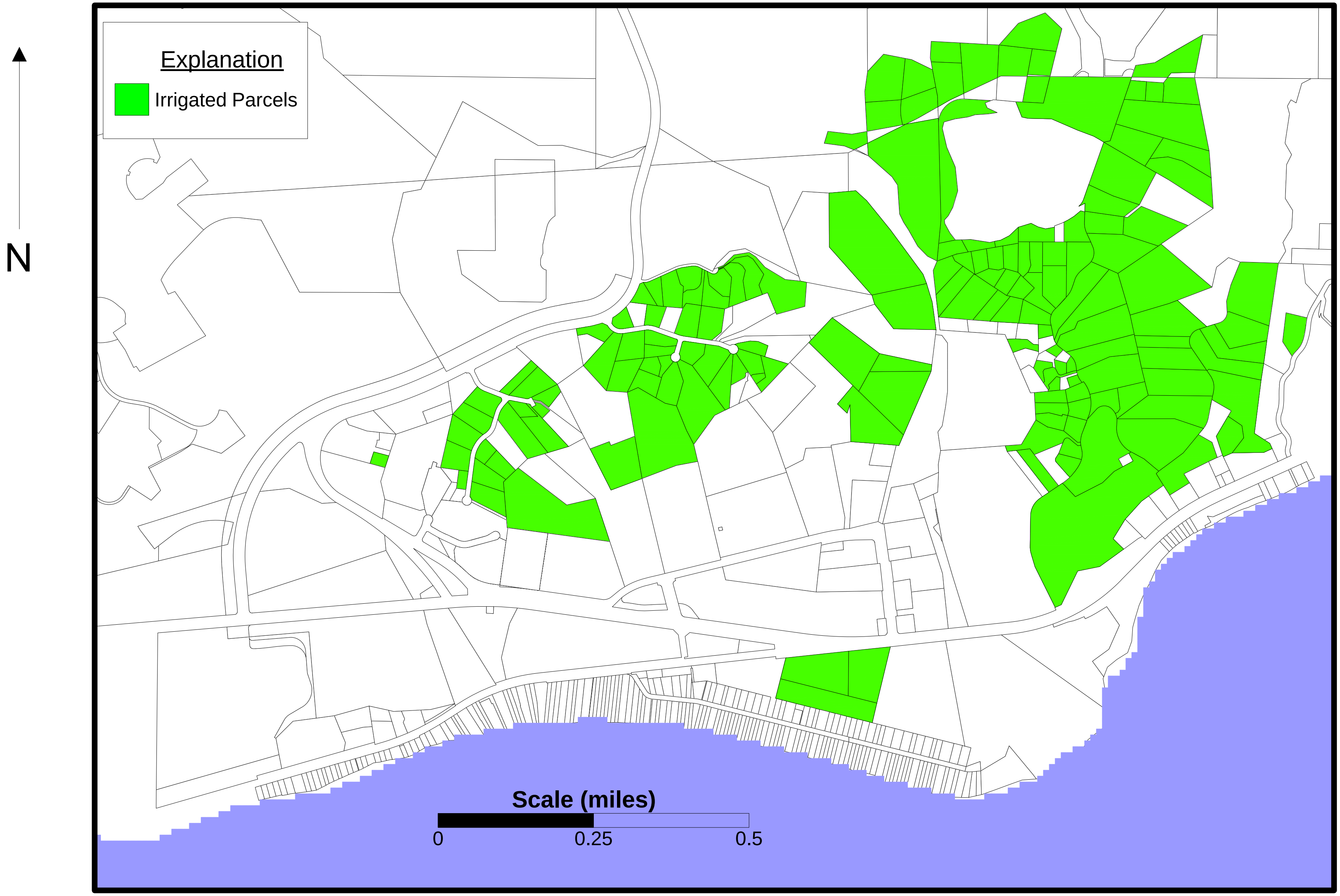


Figure 2.12 -- Map showing locations of where groundwater recharge from irrigation return occurs.

McDonald Morrissey ASSOCIATES, Inc.

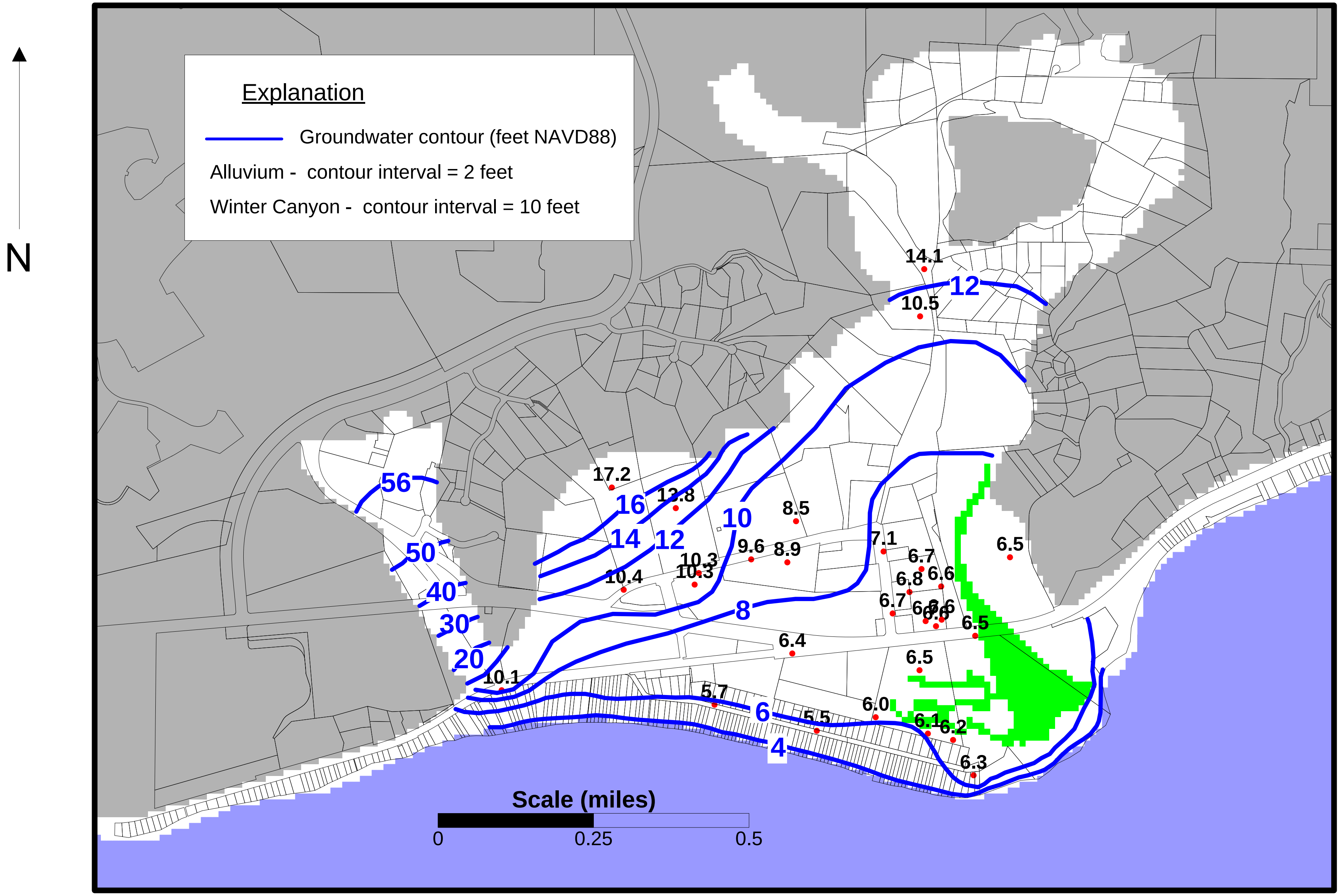


Figure 2.13 -- Map showing shallow water levels measured on September 25, 2003 during flooded lagoon condition (modified from Stone Environmental, Inc., 2004).

McDonald Morrissey ASSOCIATES, Inc.

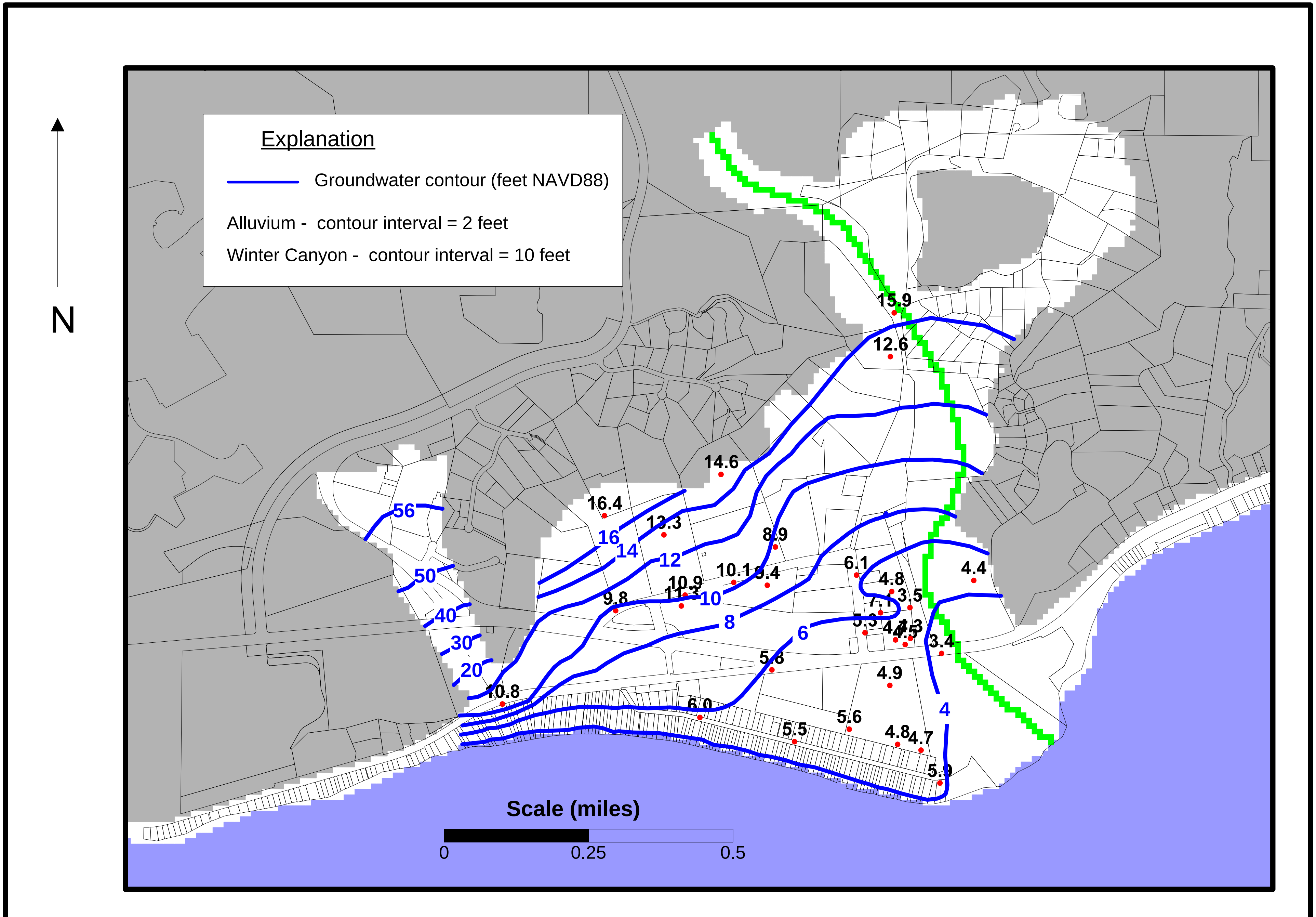


Figure 2.14 -- Map showing shallow water levels measured on March 9, 2004 during breached lagoon condition (modified from Stone Environmental, Inc. 2004).

McDonald Morrissey ASSOCIATES, Inc.

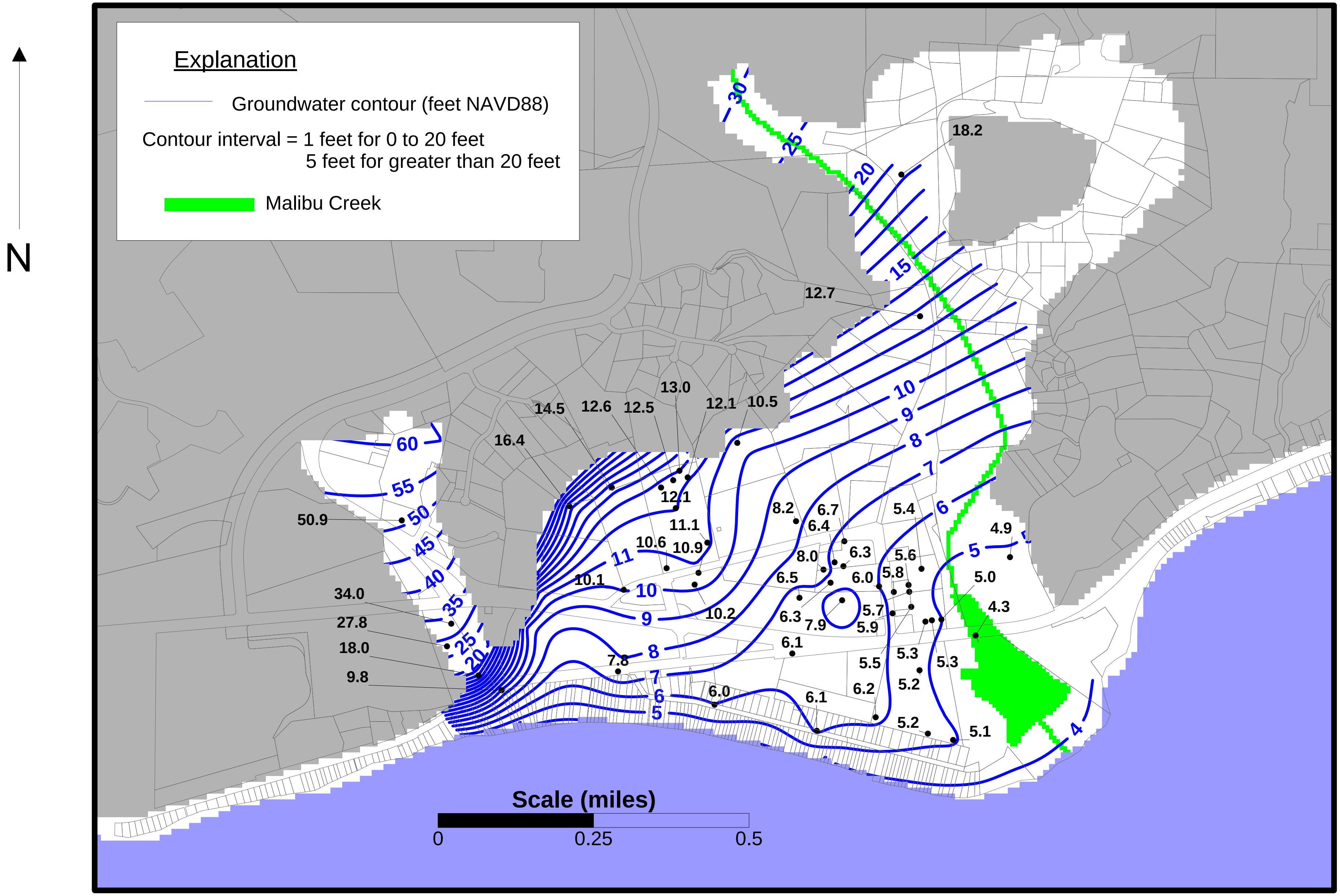
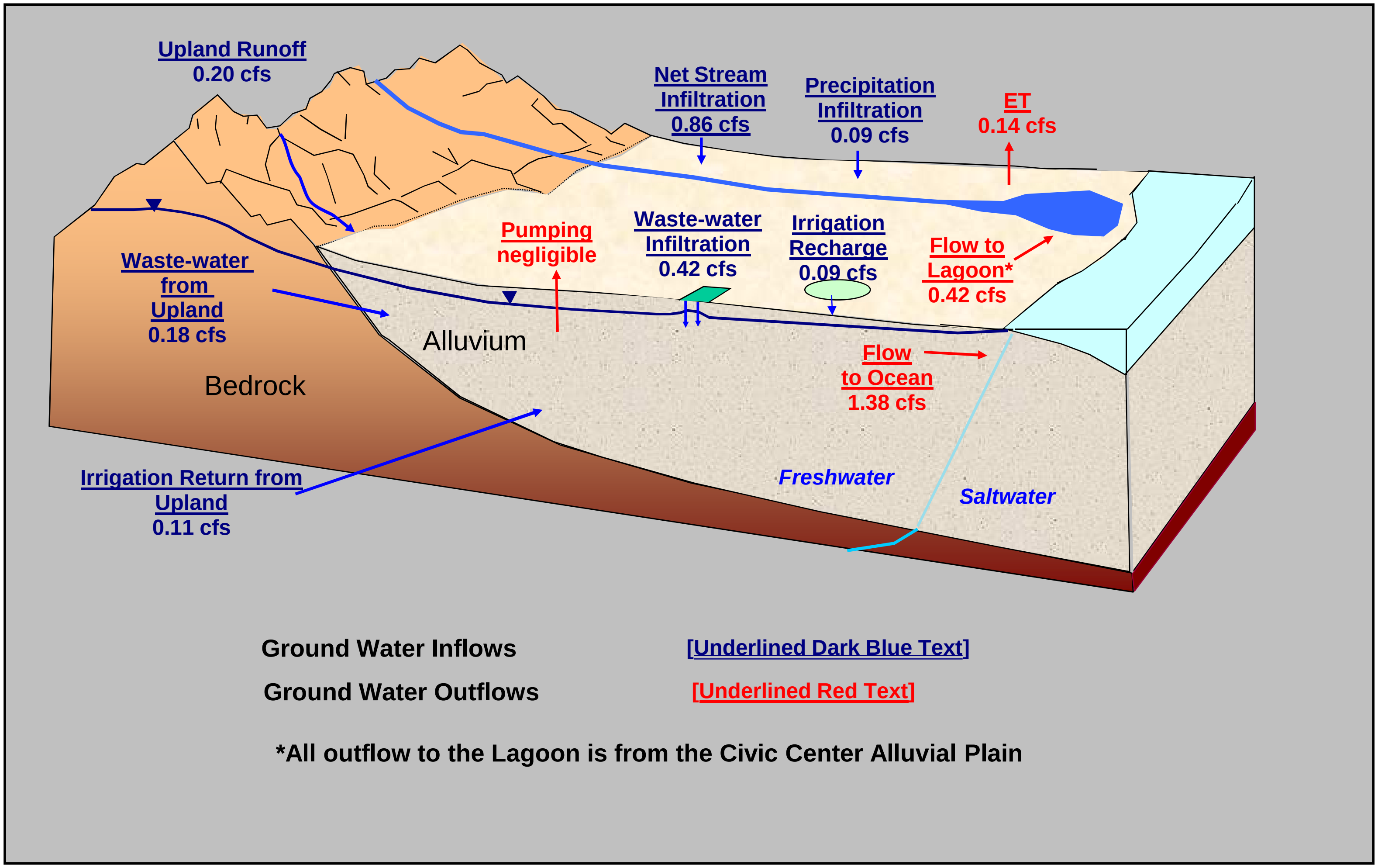


Figure 2.15 -- Map showing shallow water levels measured on December 8, 2009 during breached lagoon condition.

McDonald Morrissey Associates, Inc.



Source: malibu_Phase3_Pest_13014

Figure 2.16 -- Generalized block diagram summarizing model estimated average annual ground-water budget for the Malibu alluvium and Winter Canyon 2003-2012

McDonald Morrissey Associates, Inc.

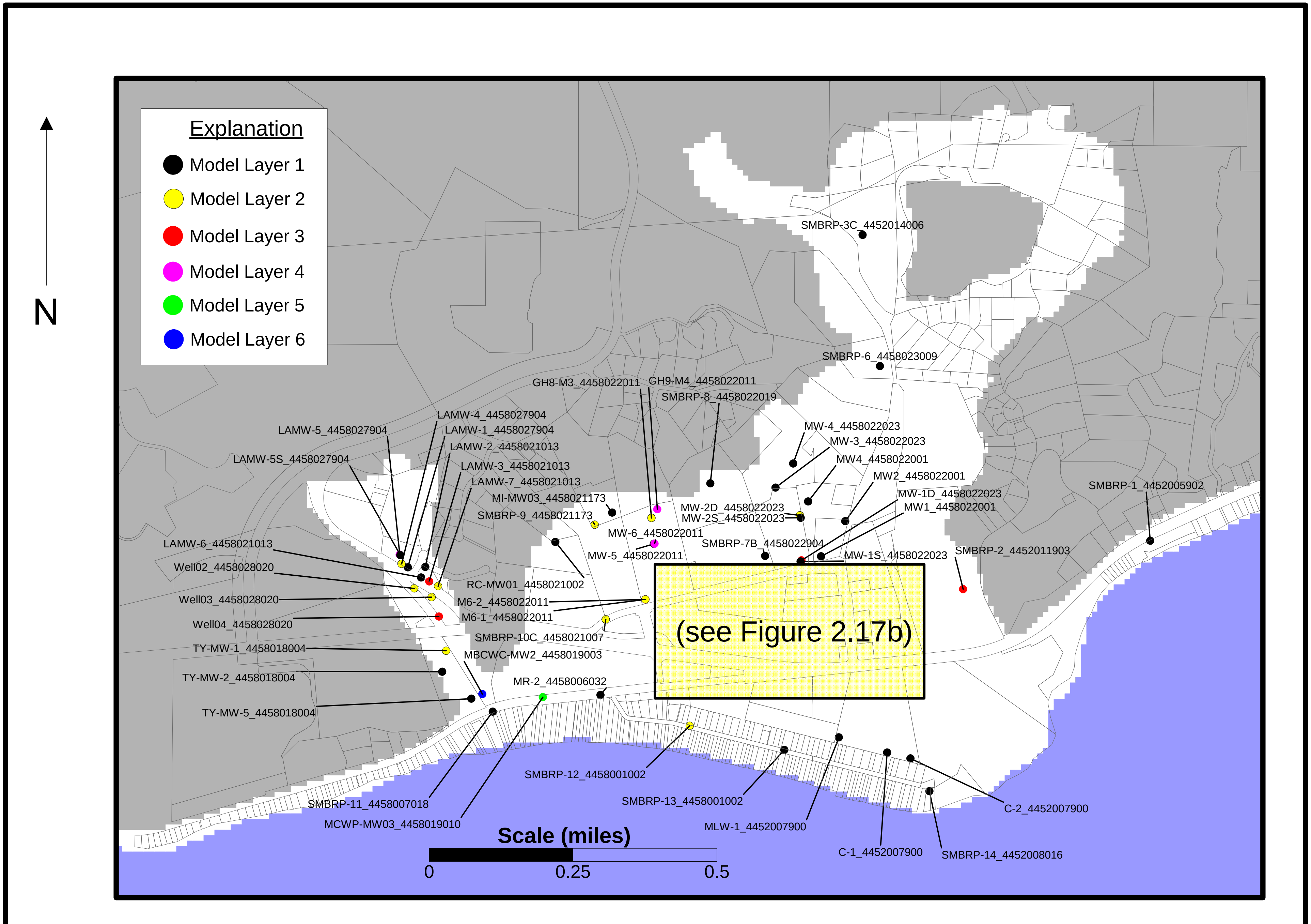


Figure 2.17a -- Map showing location of where groundwater data were used for this study.

McDonald Morrissey ASSOCIATES, Inc.

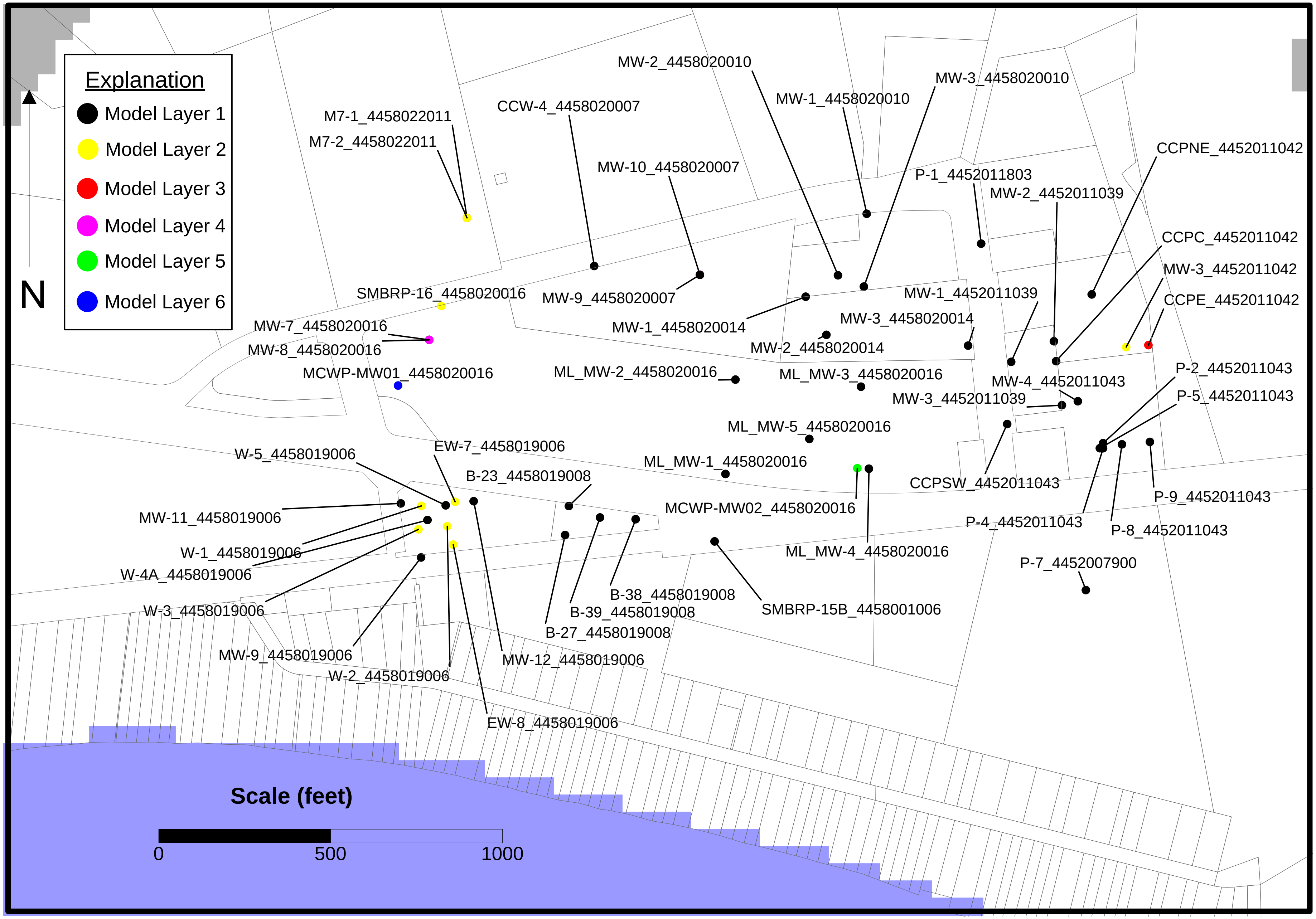


Figure 2.17b -- Map showing location where groundwater level data were used for this study.

McDonald Morrissey ASSOCIATES, Inc.

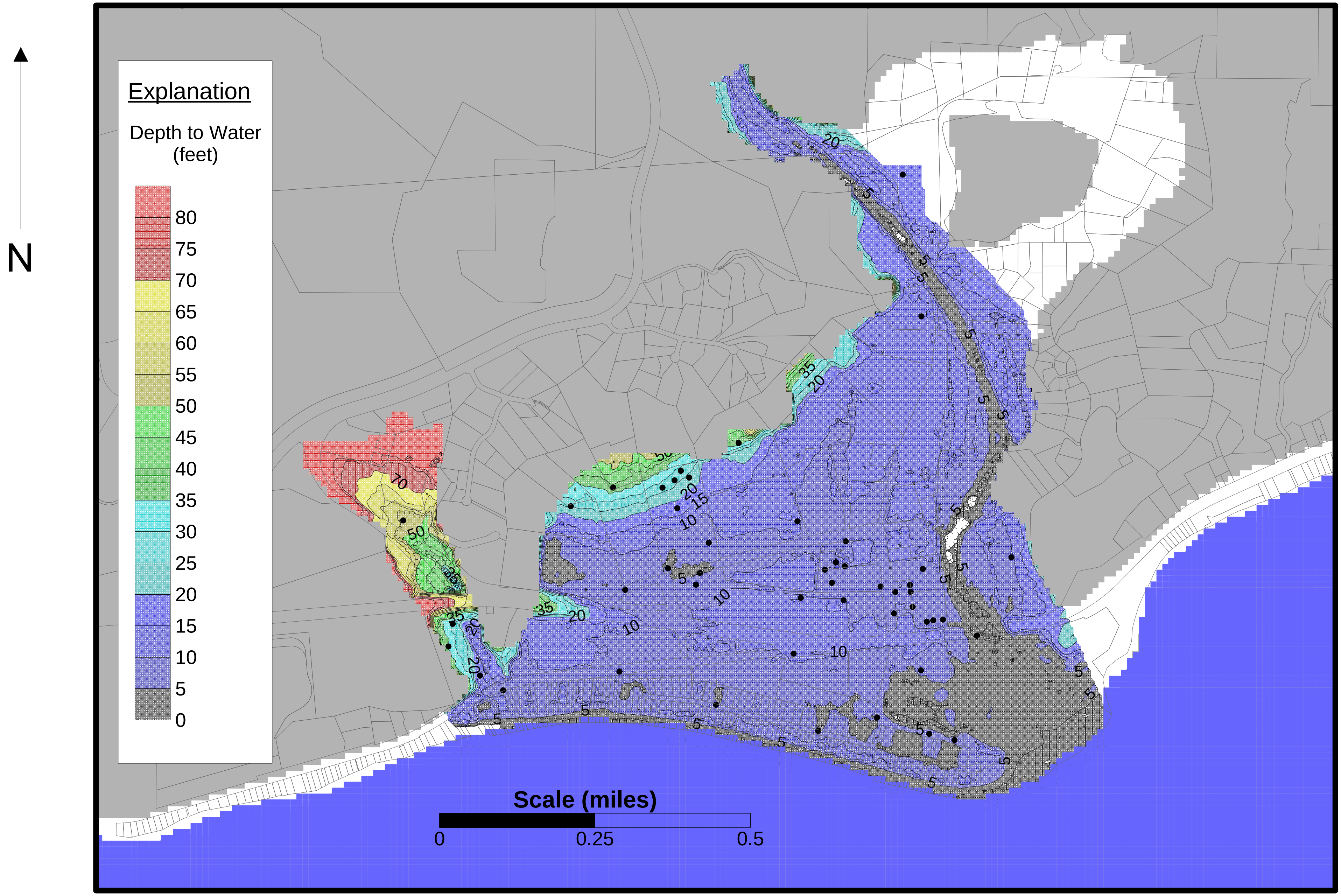


Figure 2.18 -- Map showing distance from land surface to groundwater on December 8, 2009.

McDonald Morrissey Associates, Inc.

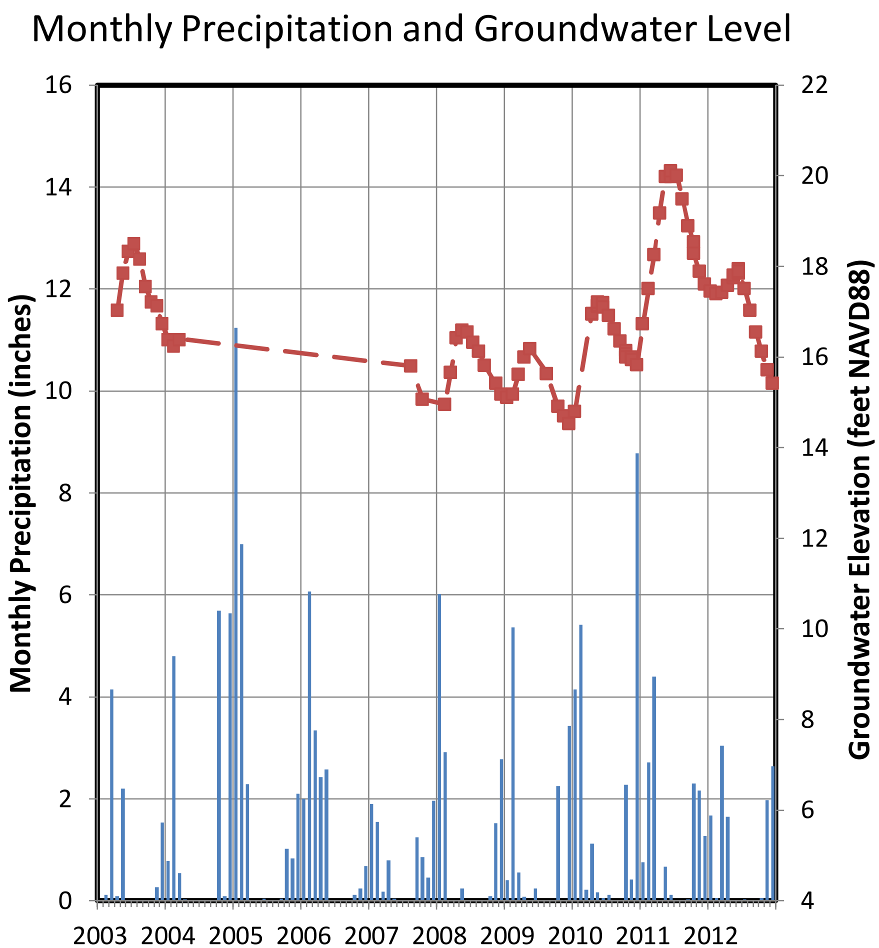
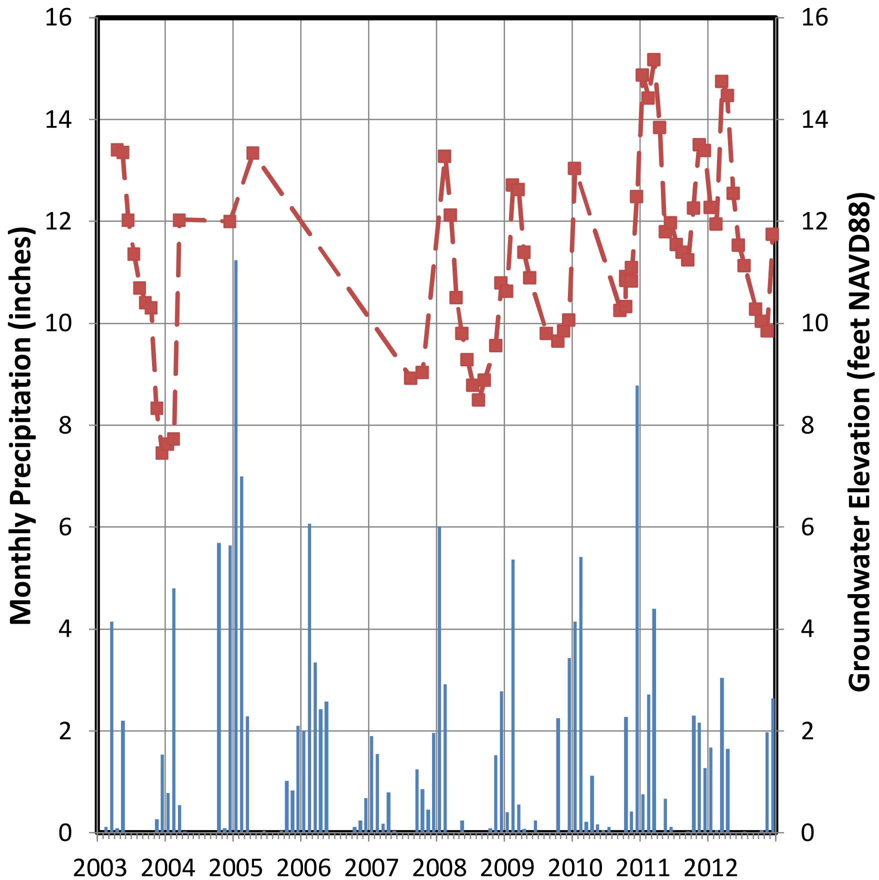


Figure 2.19a. Hydrograph showing groundwater levels at SMBRP-9, west side of the alluvium and precipitation during the period 2003-2012.

McDonald Morrissey ASSOCIATES, Inc.

Monthly Precipitation and Groundwater Level

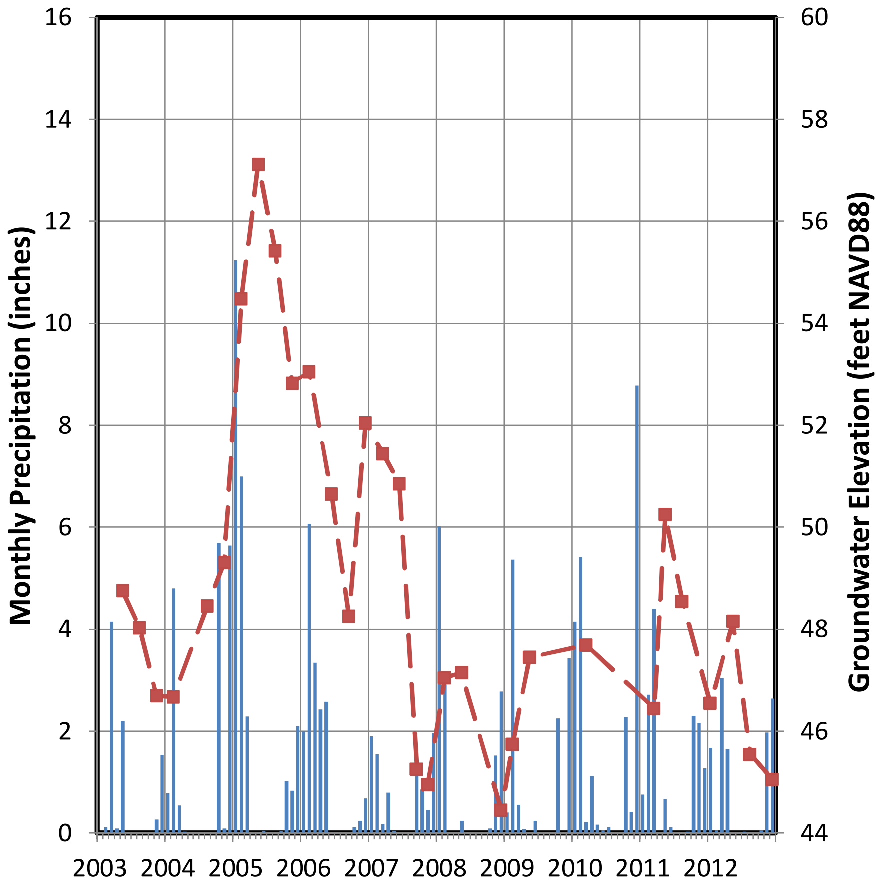


Location

Figure 2.19b. Hydrograph showing groundwater levels at SMBRP-10C west side of the alluvium and precipitation during the period 2003-2012.

McDonald Morrissey ASSOCIATES, Inc.

Monthly Precipitation and Groundwater Level



Location

Figure 2.19c. Hydrograph showing groundwater levels at Well-03 in Winter Canyon and precipitation during the period 2003-2012.

McDonald Morrissey ASSOCIATES, Inc.

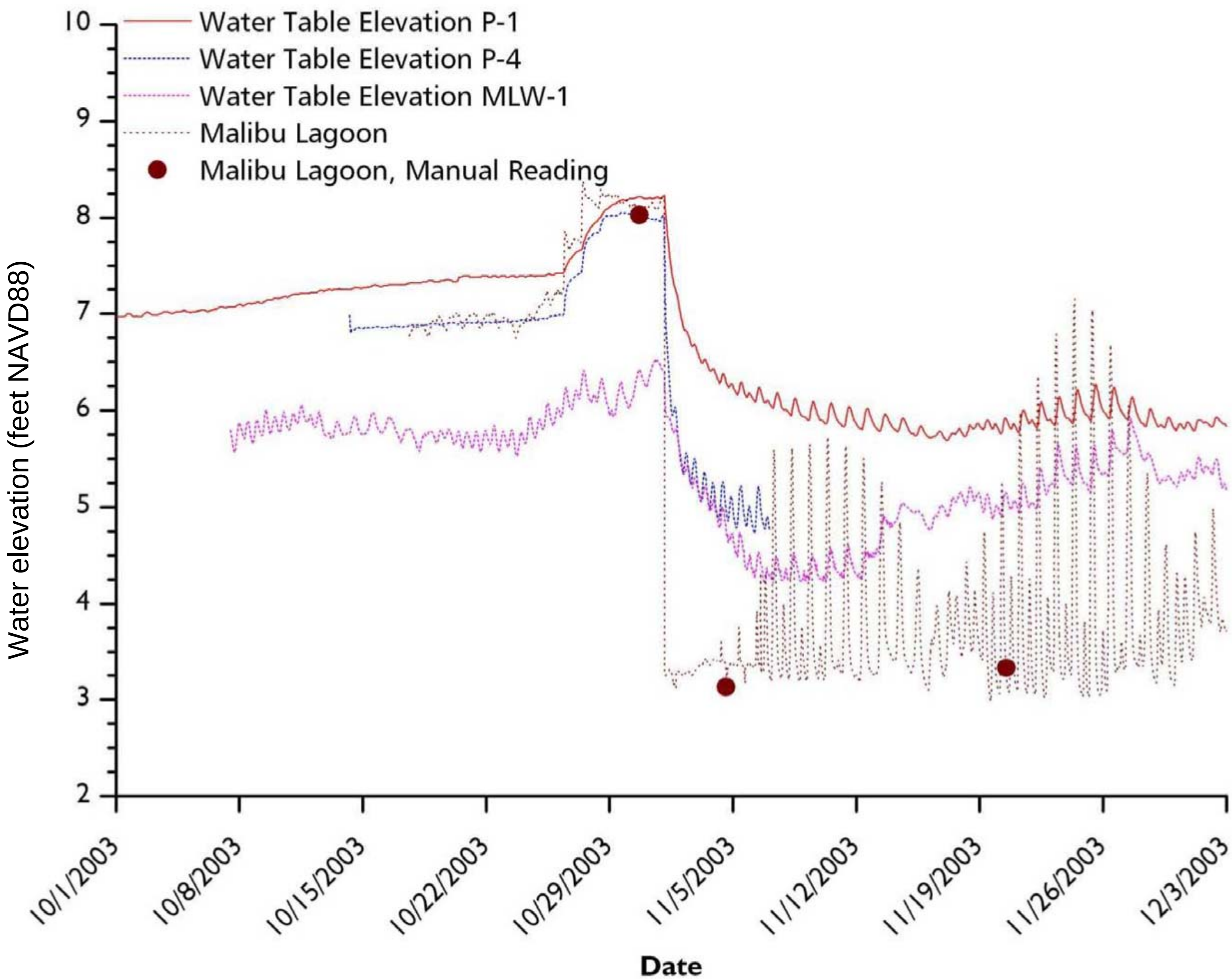


Figure 2.20 -- Graph showing lagoon stage and the groundwater levels in wells, P-9, and P-4 during a period when the lagoon transitions from a flooded to breached condition (modified from Stone Environmental, Inc., 2004).

McDonald Morrissey ASSOCIATES, Inc.

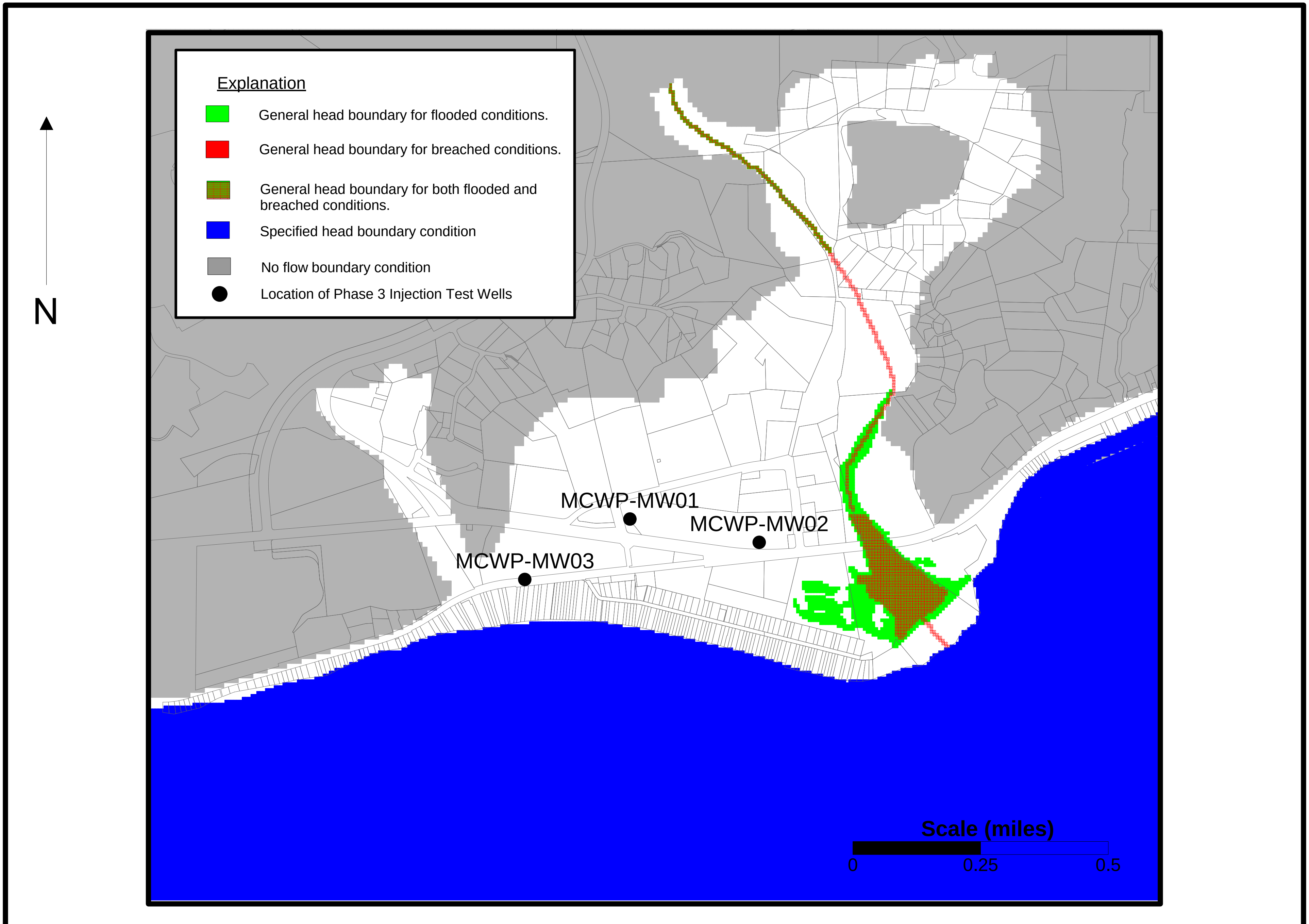
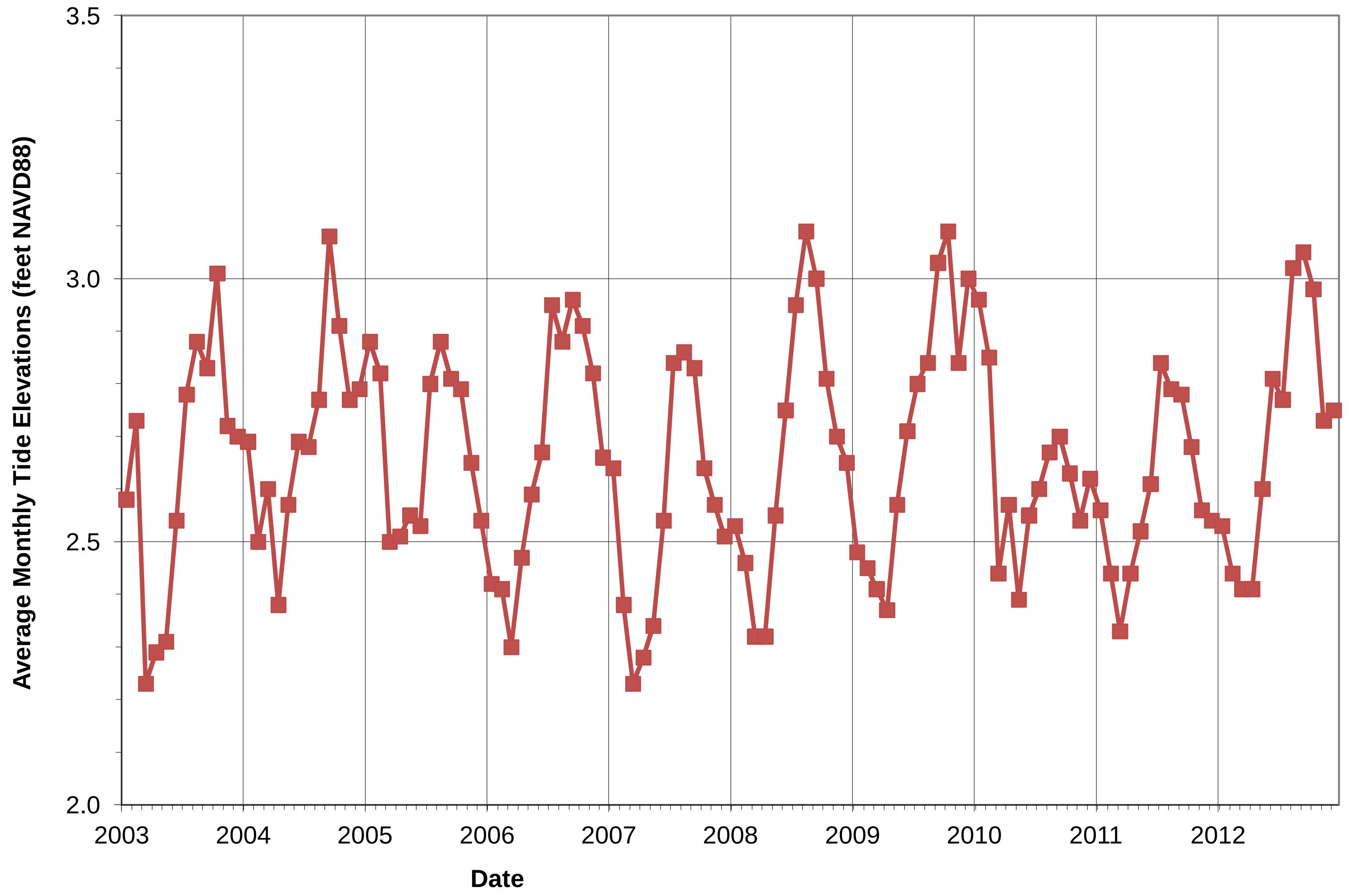


Figure 3.1 -- Map showing numerical model extent and boundary conditions for model layer 1.

McDonald Morrissey ASSOCIATES, Inc.



Source: http:\\tidesandcurrents.noaa.gov

Figure 3.2 -- Graph showing average monthly tide elevation at Santa Monica, CA - Station ID 9410840.

McDonald Morrissey ASSOCIATES, Inc.

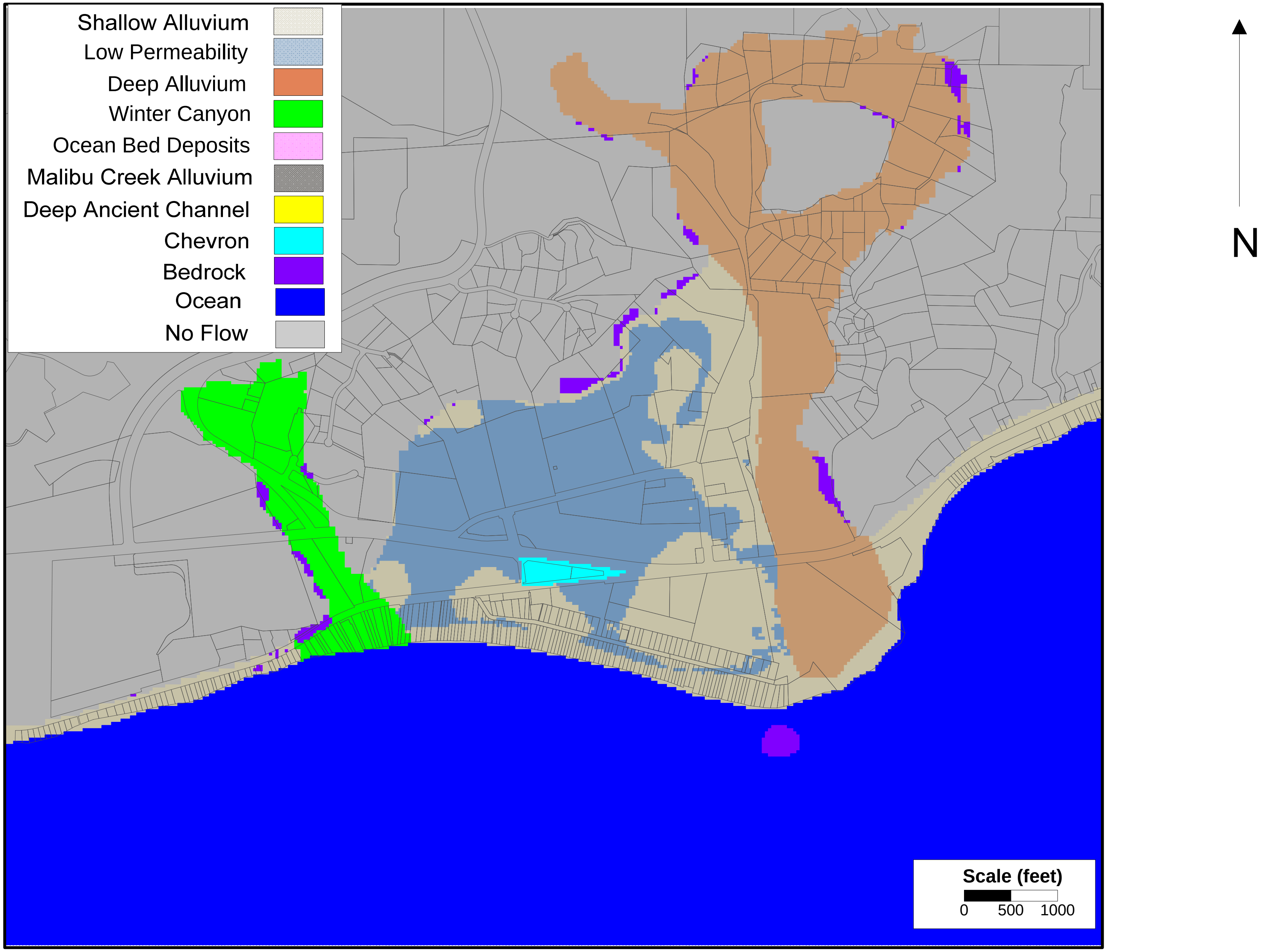


Figure 3.3 -- Map showing hydro stratigraphy zones in model layer 1.

McDonald Morrissey ASSOCIATES, Inc.

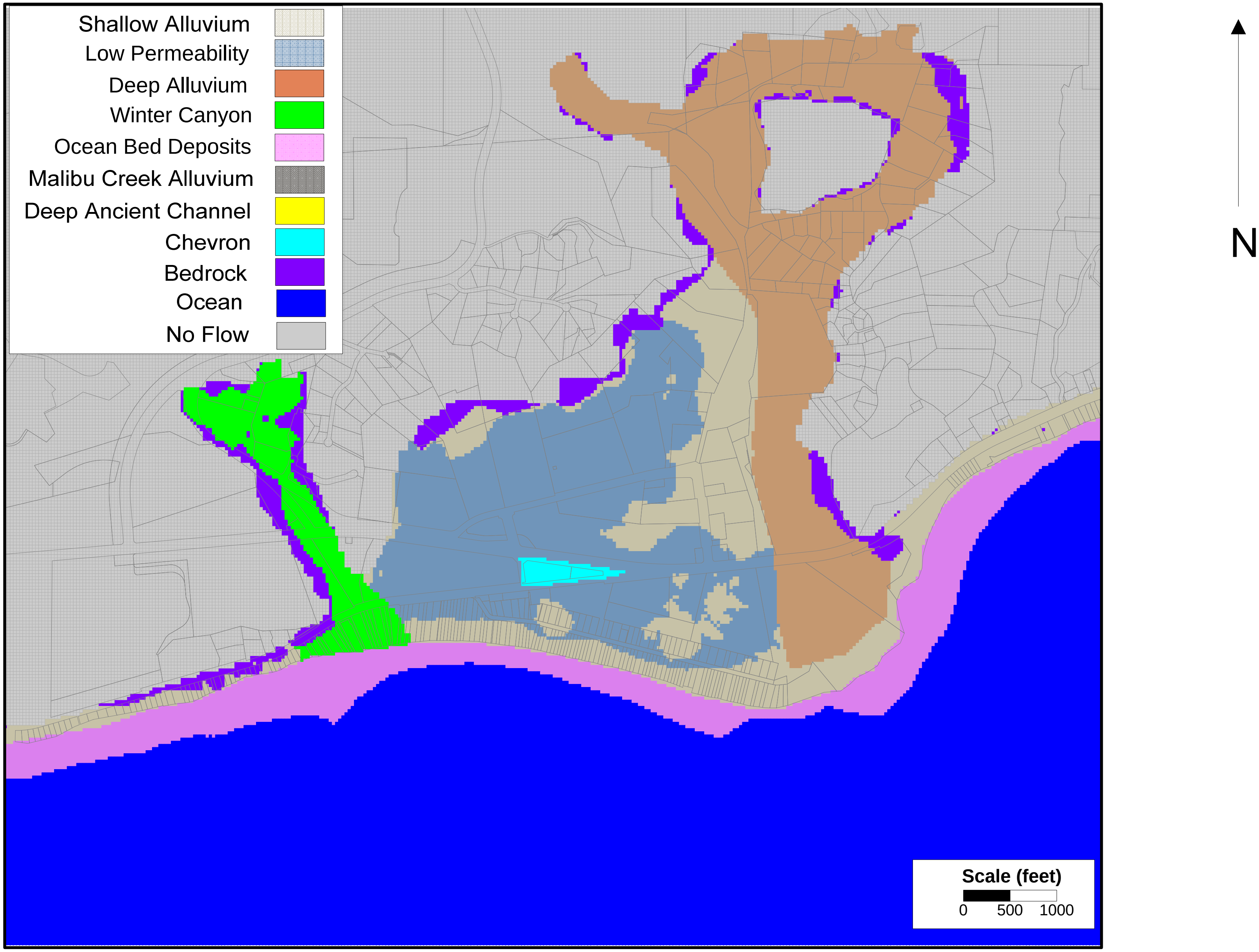


Figure 3.4 -- Map showing hydro stratigraphy zones in model layer 2.

McDonald Morrissey ASSOCIATES, Inc.

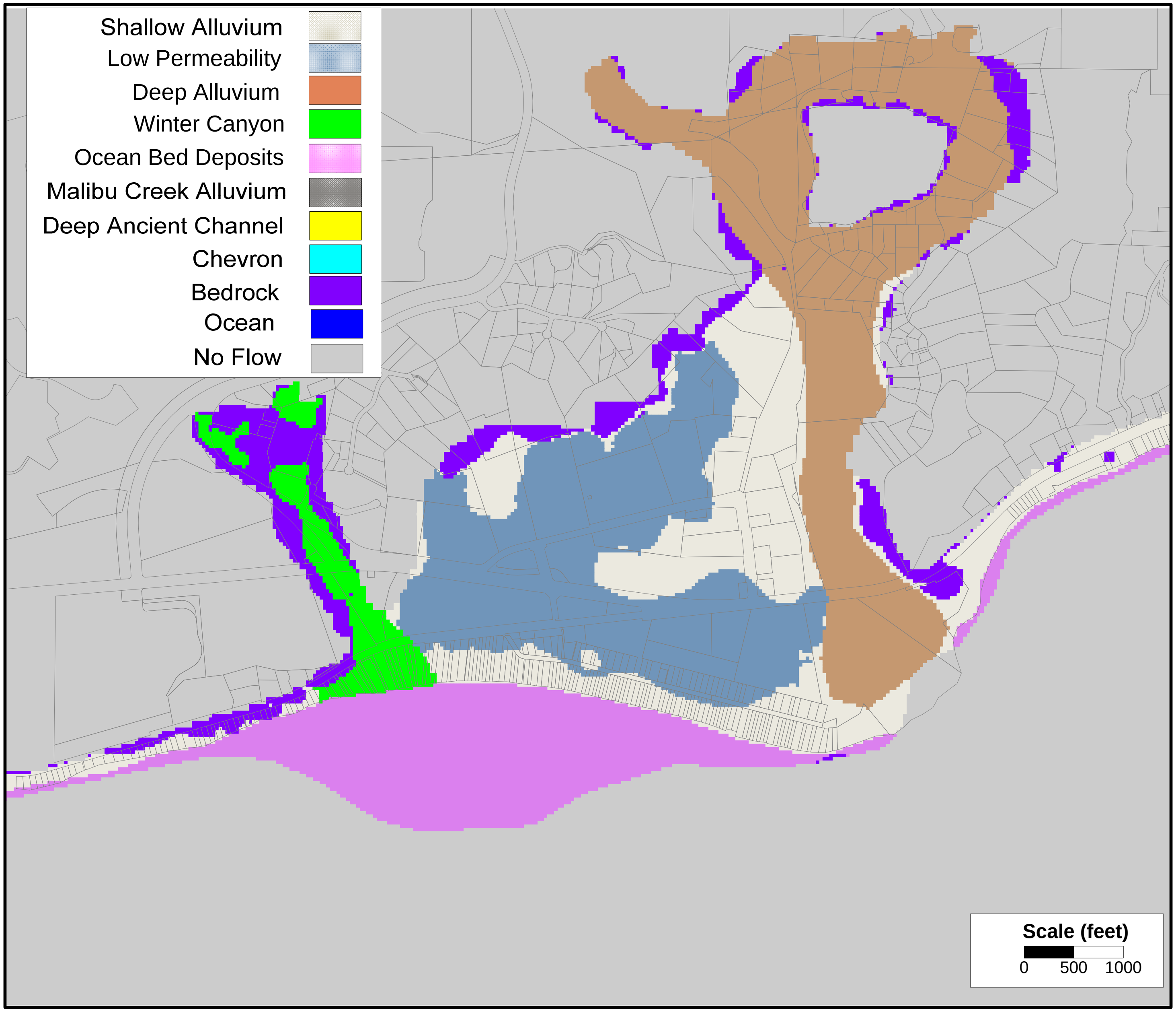


Figure 3.5 -- Map showing hydro stratigraphy zones in model layer 3.

McDonald Morrissey ASSOCIATES, Inc.

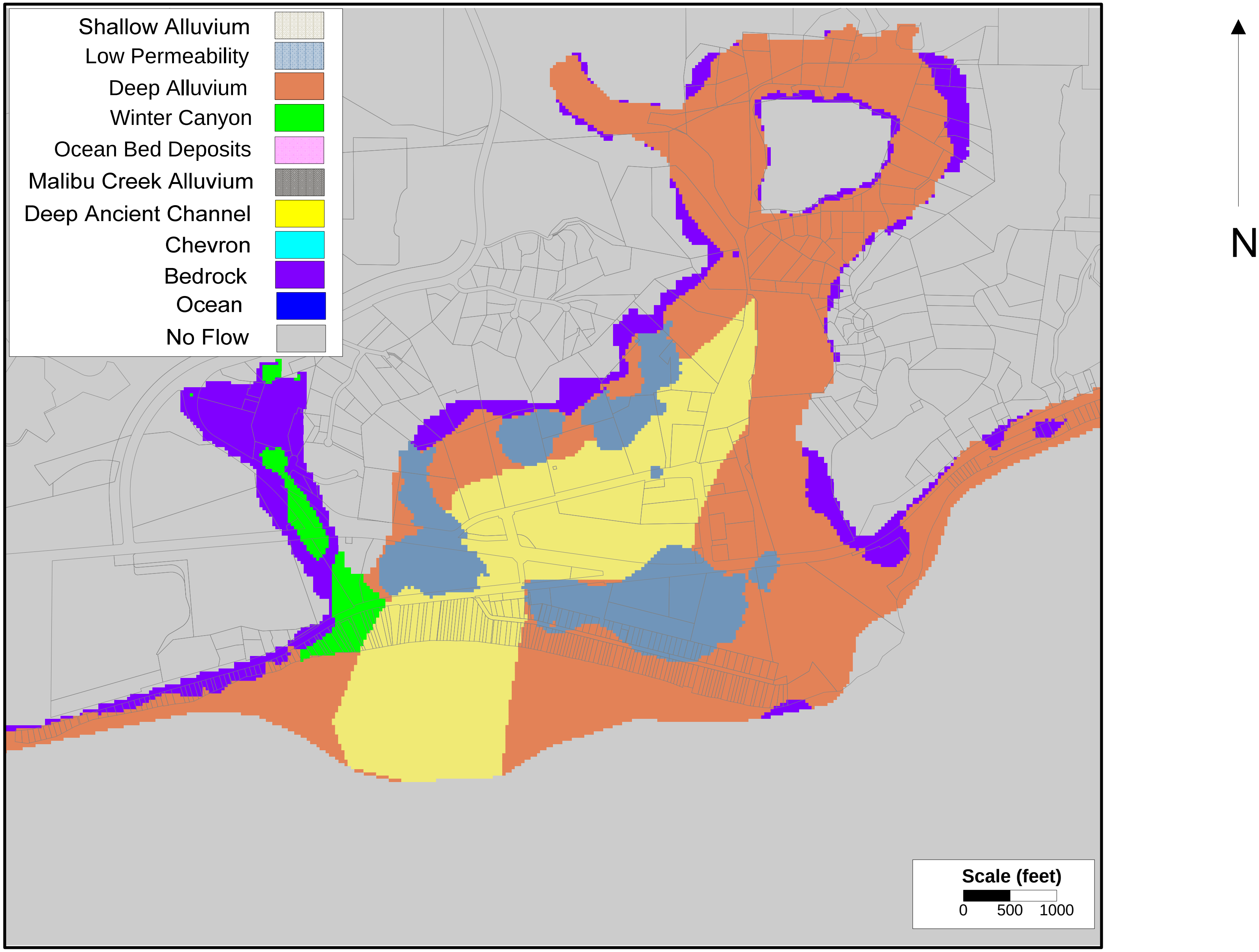


Figure 3.6 -- Map showing hydro stratigraphy zones in model layer 4.

McDonald Morrissey ASSOCIATES, Inc.

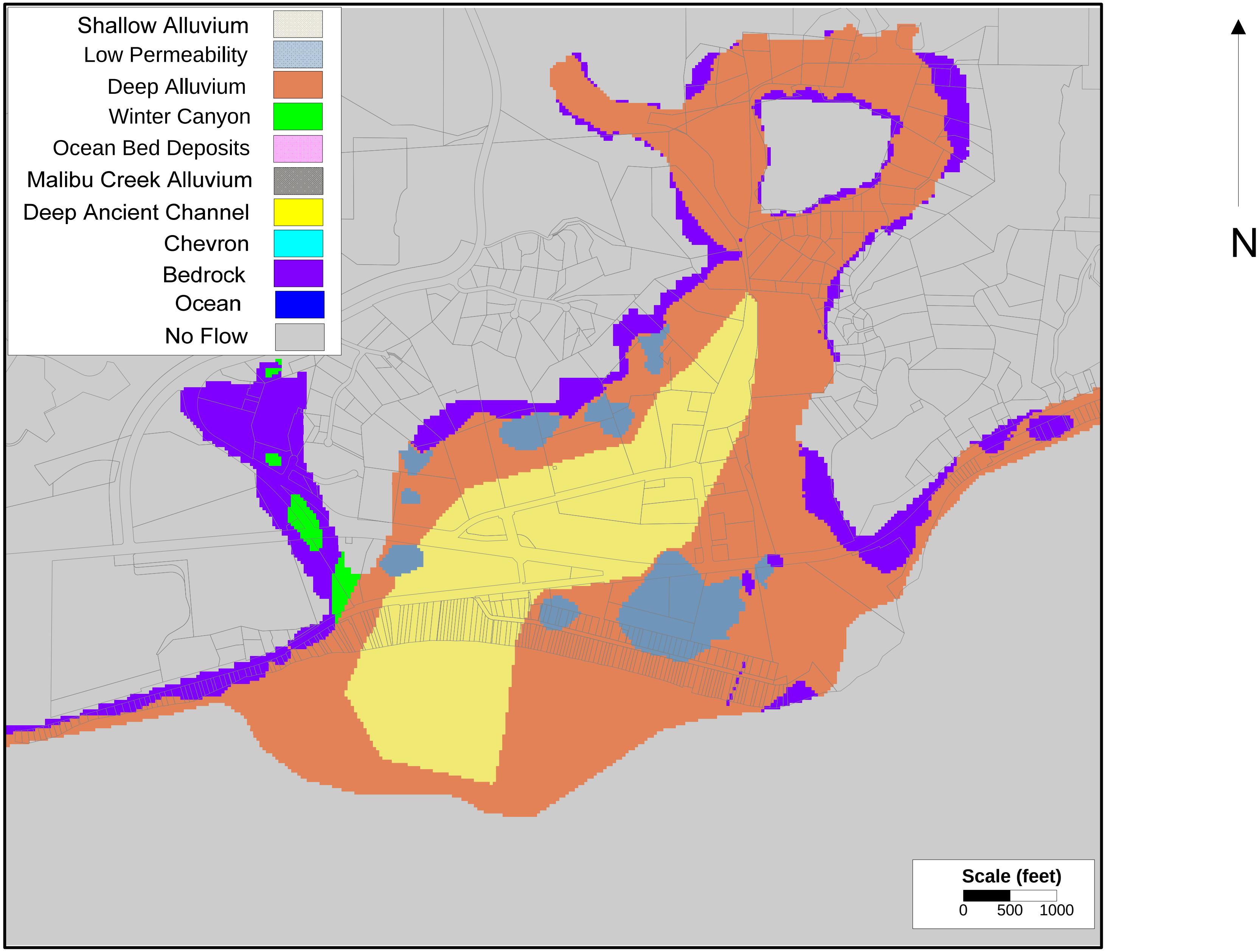


Figure 3.7 -- Map showing hydro stratigraphy zones in model layer 5.

McDonald Morrissey Associates, Inc.