A GEOCHEMICAL AND HYDROLOGICAL ASSESSMENT OF GROUNDWATER IN THE PORTUGUESE BEND LANDSLIDE, CALIFORNIA

BY

CHRISTI A. HILL

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ABSTRACT

The influence of water as a driving force in landslide movement is well known. This study incorporated geochemical, isotopic, and hydrological techniques to examine the sources and mechanisms of recharge to groundwater within the Portuguese Bend and Abalone Cove landslides of the Palos Verdes peninsula.

During the 1997-98 study year, El Nino conditions were prevalent with total precipitation twice the amount experienced during a normal rainfall year. Under these conditions, recharge in both the Altamira Canyon and Portuguese Bend groundwater basins was dominated by flow down surface fissures and soil infiltration, with modest amounts (< 20%) contributed by domestic water recharge via septic systems. These recharge percentages contrast with the contributions expected for an average rainfall year, in which domestic water is estimated to contribute from 20 to 60% of the recharge to the groundwater system.

In both landslides, tritium data indicate that groundwater residence time is on the order of several decades. In light of this estimated age, the rapid response (within one to three months) of groundwater levels to rainfall suggests the propagation of hydraulic pore pressure through the groundwater body rather than the rapid flow of water itself. In addition, an older, warmer, and chemically unique mass of water is present near the toe of the Abalone Cove landslide, indicating the possible presence of a deeper circulating body of water. The presence of a deeper circulation pattern could have important implications for movement in either landslide in the form of possible pore pressure from beneath the slide plane, and presents a topic for future research.

CHAPTER I

INTRODUCTION

The effects of water on the stability of earth material is well known to anyone who has ever built a sand castle. Dry sand falls in a heap, unable to retain shape or form other than that dictated by the angle of repose. However, just the right amount of added moisture maximizes the water's cohesive properties, allowing the sand particles to be molded into and retain shapes. Further addition of water to the sand results in loss of the cohesion and the castle collapses.

The effects of water operate on much larger scales, causing both short-term mass wasting as the result of excessive rainfall and long-term persistent landslide movement. On the Palos Verdes peninsula in southern California favorable geologic conditions have allowed for persistent landslide movement to occur in two adjacent landslide areas, Abalone Cove and Portuguese Bend (Figure 1). The two agents which appear to continuously influence the movement of both the Portuguese Bend and the Abalone Cove landslides are the wave erosion at the toes of the slides and the dynamics of groundwater within the landslide masses.

Correlations have been established between the amount of groundwater present and the amount of landslide movement (Ehlig, 1979). Groundwater levels are ultimately influenced by precipitation and as a result there is also an observed relationship between rainfall occurrence and landslide movement.



Figure 1. Map showing location of Pleistocene landslide and reactivated Portuguese Bend and Abalone Cove landslides (Modified from Ehlig, 1986 and Proffer, 1992). A-A' and B-B' indicate location of cross sections in Figure 2.

A. PURPOSE OF RESEARCH

In order to mitigate the influence of groundwater dynamics on landslide movement, it is essential to have an understanding of the sources of groundwater within the landslide mass. Previously identified sources of recharge within the study area include infiltration from rainfall, storm runoff infiltration, and domestic water inflow from septic systems and irrigation (Proffer, 1992). However, the proportions of these sources contributing to the groundwater reservoir and their role in groundwater dynamics have not been well established.

The purpose of this research was to confirm and quantify the sources, mechanisms, and relative importance of recharge to groundwater within the Portuguese Bend and Abalone Cove landslide areas. Because landslide movement, especially in Portuguese Bend, is persistent and not just confined to periods of heavy rainfall, a better understanding of the role of all water sources in the recharge of groundwater is essential in comprehending the relationship between groundwater dynamics and landslide movement, and in making decisions on mitigation options.

B. TECTONIC SETTING

The Palos Verdes peninsula is a northwest-trending, doubly-plunging anticlinal structure, ~ 14 km long and up to 8 km wide (Figure 1). The overall structure has been created by Quaternary uplift within the hanging wall of the Palos Verdes fault, resulting in seaward-dipping marine strata on the southern portion of the peninsula. Multiple marine terraces ring the peninsula, providing evidence of this recent uplift (Woodring, 1946).

C. GEOLOGY

The regional geology of the area was first described by Woodring et al. (1946). The Mesozoic Catalina Schist forms the basement (core) of the anticline. The Catalina Schist is stratigraphically overlain by the Monterey Formation, which is subdivided into the Middle Miocene Altamira Shale, the late Middle to early Upper Miocene Valmonte Diatomite, and the late Upper Miocene to early Pliocene Malaga Mudstone. The Altamira Shale is predominant in the study area and is composed of tuffaceous, cherty, and phosphatic members.

The tuffaceous member was deposited during the infilling of a submarine tectonic basin south of the peninsula and was subsequently uplifted during formation of the anticline. Its thickness throughout the peninsula ranges from ~ 90 to 1,200 meters. It includes biogenic cherty and phosphatic shale, siltstone and fine-grained sandstone, pillow basalts, basaltic sills, tuff turbidites, ashfall and debris flow tuffs, and dolostone. The dolostone was formed by diagenesis of calcareous muds (Conrad and Ehlig, 1983). Dolomite also occurs near basaltic intrusions both as concretionary lens and as veins in the basalt. There is extensive development of dolomite, barite, and quartz veining within and adjacent to the basalt intrusions suggesting significant geothermal activity (Conrad and Ehlig, 1983). In the vicinity of Portuguese Bend, the most easily-recognized stratigraphic unit within the tuffaceous member is the ~ 20m-thick Portuguese Tuff. It is an irregularly-bedded tuff which appears to have been deposited by turbidity currents during a single eruptive event (Ehlig, 1992). The tuffaceous member of the Altamira

Shale is the most influential unit in terms of landslide activity because its weathered tuffs form weak bentonite beds that serve as slip surfaces.

Structurally, the strata in the study area form a topographic amphitheater bounded on the north, east, and south by ridges of fairly stable bedrock. The amphitheater most likely formed by differential compaction of sediments in a basin bounded by fairly incompressible Catalina Schist and basaltic intrusions. Uplift of the compacted sediments on the limb of the peninsular anticline resulted in undulating, southward-dipping strata, more steeply tilted under the landward portion of the amphitheater than under the seaward portion (Ehlig, 1992). Cross sections of each of the two landslides are illustrated in Figure 2.

It is the combination of seaward-dipping strata and weak bentonite layers that provides a favorable environment for landslide activity throughout the southern portion of the Palos Verdes peninsula (Ehlig, 1992).

D. LANDSLIDE HISTORY

One of the first descriptions of landslide activity in the Portuguese Bend area was provided by Woodring et al. (1946). They mapped the extent of an ancient landslide complex in which the most recent movement appeared to be Pleistocene in age. The entire Pleistocene complex encompasses ~ 3.5 km^2 of the structural embayment described above (Figure 1). The origin of the ancient complex is still under debate. Jahns and VonderLinden (1973) suggested that the complex originated as several semi-independent slides which formed during three separate time intervals. Ehlig (1992) interpreted the origin of the complex as a single megaslide. In 1956, the coastal portion of the ancient

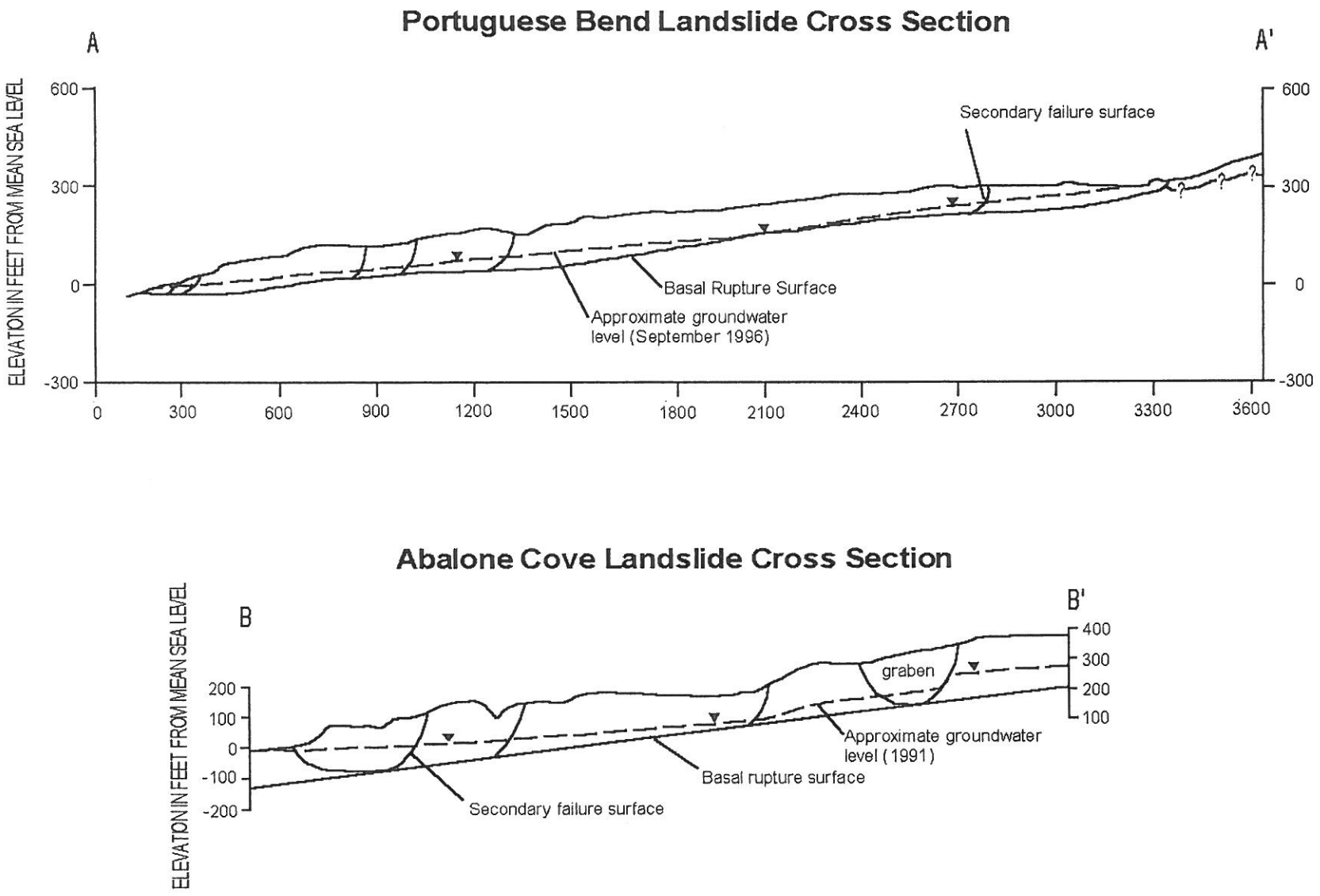


Figure 2. Vertical cross sections through active portions of landslides. See Figure 1 for locations of cross sections.

complex was reactivated as the Portuguese Bend landslide. Portions of it have moved as much as 240 meters and resulted in the destruction of 130 of approximately 160 homes within the area.

The current Portuguese Bend landslide is moving as a series of five semi-independent subslides. The five subslides occupy ~ 1 km^2 and can be divided into two groups: one group which moves into Portuguese Bend, and a second group in the western portion that moves into an unnamed cove between Inspiration Point and Portuguese Point (Figure 1).

The Abalone Cove Landslide occurs immediately adjacent to the west of the Portuguese Bend landslide and occupies ~ 0.3 km^2 of the ancient complex (Figure 1). The coastal segment of this slide started moving by February 1974, and the upper portion began moving in 1978, apparently in response to high rainfall. A portion of the slide moved nine meters and damaged several homes prior to stabilization by dewatering.

E. LANDSLIDE STABILITY

Subsurface Conditions

Most pyroclastic glass in the study area has been diagenetically altered. The composition of the clay material in the landslide area has been studied by several investigators. Kerr et al. (1967) analyzed the x-ray diffractometer patterns for five different samples of bentonite (collected from five separate locations in the vicinity of the Portuguese Bend landslide). All five samples were identified as montmorillonite with calcium as the dominant interlayer cation. Novak (1982) and Ehlig and Yen (1997) also used x-ray diffractometer patterns but identified the clay as sodium montmorillonite. The

tested shear strength of the landslide bentonite lies between the reported strength envelopes of both calcium and sodium montmorillonite but more closely resembles the curve of sodium montmorillonite (Ehlig and Yen, 1997).

Because of the cation exchange ability of clay, it appears likely that both types of montmorillonite occur in the landslide area. During weathering, which is prominent in the uphill areas of the study area, calcium is typically exchanged for sodium in the clays. In the less-weathered downhill areas more sodium is retained, resulting in clay material that holds more water and is weaker overall (Ehlig and Yen, 1997).

The slide planes for both the Abalone Cove and Portuguese Bend landslides occur slightly above or within the altered Portuguese Tuff. Important to the understanding of landslide movement is the observation of Ehlig and Yen (1997) that the clay strength in the Portuguese Bend landslide area is dependent upon the rate of displacement. As a result, the slower the rate of shear displacement, the lower the apparent clay shearing strength resisting the displacement. This relationship between clay strength and displacement could possibly explain the slower, but continuous movement of the Portuguese Bend landslide even in the absence of rainfall.

Mechanisms of Movement

Terzaghi, is his classic 1950 landslide paper, discussed the delicate balance between the fundamental shearing resistance (or strength) of a material and the shearing stresses which can act on that material. He divided the causes of landslide movement into external and internal ones. External causes produce an increase in shearing stress while leaving the shearing resistance unaltered. Examples of external causes include

steepening or heightening of slope by natural (i.e. erosion) or human (excavation) processes, deposition of material on the upper edge of a slope, increase in weight of material from saturation with heavy rainfall, or earthquake shocks. Internal causes create a decrease in shearing resistance and lead to slope failure without altering surface conditions. Loss in cohesion of material or increase in pore water pressure are examples of internal causes.

In the cases of both subject landslides, probable external causes have been identified. The Portuguese Bend landslide began moving not long after the placement of roadfill along the upper portion of the slope. The Abalone Cove landslide began moving following periods of heavy rainfall. Both landslides continue to be plagued by the undercutting at the base of the slides by wave erosion.

The influence of water (or lack of water) on the movement of both landslides as an internal cause is reflected in different ways. An aggressive dewatering program has slowed the movement of the Abalone Cove landslide to an almost imperceptible creep. The Portuguese Bend landslide has not responded as favorably to dewatering and shows an increase in movement following periods of heavy rainfall.

General Effects of Water on Landslide Movement

A common misconception about subsurface water is that it has a lubricating effect on soil material. Almost any soil has enough moisture present at any time to "lubricate" the particles, yet mass movement is not a constant phenomenon on every slope. A small amount of water occurring as a film on soil particles actually helps to hold particles together through water's adhesive and cohesive properties. However, replacement of air

within the pore spaces with water eliminates the surface tension, resulting in a loss of cohesion. Water can also cause loss of soil cohesion by dissolution of binding materials in the soil (Terzaghi, 1950).

Infiltration of water into subsurface pore spaces can result in an increase in hydrostatic pore pressure. This type of pressure can result from an increase in hydraulic head accompanying a rise in the local water table. The effective stress of soil material, or its shear strength, is highly dependent on frictional contact between soil particles. Hydrostatic pressure decreases the strength of the soil material in one of two ways: 1) it increases the spacing between soil particles, thereby reducing their frictional contact; or 2) the weight of the overlying material is increasingly supported by the pore water which has no shear strength (Watson and Burnett, 1993).

In addition, groundwater can have an increased effect in compound landslides (slide masses with more than one slide plane) such as the Portuguese Bend slide for several reasons: 1) multiple slide planes provide a greater surface area than a single slide plane upon which the water can act; 2) the subslides are more rapidly saturated by water infiltration; and 3) movement-inducing pore pressures can often be reached more rapidly in secondary slides (Cronin, 1992).

F. ORGANIZATION OF STUDY

This study integrates hydrological, geochemical, and isotopic data to examine the sources, mechanisms, and effects of groundwater recharge on landslide movement. Hydrologic data from rainfall, runoff, domestic water, and groundwater measurements were used to develop surface and groundwater budgets for each landslide area. The

geochemical section includes chemical analysis of major ions, the stable isotopes of oxygen and hydrogen, and the radioactive isotope tritium. The major ions provided clues to the possible influences on groundwater chemistry (i.e. subsurface lithology or seawater intrusion). The isotopic data were used as tracers of groundwater sources and to assess groundwater age. In addition, the isotopes were used in mass balance calculations as an independent check on the results of the hydrologic budget calculations.

G. TERMS AND DEFINITIONS

The following terms appear throughout the paper and definitions are provided here for easy reference:

- ‰ – parts per thousand (per mil).
- δD – concentration of hydrogen-2 isotope (deuterium) determined in similar manner to $\delta^{18}O$.
- $\delta^{18}O$ – concentration of oxygen-18 isotope in sample determined from the equation:
$$\delta^{18}O_{sample} = \left\{ \left(\frac{(^{18}O/^{16}O)_{sample}}{(^{18}O/^{16}O)_{reference}} \right) - 1 \right\} \times 1000\ ‰$$
- Effective uniform depth (EUD) of precipitation – average areal precipitation falling within a given drainage basin in linear units (i.e. mm or in.) for a defined time period.
- Local meteoric water line (LMWL) – linear relationship between δD and $\delta^{18}O$ of precipitation; determined from sampling of local rainfall.
- Total dissolved ions (TDI) – total sum of cation and anion concentrations for a given sample.
- Tritium unit (TU) – concentration of tritium where: 1 TU = 1 ^{3}H per 10^{18} hydrogen atoms.

CHAPTER II

HYDROLOGIC PARAMETERS AND BUDGET CALCULATIONS

As stated previously, identified sources of input to the groundwater system include rainfall and storm runoff infiltration, and domestic water seepage from septic systems. Groundwater in each basin generally flows toward the ocean with an average hydraulic gradient of ~ 0.08 ft/ft in Altamira Canyon and ~ 0.15 in Portuguese Bend. Hydraulic conductivity of the subsurface material in the area ranges from ~ 0.12 m/day (0.39 ft/day) in Altamira Canyon to ~ 0.08 m/day (0.26 ft/day) in Portuguese Bend (Ehlig and Yen, 1997; Proffer, 1992). For the purpose of these calculations, it was assumed that the boundaries of both groundwater basins closely paralleled the surface drainage basins in areal extent.

In order to gain an initial estimate of the percent contribution of each hydrologic source component to the water within the slide masses, a hydrologic budget was calculated for both the Altamira Canyon and Portuguese Bend drainage basins. Budgets were first derived for the surface drainage basin and the output from the surface into the subsurface was then incorporated into the groundwater budget.

A. ALTAMIRA CANYON BASIN - SURFACE WATER BUDGET

Input Variables

Rainfall

Rainfall measurements were taken on a weekly basis from a nine-station rain gauge network in the study area. At one of the stations (BD), rainfall measurements were

taken for each individual rainfall event. Figure 3 illustrates the rain gauge station locations and the extent of the Abalone Cove and the adjacent Portuguese Bend drainage basins. Rain samples were collected in a small bucket at a central location in the study area (Station BD). The samples were mixed and placed into vials at the end of each particular storm. Rainfall measurements were taken from plastic rain gauges attached to fixed points throughout the sample area. The gauges could measure up to 126 millimeters of rainfall per event.

The Altamira Canyon surface drainage basin is ~ 3.3 km^2 (815 acres) in size while the Portuguese Bend basin measures ~ 2.5 km^2 (618 acres). Data for three of the stations (1011B, SF, and 1216) were obtained from the Los Angeles County Department of Public Works. The data from all 12 stations are presented in Table 1. Three stations had missing data as a result of stolen or broken gauges. The missing data at a given station (Z) were estimated from the data of three surrounding index stations (A, B, and C) using the following equation (Fetter, 1988):

$$P_Z = 1/3\ [(N_Z/N_A)P_A + (N_Z/N_B)P_B + (N_Z/N_C)P_C]$$

where P represents the actual precipitation at the index stations and N is the mean annual precipitation at each of the stations.

In order to estimate the weekly effective uniform depth (EUD) of precipitation in each of the drainage basins, the Theisson polygon method was used. This method is effective when the distribution of rain gauges is non-uniform. Polygons of appropriate size are constructed around each rain gauge to account for their varied distribution. The polygon area surrounding each gauge is expressed as a percentage of the total area of the

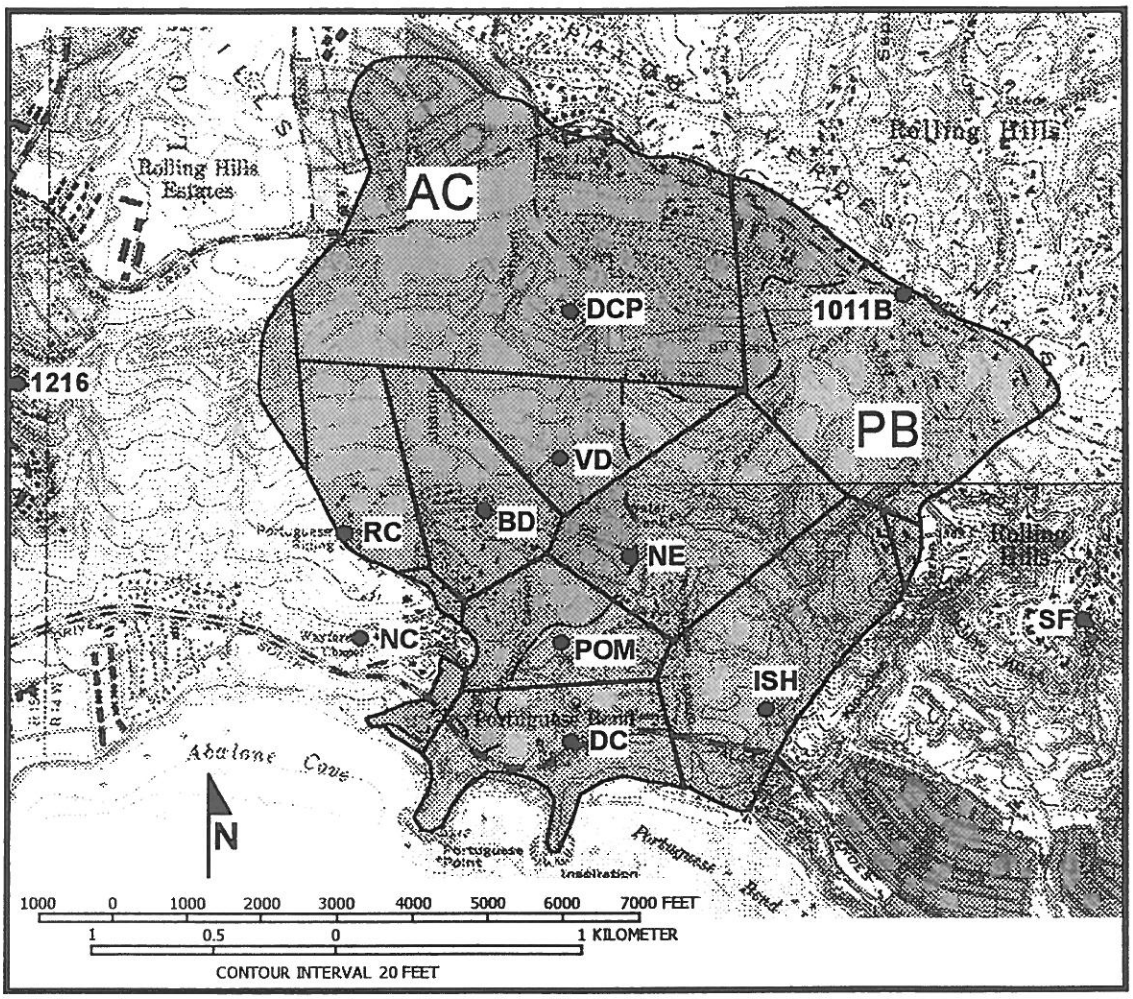


Figure 3. Drainage basins and rain gauge network for study area. Gray areas represent each drainage basin (dark gray - Altimira Canyon, light gray - Portuguese Bend). Polygons represent weighted areas for each rain gauge. ● NC represents rain gauge station.

TABLE 1. TOTAL WEEKLY PRECIPITATION FROM RAIN GAUGE STATIONS IN THE STUDY AREA (1997-98).

	Rain Gauge Designations											
Week	**1011B**	**DCP**	**SF**	**1216**	**VD**	**BD**	**NE**	**RC**	**POM**	**NC**	**ISH**	**DC**
elevation	*1265*	*1180*	*1140*	*810*	*510*	*430*	*422*	*404*	*356*	*270*	*182*	*162*
9/1-9/7/1997	-	-	-	-	-	-	-	-	-	-	-	-
9/8-9/14	-	-	-	-	-	-	-	-	-	-	-	-
9/15-9/21	-	-	-	-	-	-	-	-	-	-	-	-
9/22-9/28	11.7	-	8.9	7.9	-	-	-	-	-	-	-	-
9/29-10/5	-	-	-	-	-	-	-	-	-	-	-	-
10/6-10/12	-	-	-	-	-	-	-	-	-	-	-	-
10/13-10/19	-	-	-	-	-	-	-	-	-	-	-	-
10/20-10/26	-	-	-	-	-	-	-	-	-	-	-	-
10/27-11/2	-	-	-	-	-	-	-	-	-	-	-	-
11/3-11/9	-	-	-	-	-	-	-	-	-	-	-	-
11/10-11/16	45.0	32.0	45.5	38.4	30.0	28.0	23.5	24.0	20.0	22.5	19.0	17.5
11/17-11/23	-	-	-	-	-	3.0	-	-	-	-	-	-
11/24-11/30	19.6	12.0	18.5	14.2	26.0	21.5	13.0	12.0	14.0	9.0	18.0	16.5
12/1-12/7	62.5	44.0	50.8	58.7	53.5	56.0	47.0	50.0	44.0	45.0	42.0	45.5
12/8-12/14	-	-	10.2	-	-	-	-	-	-	-	-	-
12/15-12/21	57.9	17.0	42.2	25.7	36.0	37.0	27.0	31.0	26.5	27.0	35.0	29.5
12/22-12/28	-	-	5.1	-	-	-	-	-	-	-	-	-
12/29-1/4/1998	10.9	7.0	89.4	16.8	11.5	13.0	8.5	10.0	8.0	7.5	7.0	8.5
1/5-1/11	30.5	16.0	30.5	28.2	26.0	24.0	24.0	22.0	24.0	18.0	**23.8**	24.0
1/12-1/18	5.8	5.5	57.7	20.3	6.0	3.0	3.5	3.0	2.5	2.0	**2.8**	2.5
1/19-1/25	-	-	-	-	-	5.0	-	-	-	-	-	-
1/26-2/1	20.6	11.5	20.1	25.7	19.5	18.0	13.5	14.0	12.0	11.0	14.5	13.0
2/2-2/8	139.2	278.0	97.0	145.5	117.0	133.0	108.0	114.0	102.5	101.0	110.0	104.0
2/9-2/15	50.8	24.5	50.8	33.0	50.0	47.5	45.0	42.0	41.5	37.0	44.0	40.5
2/16-2/22	61.0	46.0	74.9	64.0	**61.7**	67.5	62.0	61.0	57.5	54.0	61.0	58.0
2/23-3/1	48.0	31.0	55.9	47.8	43.5	43.0	34.0	38.0	35.0	32.0	36.0	38.0
3/2-3/8	9.9	-	10.2	-	-	-	-	-	-	-	-	-
3/9-3/15	16.5	**18.9**	12.7	30.5	28.0	26.0	19.0	21.0	15.5	16.0	15.0	18.0
3/16-3/22	-	-	-	-	-	-	-	-	-	-	-	-
3/23-3/29	45.7	**34.3**	43.2	35.8	**31.3**	38.0	28.5	26.0	28.5	20.5	31.0	26.5
3/30-4/5	31.2	**23.5**	31.2	24.1	**21.7**	22.0	19.5	18.0	19.5	14.5	21.0	18.5
4/6-4/12	26.7	**21.4**	30.5	15.2	17.0	17.5	16.0	19.5	16.0	19.5	18.0	17.0
4/13-4/19	-	-	-	1.0	-	-	-	-	-	-	-	-
4/20-4/26	-	-	-	-	-	-	-	-	-	-	-	-
4/27-5/3	-	-	-	2.5	-	-	-	-	-	-	-	-
5/4-5/10	21.6	**17.8**	8.9	20.3	16.5	17.0	16.5	17.0	13.0	13.5	10.0	12.5
5/11-5/17	25.1	**20.7**	-	20.8	19.5	20.0	19.0	16.0	18.5	13.5	18.0	16.0
5/18-5/24	-	-	-	-	-	-	-	-	-	-	-	-
5/25-5/31	-	-	-	-	-	-	-	-	-	-	-	-
6/1-6/7	-	-	-	2.5	-	-	-	-	-	-	-	-
6/8-6/14	-	-	1.0	0.8	-	-	-	-	-	-	-	-
6/15-6/21	-	-	1.0	1.0	-	-	-	-	-	-	-	-
6/22-6/28	-	-	-	-	-	-	-	-	-	-	-	-
6/29-7/5	-	-	-	-	-	-	-	-	-	-	-	-
7/6-7/12	-	-	-	-	-	-	-	-	-	-	-	-
7/13-7/19	-	-	-	-	-	-	-	-	-	-	-	-
7/20-7/26	-	-	-	-	-	-	-	-	-	-	-	-
7/27-8/2	-	-	-	-	-	-	-	-	-	-	-	-
8/3-8/9	-	-	-	-	-	-	-	-	-	-	-	-
8/10-8/16	-	-	-	-	-	-	-	-	-	-	-	-
8/17-8/23	-	-	-	-	-	-	-	-	-	-	-	-
8/24-8/31	-	-	-	-	-	-	-	-	-	-	-	-
TOTAL	**728.5**	**661.2**	**787.1**	**672.8**	**614.7**	**640.0**	**527.5**	**538.5**	**498.5**	**463.5**	**526.1**	**506.0**

Stations are listed from left to right in order of decreasing elevation (see Figure 3 for locations).
All measurements in millimeters and dashes (-) = no rainfall measured.
Numbers in bold are estimates of missing data (derived from surrounding stations as detailed in text).

basin and the amounts of rainfall for each gauge are weighted as a function of the polygon area. This method has two advantages: 1) it adjusts for the non-uniform distribution of rain gauges by applying a weighting factor, and 2) allows repeated use of the established polygon network to process large numbers of data sets. The polygon network established for the study area is illustrated in Figure 3 and the calculated weekly EUDs of precipitation for Altamira Canyon and Portuguese Bend drainage basins are presented in Tables 2 and 3, respectively. Although both Tables 2 and 3 have the same stations headings listed, only the stations with polygons falling within the drainage basin of interest have values listed in each respective table.

The total net EUD of precipitation during the study year was 632 mm (~ 25 in.) in the Altamira Canyon drainage basin and 592 mm (~ 23 in.) in the Portuguese Bend drainage basin. These totals represent almost twice the annual mean rainfall of ~ 328 mm (12.9 in.) reported in the study area (Ehlig, 1992). Figure 4 shows a graph over time of the weekly EUD of precipitation in each of the drainage basins. The profiles are almost identical in form with the Altamira Canyon basin reflecting its greater total EUD of precipitation. The amount of rainfall in the study area shows a rough, positive correlation with increasing topographic elevation (Figure 5).

Total volume of rainfall in the Altamira Canyon basin for the study year was calculated by multiplying the total EUD for the basin (632 mm) by the basin surface area (3.3 km^2) yielding a total of 20.9 x 10^5 m^3 (~ 1,694 acre-ft).

TABLE 2. NET EFFECTIVE UNIFORM DEPTH (EUD) OF PRECIPITATION IN THE ALTAMIRA CANYON DRAINAGE BASIN FOR THE STUDY YEAR (1997-98).

	Rain Gauge Designations												
Week	**1011B**	**DCP**	**SF**	**1216**	**VD**	**BD**	**NE**	**RC**	**POM**	**NC**	**ISH**	**DC**	**Net EUD**
9/1-9/7/1997	-	-	-	-	-	-	-	-	-	-	-	-	-
9/8-9/14	-	-	-	-	-	-	-	-	-	-	-	-	-
9/15-9/21	-	-	-	-	-	-	-	-	-	-	-	-	-
9/22-9/28	1	-	0	0	-	-	-	-	-	-	-	-	**1**
9/29-10/5	-	-	-	-	-	-	-	-	-	-	-	-	-
10/6-10/12	-	-	-	-	-	-	-	-	-	-	-	-	-
10/13-10/19	-	-	-	-	-	-	-	-	-	-	-	-	-
10/20-10/26	-	-	-	-	-	-	-	-	-	-	-	-	-
10/27-11/2	-	-	-	-	-	-	-	-	-	-	-	-	-
11/3-11/9	-	-	-	-	-	-	-	-	-	-	-	-	-
11/10-11/16	3	17	0	1	3	3	1	2	1	0	0	0	**30**
11/17-11/23	-	-	-	-	-	0	-	-	-	-	-	-	**0**
11/24-11/30	1	6	0	0	2	2	0	1	1	0	0	0	**15**
12/1-12/7	4	23	0	1	5	6	2	4	2	1	0	1	**48**
12/8-12/14	-	-	0	-	-	-	-	-	-	-	-	-	-
12/15-12/21	3	9	0	1	3	4	1	3	1	0	0	0	**26**
12/22-12/28	-	-	0	-	-	-	-	-	-	-	-	-	-
12/29-1/4/1998	1	4	0	0	1	1	0	1	0	0	0	0	**9**
1/5-1/11	2	8	0	1	2	3	1	2	1	0	0	0	**20**
1/12-1/18	0	3	0	0	1	0	0	0	0	0	0	0	**5**
1/19-1/25	-	-	-	-	-	1	-	-	-	-	-	-	**1**
1/26-2/1	1	6	0	1	2	2	0	1	1	0	0	0	**14**
2/2-2/8	8	145	0	4	10	14	4	10	5	2	0	1	**203**
2/9-2/15	3	13	0	1	4	5	2	4	2	1	0	0	**34**
2/16-2/22	4	24	0	2	5	7	2	5	3	1	0	1	**54**
2/23-3/1	3	16	0	1	4	5	1	3	2	1	0	0	**36**
3/2-3/8	1	-	0	-	-	-	-	-	-	-	-	-	**1**
3/9-3/15	1	10	0	1	2	3	1	2	1	0	0	0	**21**
3/16-3/22	-	-	-	-	-	-	-	-	-	-	-	-	-
3/23-3/29	3	18	0	1	3	4	1	2	1	0	0	0	**34**
3/30-4/5	2	12	0	1	2	2	1	2	1	0	0	0	**23**
4/6-4/12	2	11	0	0	2	2	1	2	1	0	0	0	**20**
4/13-4/19	-	-	-	0	-	-	-	-	-	-	-	-	-
4/20-4/26	-	-	-	-	-	-	-	-	-	-	-	-	-
4/27-5/3	-	-	-	0	-	-	-	-	-	-	-	-	**0**
5/4-5/10	1	9	0	0	1	2	1	1	1	0	0	0	**17**
5/11-5/17	1	11	-	1	2	2	1	1	1	0	0	0	**20**
5/18-5/24	-	-	-	-	-	-	-	-	-	-	-	-	-
5/25-5/31	-	-	-	-	-	-	-	-	-	-	-	-	-
6/1-6/7	-	-	-	0	-	-	-	-	-	-	-	-	**0**
6/8-6/14	-	-	0	0	-	-	-	-	-	-	-	-	-
6/15-6/21	-	-	0	0	-	-	-	-	-	-	-	-	-
6/22-6/28	-	-	-	-	-	-	-	-	-	-	-	-	-
6/29-7/5	-	-	-	-	-	-	-	-	-	-	-	-	-
7/6-7/12	-	-	-	-	-	-	-	-	-	-	-	-	-
7/13-7/19	-	-	-	-	-	-	-	-	-	-	-	-	-
7/20-7/26	-	-	-	-	-	-	-	-	-	-	-	-	-
7/27-8/2	-	-	-	-	-	-	-	-	-	-	-	-	-
8/3-8/9	-	-	-	-	-	-	-	-	-	-	-	-	-
8/10-8/16	-	-	-	-	-	-	-	-	-	-	-	-	-
8/17-8/23	-	-	-	-	-	-	-	-	-	-	-	-	-
8/24-8/31	-	-	-	-	-	-	-	-	-	-	-	-	-
												Total	**632**

All measurements are in millimeters and dashes (-) = no rainfall measured.
Shaded stations do not fall within the drainage basin and are not applicable.

TABLE 3. NET EFFECTIVE UNIFORM DEPTH (EUD) OF PRECIPITATION IN THE PORTUGUESE BEND DRAINAGE BASIN FOR THE STUDY YEAR (1997-98).

	Rain Gauge Designations												
Week	1011B	DCP	SF	1216	VD	BD	NE	RC	POM	NC	ISH	DC	Net EUD
9/1-9/7/1997	-	-	-	-	-	-	-	-	-	-	-	-	-
9/8-9/14	-	-	-	-	-	-	-	-	-	-	-	-	-
9/15-9/21	-	-	-	-	-	-	-	-	-	-	-	-	-
9/22-9/28	4	-	0	0	-	-	-	-	-	-	-	-	**4**
9/29-10/5	-	-	-	-	-	-	-	-	-	-	-	-	-
10/6-10/12	-	-	-	-	-	-	-	-	-	-	-	-	-
10/13-10/19	-	-	-	-	-	-	-	-	-	-	-	-	-
10/20-10/26	-	-	-	-	-	-	-	-	-	-	-	-	-
10/27-11/2	-	-	-	-	-	-	-	-	-	-	-	-	-
11/3-11/9	-	-	-	-	-	-	-	-	-	-	-	-	-
11/10-11/16	14	0	0	0	1	0	5	0	1	0	5	2	**28**
11/17-11/23	-	-	-	-	-	0	-	-	-	-	-	-	-
11/24-11/30	6	0	0	0	1	0	3	0	1	0	5	2	**17**
12/1-12/7	19	0	0	0	2	0	9	0	2	0	11	6	**50**
12/8-12/14	-	-	0	-	-	-	-	-	-	-	-	-	**0**
12/15-12/21	18	0	0	0	1	0	5	0	1	0	9	4	**39**
12/22-12/28	-	-	0	-	-	-	-	-	-	-	-	-	-
12/29-1/4/1998	3	0	1	0	0	0	2	0	0	0	2	1	**10**
1/5-1/11	9	0	0	0	1	0	5	0	1	0	6	3	**26**
1/12-1/18	2	0	0	0	0	0	1	0	0	0	1	0	**4**
1/19-1/25	-	-	-	-	-	0	-	-	-	-	-	-	-
1/26-2/1	6	0	0	0	1	0	3	0	1	0	4	2	**16**
2/2-2/8	43	0	1	0	3	0	22	0	6	0	28	15	**117**
2/9-2/15	16	0	0	0	1	0	9	0	2	0	11	6	**46**
2/16-2/22	19	0	1	0	2	0	12	0	3	0	15	8	**61**
2/23-3/1	15	0	0	0	1	0	7	0	2	0	9	5	**40**
3/2-3/8	3	-	0	-	-	-	-	-	-	-	-	-	**3**
3/9-3/15	5	0	0	0	1	0	4	0	1	0	4	3	**17**
3/16-3/22	-	-	-	-	-	-	-	-	-	-	-	-	-
3/23-3/29	14	0	0	0	1	0	6	0	2	0	8	4	**34**
3/30-4/5	10	0	0	0	1	0	4	0	1	0	5	3	**24**
4/6-4/12	8	0	0	0	0	0	3	0	1	0	5	2	**20**
4/13-4/19	-	-	-	0	-	-	-	-	-	-	-	-	-
4/20-4/26	-	-	-	-	-	-	-	-	-	-	-	-	-
4/27-5/3	-	-	-	0	-	-	-	-	-	-	-	-	-
5/4-5/10	7	0	0	0	0	0	3	0	1	0	3	2	**16**
5/11-5/17	8	0	-	0	1	0	4	0	1	0	5	2	**20**
5/18-5/24	-	-	-	-	-	-	-	-	-	-	-	-	-
5/25-5/31	-	-	-	-	-	-	-	-	-	-	-	-	-
6/1-6/7	-	-	-	0	-	-	-	-	-	-	-	-	-
6/8-6/14	-	-	0	0	-	-	-	-	-	-	-	-	-
6/15-6/21	-	-	0	0	-	-	-	-	-	-	-	-	-
6/22-6/28	-	-	-	-	-	-	-	-	-	-	-	-	-
6/29-7/5	-	-	-	-	-	-	-	-	-	-	-	-	-
7/6-7/12	-	-	-	-	-	-	-	-	-	-	-	-	-
7/13-7/19	-	-	-	-	-	-	-	-	-	-	-	-	-
7/20-7/26	-	-	-	-	-	-	-	-	-	-	-	-	-
7/27-8/2	-	-	-	-	-	-	-	-	-	-	-	-	-
8/3-8/9	-	-	-	-	-	-	-	-	-	-	-	-	-
8/10-8/16	-	-	-	-	-	-	-	-	-	-	-	-	-
8/17-8/23	-	-	-	-	-	-	-	-	-	-	-	-	-
8/24-8/31	-	-	-	-	-	-	-	-	-	-	-	-	-
												Total	592

All measurements are in millimeters and dashes (-) = no rainfall measured.
Shaded stations do not fall within the drainage basin and are not applicable.

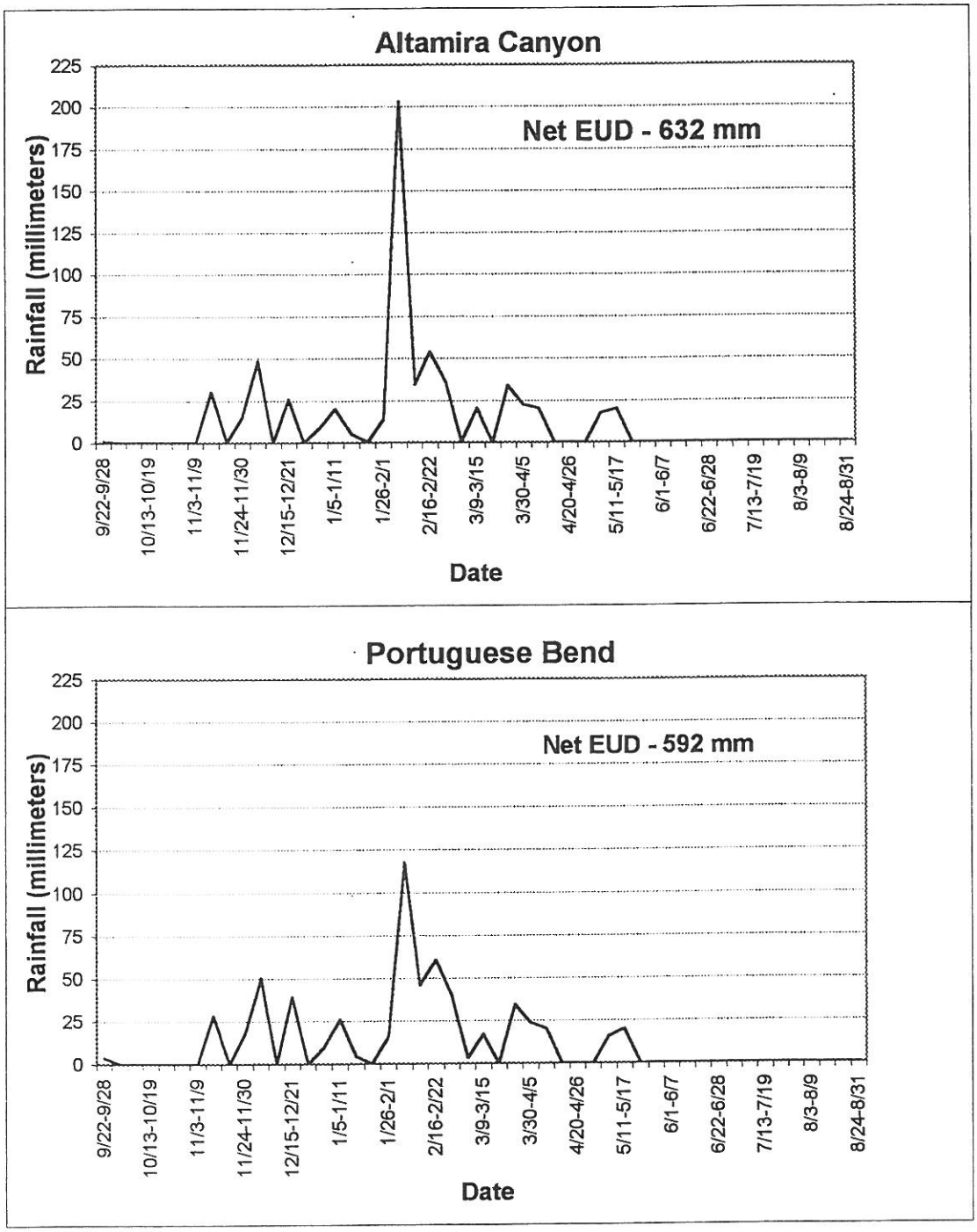


Figure 4. Effective uniform depth (EUD) of precipitation over the study period in the Altamira Canyon and Portuguese Bend drainage basins. Corresponding profiles reflect similar rainfall patterns in both basins.

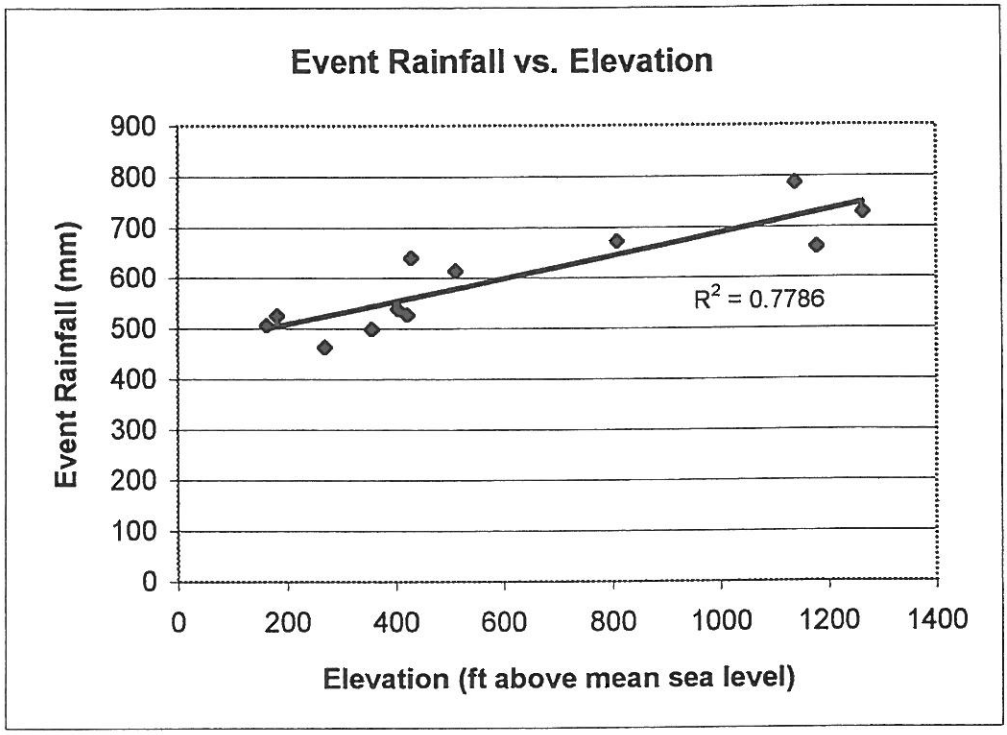


Figure 5. Correlation of total event rainfall with elevation in the study area. There is a general increase in rainfall amount with increasing elevation.

Landscape Irrigation

Surface water is also supplied by domestic watering of lawns and plants. Water supply records for each basin were obtained from the California Water Service for the years 1995-1999. Based on these records, a total of 98,907 m^3 (~ 80 acre-ft) of water was supplied to the Altamira basin area during the 1997-98 study year (Table 4). In practice, landscape irrigation is typically discontinued during periods of rainfall and therefore it is assumed that most domestic water delivered to residences during these periods enters directly into the septic systems. Figure 6 illustrates water consumption in the two basins over the study year. During the study period rainy season, the highest amount of rainfall occurred during the month of February (Table 2). The monthly water consumption for February totaled 4,196 m^3 (~ 3 acre-ft). By applying this amount as a base level of monthly household consumption and assuming that any amount over the base level is probably used for landscape irrigation, an estimate of irrigation water can be obtained. For the year-long study, the base level of household consumption would total 50,352 m^3 (~ 41 acre-ft) with the remaining 48,555 m^3 (~ 39 acre-ft) available for irrigation watering. Most irrigation occurs during times of little to no rainfall, warmer temperatures, and (in the Mediterranean climate of the study area) conditions of relatively low humidity. For the purposes of these calculations it was assumed that water applied for irrigation was either evaporated or transpired and did not contribute to the groundwater system.

TABLE 4. WATER CONSUMPTION DATA FOR ALTAMIRA CANYON AND PORTUGUESE BEND BASINS

	1997-98 (El Nino year)	
Month	Altamira Canyon	Portuguese Bend
Sep	12,268	2,625
Oct	10,866	1,869
Nov	11,769	2,494
Dec	5,345	1,008
Jan	5,246	821
Feb	4,196	756
Mar	4,077	841
Apr	4,680	736
May	7,007	1,062
Jun	8,867	1,693
Jul	10,988	1,554
Aug	13,598	2,950
Year Total	**98,907**	**18,408**

(Note: All amounts reported in cubic meters (= 8.107×10^{-4} acre-ft))

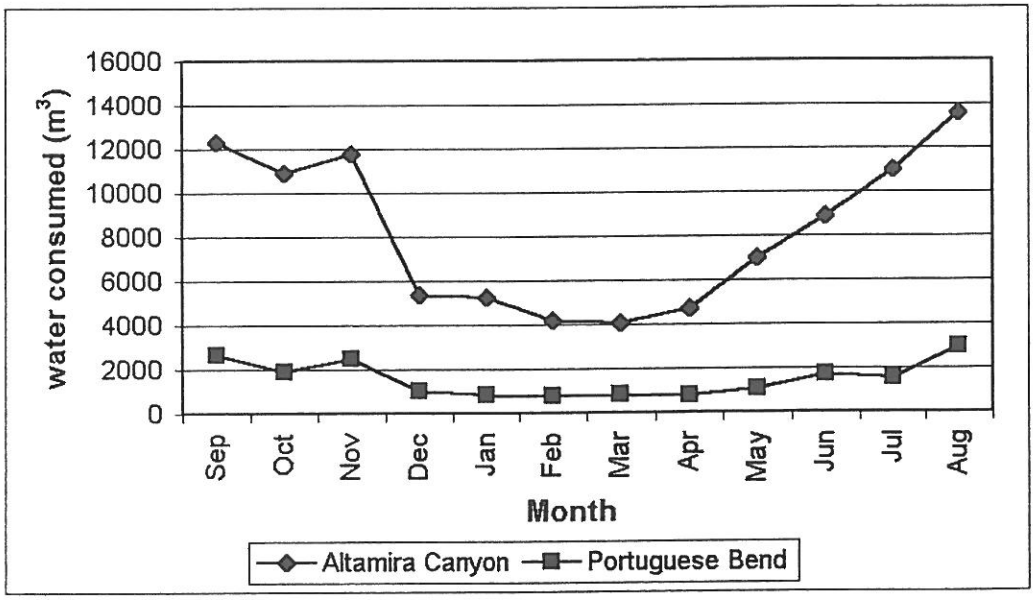


Figure 6. Monthly domestic water consumption in the study area (1997-98). In general, water use decreases during the wetter winter season. There are fewer residences in the Portuguese Bend area than Altamira Canyon resulting in lower overall consumption rates in Portuguese Bend.

Output Variables

Surface Runoff to Ocean

Initial estimates of the rainfall-runoff relationship in the Altamira Canyon drainage basin were calculated using the rational method. This equation is used to predict peak runoff rates from data on rainfall intensity by employing the following equation:

$$Q_p = 0.278\ CIA$$

where Q_p = peak runoff rate (m^3/sec), C = fraction of runoff, I = average rainfall intensity (mm/hr), and A = the size of the drainage basin (km^2). The coefficient C is based on land use. Less than ¼ of the Altamira Canyon drainage basin is developed as single-family residences (Figure 3). With the exception of the developed area at the crest of the basin, most homes are widely-spaced with minimal asphalt coverage. For these calculations, a coefficient (C) of 0.2 was used, based on land use of unimproved property (America Society of Civil Engineers, 1970). Using the average rainfall intensity (I) from the 3 February 1998 storm (~ 4 mm/hr), and a basin area (A) of 3.3 km^2, the peak runoff rate for the basin during this 11-hour storm event was predicted to be ~ 1.1 m^3/sec (39 cfs).

In order to assess the role that surface runoff plays in the overall basin surface water budget, rainfall and runoff measurements were collected during a storm event on 3 February 1998. Total runoff-producing rainfall at station BD during the storm event measured 44 mm (~ 1.7 in.). This storm amount represented ~ 33% of total rainfall at the station for the week of 2/2 through 2/8. Total basin EUD for the same week was

~ 203 mm (~ 8 in.). Assuming that the storm also represented ~ 33% of the total weekly basin EUD, it is estimated that ~ 67 mm (~ 2.6 in.) of rain fell on the overall basin during this storm. With a basin area of 3.3 km^2 (816 acres), the volume of rain falling on the basin during the 3 February storm was ~ 2.2 x 10^5 m^3 (~ 179 acre-ft).

Runoff samples were collected from the middle of the runoff stream approximately 3 to 6 inches below the surface. A General Oceanics Inc. flowmeter was lowered into the water for a 10-second interval and a meter reading was taken at the beginning and end of each interval. Three readings were taken for each sampling and averaged to obtain the final measurement. During low stages of stream flow, three float measurements were taken over a given distance and averaged to obtain a velocity measurement.

The measurements were taken at two locations along Altamira Canyon: 1) the Sweetbay culvert, located upgradient of the upper edge of the Abalone Cove landslide and; 2) the Narcissa culvert, located within the Abalone Cove landslide (Figure 7). The culverts are large 10-foot-diameter pipes which direct water flowing down Altamira Canyon beneath surface streets crossing over the canyon. The Sweetbay location was selected to measure runoff along the canyon prior to entering the Abalone Cove landslide area while the Narcissa location allowed for measurement of runoff prior to leaving the landslide area.

Rainfall in the storm started at approximately 5:30 AM. The greatest amount of discharge was measured at the Sweetbay location and was manifested as two separate pulses of water movement. This separation of water masses corresponded to a short

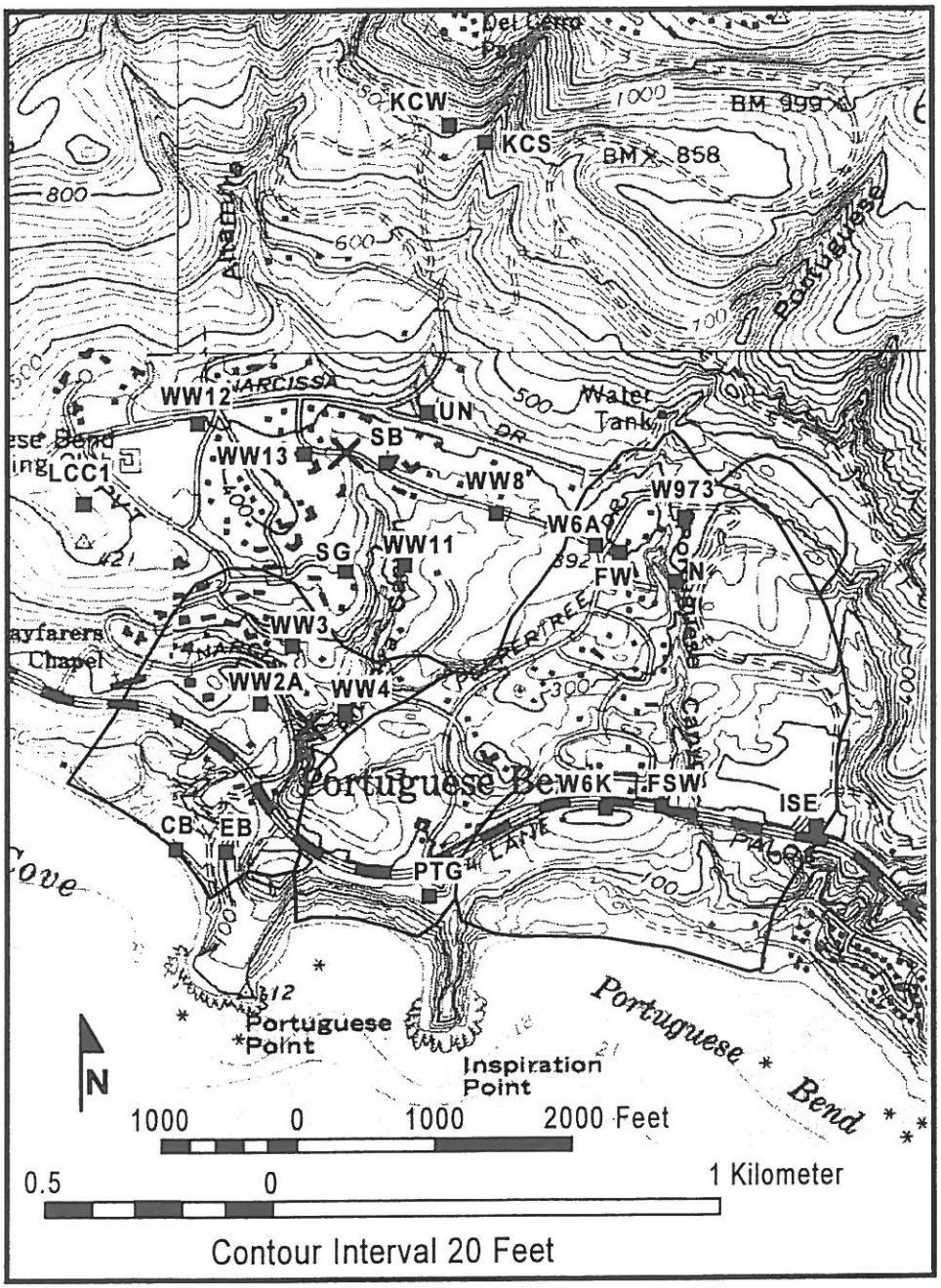


Figure 7. Groundwater and storm runoff sample locations.
■ = groundwater samples; ✕ = storm runoff samples

break in rainfall intensity and demonstrates the rapid response of runoff to precipitation in this small basin. Discharge at the Narcissa location also exhibits two corresponding pulses but had less volume overall than the Sweetbay location.

Discharge rate was calculated from velocity measurements by multiplying the flow velocity by the stream channel cross-section (Table 5) and the average results over the length of the storm ranged from ~ 1.1 m^3/sec (39cfs) at Sweetbay station to ~ 0.3 m^3/sec (9 cfs) at Narcissa station. By plotting the discharge measurements versus time (Figure 8) and calculating the area under the curve, the total volume of discharge at each runoff location during the storm was calculated. Total runoff at the Sweetbay station was calculated at ~ 42,062 m^3 (34 acre-ft) while runoff at the Narcissa location measured ~ 13,305 m^3 (11 acre-ft).

Values of runoff discharge at Sweetbay during the storm equal the discharge predicted by the rational equation. The total volume of runoff at this location (42,062 m^3) represents ~ 19% of the total event rainfall, again closely approximating the 20% runoff expected on unimproved property. The total storm runoff for the lower Narcissa culvert portion (~ 13,305 m^3) constitutes only 6% of total event rainfall (2.2 x 10^5 m^3 or 179 acre-ft) and represents the volume of water leaving the surface drainage area through the canyon during the storm event. Discharge measurements of 0.3 m^3/sec at this location represents ~ 27% of predicted discharge (1.1 m^3/sec). These lower-than-predicted values suggest a loss of runoff water between the upper (Sweetbay) and lower (Narcissa) canyon stations. Because the Narcissa station is located within a more developed area where runoff is expected to increase as a result of surface improvements,

TABLE 5. RUNOFF DISCHARGE DATA FROM ALTAMIRA CANYON DURING 3 FEBRUARY 1998 STORM EVENT

Sweetbay		
Time	Discharge (cfs)	Discharge (m^3/sec)
5:30	0	0.0
7:00	7	0.2
7:40	87	2.5
9:30	42	1.2
11:05	6	0.2
12:25	1	0.0
13:55	147	4.1
14:40	40	1.1
16:20	1	0.0
18:30	0	0.0

Narcissa		
Time	Discharge (cfs)	Discharge (m^3/sec)
5:30	0	0.0
6:45	2	0.1
8:20	20	0.6
10:10	11	0.3
11:40	1	0.0
13:30	34	1.0
15:30	4	0.1
17:40	0	0.0

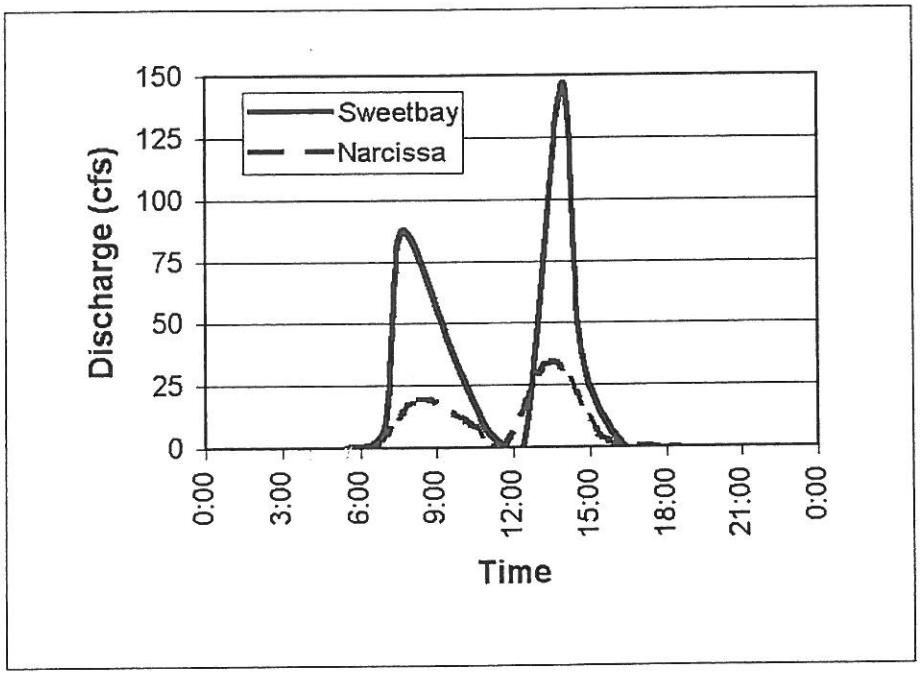


Figure 8. Graph of discharge from 3 February 1998 storm event. Although runoff is similar in both portions of the basin, total volume is less in the lower Narcissa portion indicating possible loss to the subsurface through canyon fractures.

the loss may be even greater than suggested. This apparent loss of runoff water within the canyon is discussed further in the next section.

In order to assess the total amount of storm runoff over the year-long study period, it was assumed that similar percentages of runoff from each event exited the drainage basin. In reality, the actual percentage of runoff would be expected to vary and would depend on such factors as duration of rainfall intensity and the saturation conditions of the soil during each event. Not every rainfall event, however, produced runoff down the canyon. Review of field notes indicated that runoff was most likely to occur during single storm events with greater than 20 mm (~ 0.8 in.) of total rainfall. Thirteen separate events met this criterion and the EUD was calculated for each storm. The total storm rainfall amount for the 13 events was calculated to be 14.2×10^5 m^3 (~ 1,151 acre-ft); assuming 6% of this total event rainfall left as surface flow (as occurred during the 3 February event) indicates 0.9×10^5 m^3 (~ 73 acre-ft) of total surface runoff to the Pacific Ocean over the 1997-98 study period.

Loss to Subsurface Within the Canyon

Total runoff for the 3 February 1998 storm at the two locations measured 42,062 m^3 (~ 34 acre-ft) in the upper portion of Altamira Canyon and 13,305 m^3 (~ 11 acre-ft) in the lower portion. Since the canyon is continuously connected, the discharge would be expected to be greater at the lower portion than at the upper portion. There is instead an apparent loss of water (~ 28,757 m^3 or 23 acre-ft) within the canyon between the two sample locations. Because the lower sample location also receives

diverted surface street drainage from other areas of the basin during the storm, the above estimate actually represents a minimum amount of loss.

Altamira Canyon crosses the head of the Abalone Cove landslide about 350 meters north of Palos Verdes Drive South. There is a significant drop of ~ 1.2 meters (~ 4 feet) in the floor of the canyon at this location and, during storm runoff, ponded water temporarily builds up before it continues down the canyon. The fracture zone at this location would provide a direct route for the surface drainage water to enter the subsurface, resulting in the indicated loss of water (~ 13% of the storm event rainfall).

Assuming a similar canyon response during each qualifying storm, it was estimated that 1.8×10^5 m^3 (~ 146 acre-ft) entered the subsurface through fractures in the canyon over the entire 1997-98 study period.

Evapotranspiration

Evapotranspiration is the transfer of moisture from the ground to the atmosphere, primarily through evaporation of soil moisture and transpiration from plants. Estimates of evapotranspiration were calculated using several methods. The climate of the study area is classified as Mediterranean, with typical average annual precipitation of 38 to 64 cm (~ 15 to 25 in.). The summer months are typically dry, producing semi-arid conditions. The methods of Thornwaite (1957) and Muller and Oberlander (1978) are widely used but are most appropriate in humid climates. They are presented in Table 6 below for reference but are not considered appropriate for application to the study area. The methods of Turc (1955) and Thornwaite (1948) can be applied to semi-arid and arid regions and are therefore more applicable to the study area. Both methods require the use

of temperature and precipitation values as input. The temperature values were obtained from the County of Los Angeles stations (1216, 1011B, and SF) which are located near the study area (Figure 3). The precipitation values were measured during this study and obtained from the three County of Los Angeles stations. The Turc (1955) and Thornwaite (1948) estimates are also listed in Table 6 and range from ~ 509 mm to ~ 548 mm (~ 20 to 22 in.) for the 1997-98 study year. The total volume of rainfall leaving the surface basin as evapotranspiration is estimated to range from ~ 16.8 x 10^5 m^3 to ~ 18.1 x 10^5 m^3 (1,313 to 1,467 acre-ft), approximately equal to 81 to 85% of total rainfall. This amount is added to the assumed evapotranspiration amount from irrigation water (0.5 x 10^5 m^3 or 39 acre-ft) to arrive at total evapotranspiration from the surface area for the study year.

TABLE 6. EVAPOTRANSPIRATION ESTIMATES FOR ALTAMIRA CANYON (1997-98).

Method	Application	Est. Evapotrans. (mm)	Total Volume (10^5 m^3)*
Turc (1955)	humid-arid climates	548	18.1
Thornwaite (1948)	arid regions of U.S.	509	16.8
Thornwaite (1957)	any area**	266	8.8
Muller et al (1978)	any area**	258	8.5

* The above estimates do not include an additional 0.5 x 10^5 m^3 of domestic irrigation water postulated to evapotranspire during the study year.
**Equations are used for all climatic conditions, but are most applicable in humid climates.

The remaining (~ 0.1 x 10^5 to 1.4 x 10^5 m^3 or 8 to 113 acre-ft) of rainfall during the study period is assumed to have entered the subsurface through infiltration or scattered surface fissures. Table 7 summarizes the annual surface water budget components and their percent contribution.

TABLE 7. SURFACE WATER BUDGET FOR ALTAMIRA CANYON (1997-98).

Surface Budget Component	Volume (10^5 m^3)	Volume (acre-ft)	% Contribution
Input – Rainfall	20.9	1694	~ 98
Landscape irrigation	0.5	41	~ 2
Total Input	**21.4**	**1735**	**100**
Output – Surface runoff	0.9	73	~ 4
Total evapotranspiration	17.3 – 18.6	1403 - 1508	~ 81 – 86
GW recharge through canyon	1.8	146	~ 9
Infiltration/fissures to subsurface	0.1 – 1.4	8 – 113	~ 1 – 6
Total Output	**21.4**	**1735**	**100**

B. ALTAMIRA CANYON BASIN – SUBSURFACE WATER BUDGET

Input Variables

Precipitation Recharge and Infiltration

As stated above, an estimated volume of 1.8×10^5 m^3 (~ 146 acre-ft) of water entered the subsurface of the Altamira Canyon basin during the study period via canyon recharge and ~ 0.1×10^5 to 1.4×10^5 m^3 (~ 8 to 113) of precipitation infiltrated during the same period. This total amount of recharge (1.9×10^5 to 3.2×10^5 m^3 or 154 to 259 acre-ft) from precipitation to the groundwater system represents ~ 9 to 15 % of total rainfall over the basin for the 1997-98 study period.

Domestic water

Residences and commercial properties in the Altamira Canyon drainage basin are serviced by septic systems. As discussed earlier, it is estimated that the base level of 1997-98 internal household consumption for the entire study area totaled 50,352 m^3 (~ 41 acre-ft). This represents the amount of domestic water directly recharging the groundwater body through septic system percolation.

Output Variables

Pumping of Groundwater

Fourteen wells are currently in operation to remove groundwater from the subsurface in the Altamira Canyon basin (Figure 7). Although wells EB and CB are located within the Abalone Cove landslide, they are outside the limits of the Altamira Canyon basin and are not included in the calculation of the subsurface budget. Most wells are evacuated using pumps which run when a preset, well-specific level of water is reached and therefore are not in constant operation. Pump readings are made regularly and are tabulated on a monthly basis. Well production data for the study period are presented in Table 8. Pumping from wells in the Altamira Canyon basin removed a total of 3.6×10^5 m^3 (~ 289 acre-ft) of water from the subsurface during the study period.

Subsurface Outflow

Groundwater flow is typically toward the ocean and it is assumed that the groundwater basin geometry is closely coincident with the surface drainage basin. In this geometry, groundwater could exit the study area through a fairly narrow (~ 83 meter or 270 feet wide) area at the lower basin boundary with the ocean. Using Darcy's law:

$$Q = Av,$$

where: $A = L \times b$ and $v = -K(\Delta h/\Delta x)$, with Q = flow ($m^3$/day), L = distance across the boundary in meters, b = the saturated aquifer thickness in meters, K = hydraulic conductivity (m/day), and $\Delta h/\Delta x$ = average hydraulic gradient (m/m), the estimated discharge of groundwater flow from the study area across the lower boundary can be calculated. The bottom of the saturated zone is typically associated with the bottom of

TABLE 8. DEWATERING WELL PRODUCTION IN THE ALTAMIRA CANYON BASIN (1997-98).

Well	8/25-9/24	9/24-10/16	10/16-11/14	11/14-12/13	12/30-1/26	1/26-2/24	2/24-3/30	3/30-4/27	4/27-5/18	5/18-6/25	6/25-7/15	7/15-8/11	Study period
WW-1	8,172	7,995	7,583	6,603	3141*	17,676	12,128	11,717	12,246	14,010	17,218	19,780	12,284
WW-2	8,778	7,717	5,735	7,317	5,631	4,480	5,393	2,291	4,727	3,585	2,778	1,377	4,984
WW-3	6,886	6,457	6,426	5,801	4,437	9,139	301*	6,387	5,619	5,032	4,853	5,185	6,020
WW-4	6,410	316*	6,456	4,197	4,392	9,797	12,197	5456*	9,703	5,586	2,604	2,562	6,390
WW-6	3,134	2,904	2,652	1,109	772	1,540	0*	0*	9,707	6,648	7,131	8,546	4,414
WW-7	2,834	2,837	2,746	2,833	2,697	2,846	3,142	3,228	3,379	3,361	3,410	3,319	3,053
WW-8	2,417	2,132	1,859	1,924	1,374	1,407	1,285	1,542	1,671	2,053	2,825	3,637	2,011
WW-11	15,487	15,409	20,719	14,106	9,096	11,082	19,864	20,572	22,702	23,569	24,360	25,540	18,542
WW-12	21,618	20,073	19,298	17,612	16,304	16,493	18,520	22,127	25,787	25,024	27,154	26,044	21,338
WW-13	95,023	103,477	95,641	92,821	87,873	83,669	87,047	92,093	99,110	81,034	78,145	95,385	90,943
LCC1	17,600	16,491	15,128	14,055	12,552	12,259	12,547	13,439	14,995	17,297	18,965	18,907	15,353
UN	38,617	46,818	60,228	61,259	61,074	60,462	33,159	44,961	40,929	39,695	39,230	38,874	47,109
SB	35,143	35,673	31,928	30,866	37,056	43,714	58,982	50,646	46,495	47,142	44,930	44,000	42,215
Thyme (SG)	11,677	11,687	10,901	11,279	11,695	13,798	14,471	13,005	13,762	11,501	6,605	5,760	11,345
Total/period	8.2×10^6	6.2×10^6	8.3×10^6	7.9×10^6	6.9×10^6	8.4×10^6	9.5×10^6	7.9×10^6	6.5×10^6	11×10^6	5.6×10^6	8.1×10^6	

* pump temporarily out of order part or all of period

Well production data for each sample period given in average gallons per day.

Total (gallons)	**9.4×10^7**
Total (m^3)	**356,664**

all wells — 286,000 gal/day

the landslide (Ehlig, 1979) resulting in a saturated thickness at the boundary of ~ 12 meters (40 feet). Based on nature of subsurface materials and previous studies (Proffer, 1992) the estimated hydraulic conductivity of the Altamira Canyon subsurface basin is 0.08 to 0.12 m/day (2 to 3 gpd/ft^2). Based on groundwater flow maps (Ehlig, 1992), the average hydraulic gradient at the boundary is 0.08. The resulting calculation yielded an estimated range of subsurface outflow from the area of 2,387 to 3,581 m^3/year (~ 1 to 3 acre-ft/year). This estimate is based on the assumption that there is sufficient hydraulic head to promote outflow. The pumping of groundwater from upgradient wells would likely decrease the hydraulic head within the groundwater body, therefore the above outflow amount represents a maximum range of flow across the lower boundary.

Flow Along the Abalone Cove Head Graben

During most times of the year, a component of water flows from the Altamira Canyon basin toward the Portuguese Bend basin via the head graben of the Abalone Cove landslide. This flow of water is estimated at ~20,000 gallons/day (~ 76 m^3/day) and could reverse during times of heavy rainfall (P.L. Ehlig, personal communication, August 1999). For this annual calculation it was assumed that flow continued in the direction away from the Altamira Canyon basin and totaled 27,740 m^3 (~ 23 acre-ft) for the study year.

The annual subsurface budget of the Altamira Canyon basin is illustrated in Figure 9 and summarized in Table 9.

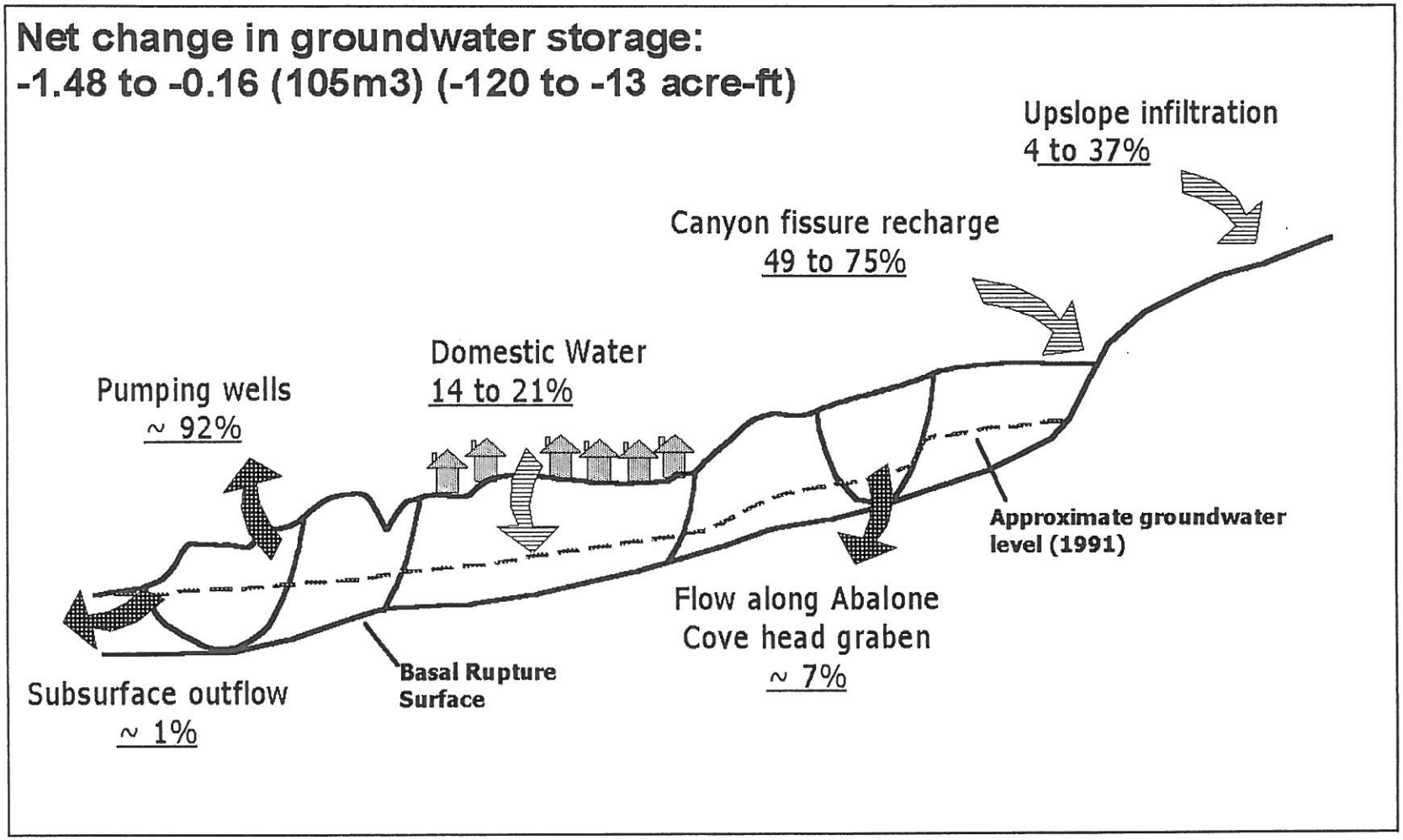


Figure 9. Altamira Canyon groundwater budget for 1997-98. Striped arrows show percent input to groundwater body and shaded arrows show percent output. Pumping and infiltration are distributed across the canyon and not localized (as indicated). Percentages represent percent contribution of each component to their particular category of input or output.

TABLE 9. GROUNDWATER BUDGET FOR ALTAMIRA CANYON (1997-98).

Subsurface Budget Component	Volume (10^5 m^3)	Volume (acre-ft)	% Contribution*
Input – Canyon recharge	1.8	146	~ 49 – 75
Upslope infiltration	0.1 – 1.4	8 – 113	~ 4 – 37
Domestic water	0.5	41	~ 14 – 21
Total Input	**2.4 – 3.7**	**195 – 300**	
Output – Pumping from wells	3.6	289	~ 92
Subsurface outflow	0.02 – 0.04	1 – 3	~ 1
Flow along the head graben	0.3	23	~ 7
Total Output	**3.86 – 3.88**	**313 – 315**	
Predicted change in groundwater storage:	***-1.48 to -0.16***	***-120 to -13***	

* % Contribution indicates the percentage of a particular component within each input or output category (ex. "pumping from wells" component constitutes ~ 92% of total output).

PORTUGUESE BEND BASIN – SURFACE WATER BUDGET

Input Variables

Rainfall

Total rainfall for the study year in the Portuguese Bend drainage area was calculated in the same manner as that of Altamira Canyon and totaled ~ 14.8 x 10^5 m^3 (1,200 acre-ft).

Landscape Irrigation

Total reported water consumption in the Portuguese Bend area for the 1997-98 study period was 18,408 m^3 (~ 15 acre-ft). Water consumption in the Portuguese Bend basin for the month of February totaled 756 m^3 (0.61 acre-ft). By applying the same assumptions discussed for Altamira Canyon, the study-period-amount of household consumption would total 9,072 m^3 (~ 7 acre-ft) leaving 9,336 m^3 (~ 8 acre-ft) for irrigation and subsequent evapotranspiration.

Output variables

Surface Outflow

The surface water budget calculation for the Portuguese Bend basin is less straightforward. Prior to landslide activity, three primary canyons drained water from the upper hillside areas, through the current landslide area to the ocean. Landslide activity has significantly modified this drainage pattern and currently no canyon completely traverses the area. Any surface drainage is conducted from the area by half-open, steel corrugated pipes on the ground surface. It was therefore not possible to conduct runoff measurements such as those obtained in Altamira Canyon. For the purposes of these calculations, it was assumed that the percentage of total rainfall leaving the Portuguese Bend basin was similar to that measured in the Altamira Canyon basin (~ 5%). For the study year, this would total ~ 0.7×10^5 m^3 (57 acre-ft).

Evapotranspiration

Evapotranspiration calculations for the Portuguese Bend basin were conducted in the same manner as those for the Altamira Canyon basin. The areal extent of the basin is ~ 2.5 km^2 (618 acres) and the estimated amount of water lost to evapotranspiration from this area over the study period ranges from ~ 13.1×10^5 to 13.4×10^5 m^3 (1,062 to 1,086 acre-ft). Including the amount of irrigation water lost to evapotranspiration, the total volume of water leaving the surface basin as evapotranspiration is estimated to range from ~ 13.2×10^5 m^3 to 13.5×10^5 m^3 (1,070 to 1,094 acre-ft).

Loss to Subsurface

Landslide activity has created many surface fissures which could allow runoff to move very quickly into the subsurface. Because surface drainage is so disrupted, much of the water remaining at the surface accumulates in depressions where it remains until it evaporates or infiltrates into the ground. In order to balance the surface water budget, it is estimated that ~ 0.7 x 10^5 to 1.0 x 10^5 m^3 (57 to 81 acre-ft) of rainfall entered the subsurface of the Portuguese Bend basin during the study year. The annual surface water budget is summarized in Table 10.

TABLE 10. SURFACE WATER BUDGET FOR PORTUGUESE BEND (1997-98).

Surface Budget Component	Volume (10^5 m^3)	Volume (acre-ft)	% Contribution
Input – Rainfall	14.8	1200	~ 99
Landscape irrigation	0.1	8	~ 1
Total Input	**14.9**	**1208**	**100**
Output – Surface runoff	0.7	57	~ 5
Total evapotranspiration	13.2 – 13.5	1070 – 1094	~ 88 – 90
Infiltration/fissures to subsurface	0.7 – 1.0	57 – 81	~ 5 – 7
Total Output	**14.9**	**1208**	**100**

D. PORTUGUESE BEND BASIN – SUBSURFACE WATER BUDGET

Input Variables

Infiltration and Fissure Recharge

As stated above, an estimated ~ 0.7 x 10^5 to 1.0 x 10^5 m^3 (57 to 81 acre-ft) of rainwater falling in the Portuguese Bend drainage basin enters the subsurface via infiltration or down surface fissures. This total amount of recharge from precipitation to the groundwater system represents ~ 5 to 7 % of total rainfall over the basin for the 1997-98 study period.

Domestic Water

Assuming similar household water usage as in the Altamira Canyon basin, it is estimated that a total of 9,072 m^3 (~ 7 acre-ft) of water were contributed to the groundwater system via septic system recharge. This volume constitutes ~ 6 to 8 % of total input to the groundwater system.

Flow Along the Abalone Cove Head Graben

Water is also assumed to be entering the Portuguese Bend groundwater basin via the connection between the two basins at the head graben of the Abalone Cove landslide. The total estimated input is 27,740 m^3 (~ 23 acre-ft).

Output Variables

Pumping of Groundwater

A total of 22 wells are present in the Portuguese Bend for potential removal of groundwater (Table 11). Removal of water in this basin is more difficult that in the Altamira basin for several reasons. Because of the increased landslide activity in the Portuguese Bend area, subsurface material has been significantly altered both physically and chemically, producing clay-rich material with increased porosity but decreased permeability. This decrease in permeability slows the retrieval of water from the subsurface via pumping wells. In addition, increasingly finer-grained material can pass through the screens in the wells, eventually filling the wells with sediment or clogging the pumps. As a result, groundwater removal is not as productive in this area. Approximately 13 of the wells remained operational throughout the entire study period.

TABLE 11. DEWATERING WELL PRODUCTION IN THE PORTUGUESE BEND BASIN (1997-98).

Well	8/25-9/24	9/24-10/29	10/29-11/21	11/21-12/16	12/16-1/13	1/13-2/5	2/5-3/9	3/9-4/13	4/13-5/11	5/11-6/9	6/9-7/13	7/13-8/6	8/6-8/31	Study Period
W6A	12,284	11,086	9,790	9,196	8,025	8,052	7,777	7,763	8,361	10,471	13,094	14,945	14,728	10,429
W6B	400	391	387	380	375	370	81	31	232	459	401	336	424	328
W6I	39	27	0	0	0	0	0	0	0	0	0	0	0	5
W6J	1,350	639	123	626	688	0	0	0	0	0	-	0	0	286
W6K	987	0	2,709	1,541	1,425	1,360	1,303	1,314	1,226	1,334	1,226	1,241	1,265	1,302
FW	4,394	2,951	2,692	2,198	1,739	1,575	1,468	1,501	1,818	2,268	-	6,782	7,184	3,048
FSW	510	0	409	194	896	756	713	584	449	615	610	582	454	521
INE	0	0	0	0	0	0	0	0	0	-	438	461	470	114
IEC	0	0	0	0	0	0	0	0	0	0	0	-	242	20
ISE	321	253	293	277	300	304	88	15	195	339	327	319	318	258
IW	117	19	38	66	2	1	32	41	68	83	-	256	267	83
N	1,423	1,389	1,343	1,284	1,250	1,230	1,178	757	1,239	1,255	1,238	1,125	1,152	1,220
P	38	0	0	0	0	0	0	0	0	-	2,148	1	292	207
T	776	739	820	904	954	1,047	1,002	963	584	0	1,127	1,648	564	856
W sump	0	0	0	0	0	0	0	0	0	0	0	171	19	15
C sump	385	349	340	329	336	327	368	16	0	646	542	507	468	355
E sump	0	0	0	0	0	0	0	0	0	0	387	329	302	78
PTG	1,861	1,718	1,726	1,476	1,583	2,022	1,782	1,806	2,134	2,253	2,058	912	1,763	1,776
W971&2	580	441	263	256	278	308	337	297	586	547	535	522	512	420
W973	-	-	501	371	1,140	1,019	1,351	937	690	527	477	404	65	680
LT	-	-	-	-	-	-	-	-	-	188	36	25	21	68
W98E & W	-	-	-	-	-	-	-	-	-	-	-	170	80	125
Total/period	7.6×10^5	7.0×10^5	4.9×10^5	4.8×10^5	5.3×10^5	4.2×10^5	5.6×10^5	5.6×10^5	4.9×10^5	6.1×10^5	8.4×10^5	7.4×10^5	7.6×10^5	

Total (gallons)	**8.0×10^6**
Total (m^3)	**30,091**

Well production data for each sample period given in average gallons per day.

These wells, combined with partial operation of other wells, produced a total of 30,091 m^3 (~ 24 acre-ft) of water over the study year.

Subsurface Outflow

Subsurface outflow was conducted using the same method employed above with the following parameters: L = ~ 1,372 meters (4,500 ft); b = ~ 15 meters (50 ft); K = 0.008 to 0.08 m/day (0.03 to 0.26 ft/day); and $\Delta h/\Delta x = 0.15$. The K values were selected to represent subsurface materials ranging in composition from silty to clayey soils (Fetter, 1988). The annual calculated range of subsurface outflow was 9,325 to 93,252 m^3/year (~ 8 to 76 acre-ft/year). Subsurface outflow is dependent on the presence of sufficient hydraulic head to drive the flow. Should a sufficient hydraulic head be absent, the amount of water leaving the area at the lower basin-ocean boundary would be possibly decrease below the above range.

The total estimated subsurface budget of the Portuguese Bend basin over the study period is illustrated in Figure 10 and summarized in Table 12.

TABLE 12. GROUNDWATER BUDGET FOR PORTUGUESE BEND (1997-98).

Subsurface Budget Component	Volume (10^5 m^3)	Volume (acre-ft)	% Contribution*
Input – Recharge/Infiltration	0.7 - 1.0	57 – 81	66 – 73
Domestic water	0.09	7	6 - 8
Flow along the head graben	0.28	23	21 – 26
Total Input	**1.07 - 1.37**	**87 – 111**	
Output – Subsurface outflow	0.09 - 0.93	8 – 76	25 - 76
Pumping from wells	0.3	24	24 – 75
Total Output	**.39 - 1.23**	**32 – 100**	
Predicted change in groundwater storage:	***-0.16 to 0.98***	***-13 to 79***	
Observed change in groundwater storage:	*0.7*	*57*	

* % Contribution indicates the percentage of a particular component within each input or output category (ex. "pumping from wells" component constitutes ~ 24 - 75% of total output).

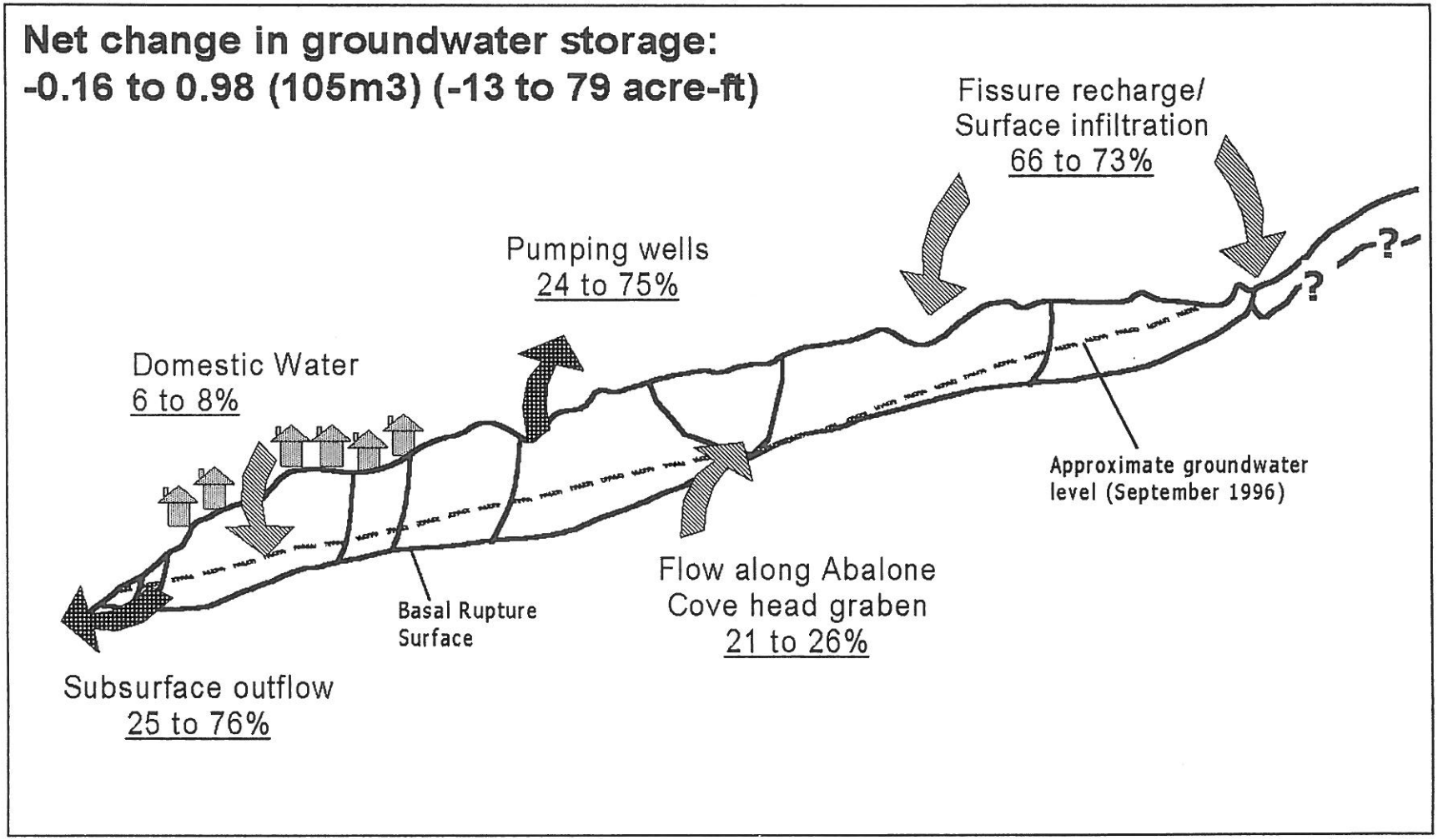


Figure 10. Portuguese Bend groundwater budget for 1997-98. Striped arrows show percent input to groundwater body and shaded arrows show percent output. Pumping and infiltration are distributed across the canyon and not localized (as indicated). Percentages represent percent contribution of each component to their particular category of input or output.

E. GROUNDWATER AND LANDSLIDE RESPONSE TO RAINFALL

Groundwater Levels

Groundwater measurements collected over the 1997-98 study period were obtained from Dr. Perry Ehlig. Depth-to-water measurements were collected by Dr. Ehlig on a monthly basis from groundwater monitoring wells in the study area. Table 13 lists depth-to-water measurements in the Portuguese Bend monitoring wells during a two-year period, including the year-long study period. Monitoring well locations in the Portuguese Bend area are illustrated in Figure 11 and available well construction details are presented in Appendix A. According to Dr. Ehlig, there are three monitoring wells in the Abalone Cove area that are measured regularly but their proximity to pumping wells makes the data less useful in assessing groundwater levels and movement (P.L. Ehlig, personal communication, August 1999). Groundwater elevations in the Portuguese Bend landslide range from ~ 102 meters (335 feet) above mean sea level (asl) in the upper portion of the basin to ~ 27 meters (90 feet) asl near the ocean.

Kelvin Canyon Spring

Discharge measurements from the Kelvin Canyon spring (KCS on upper part of Figure 7) were obtained and provided to me by the City of Rancho Palos Verdes. The measurements of surface runoff were taken at a weir by measuring the time needed to accumulate five gallons of water in a bucket. At least three measurements were taken during each sampling episode and averaged. The measurements obtained during the study period are listed in Table 14 and range from 9 to 33 gallons per minute

TABLE 13. DEPTH-TO-WATER MEASUREMENTS IN THE PORTUGUESE BEND MONITORING WELLS

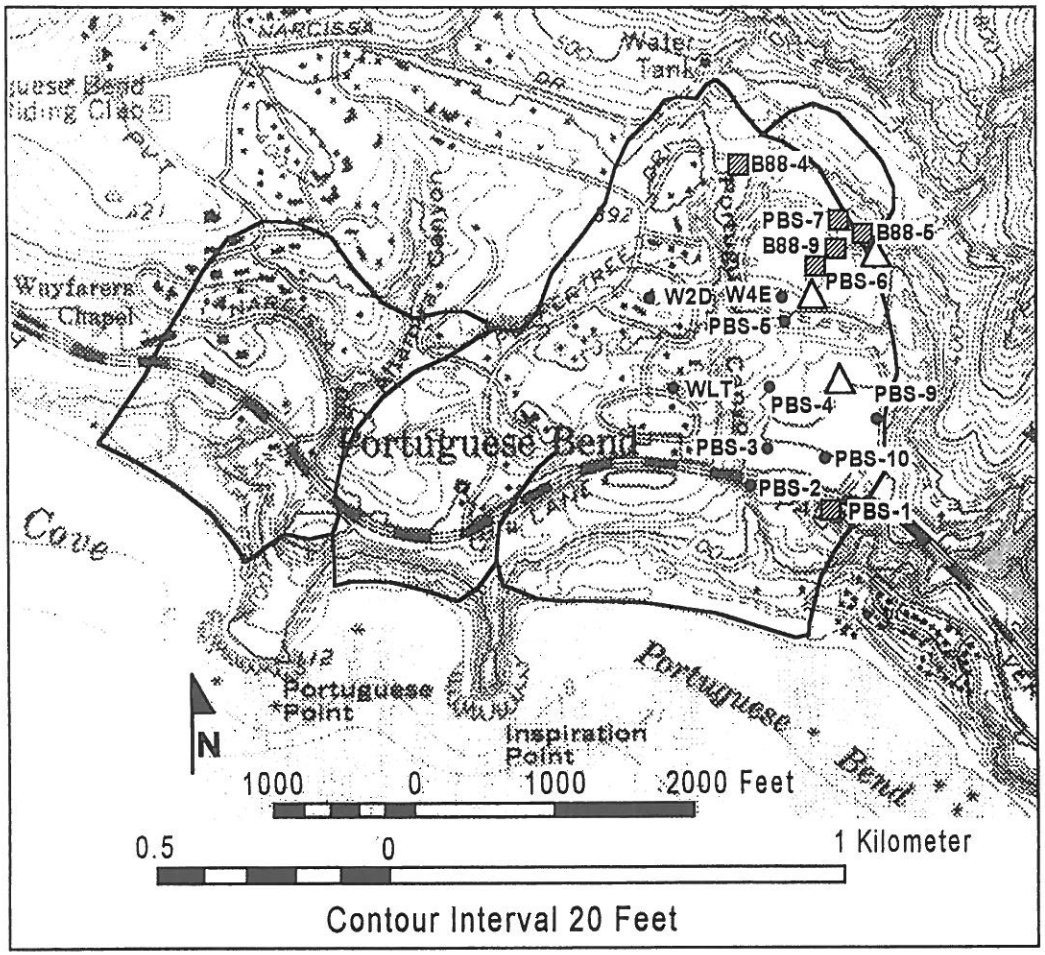
		Month-Year											
Well No.	**Well elev.**	**J-97**	**F-97**	**M-97**	**A-97**	**M-97**	**J-97**	**J-97**	**A-97**	**S-97**	**O-97**	**N-97**	**D-97**
W2D	343	126.77	126.42	126.42	126.67	126.57	126.68	126.71	126.61	**126.49**	**126.84**	**126.61**	**126.79**
W4E	303	52.48	51.92	51.71	51.57	51.16	51.09	51.22	51.59	**51.83**	**52.52**	**52.74**	**52.87**
WLT	281	93.96	93.85	93.74	93.68	93.65	93.74	93.98	94.19	**94.29**	**94.77**	**94.94**	**95.21**
B88-4	343	12.9	11.11	11.88	12.47	13.02	13.07	12.99	12.98	**13.14**	**13.82**	**13.95**	**14.01**
B88-5	299	28.75	29.43	28.43	32.97	30.51	30.2	30.82	30.74	**31.26**	**31.51**	**31.76**	**31.39**
B88-9	304	36.48	35.91	36.12	35.46	34.78	35.47	36.12	36.45	**36.63**	**37.04**	**37.2**	**37.55**
PBS-1	180	73.42	73.17	79.95	81.62	84.21	80.08	83.82	85.23	**85.58**	**86.36**	**86.77**	**87.14**
PBS-2	156	28.19	26.82	26.66	27.71	28.33	29.02	28.34	28.28	**28.72**	-	-	-
PBS-3	216	96.47	95.59	94.93	94.45	94.38	94.06	93.87	93.67	**93.72**	**93.81**	**93.87**	**94.53**
PBS-4	249	77.36	77.23	77.13	77.02	76.45	76.28	76.29	76.21	**75.98**	**76.41**	**76.28**	**76.58**
PBS-5	288	68.48	67.76	60.24	52.93	52.32	52.11	52.39	52.51	**50.69**	**50.53**	**50.52**	**50.66**
PBS-6	310	50.54	48.28	48.29	47.94	47.91	47.92	47.96	48.01	**47.94**	**48.24**	**48.32**	**48.39**
PBS-7	299	10.81	2.22	5.72	7.3	8.72	9.86	10.78	11.88	**12.39**	**13.16**	**13.24**	**13.57**
PBS-9	185	38.25	36.23	37.56	38.47	39.02	39.69	41.78	45.75	**49.17**	**50.64**	**50.96**	**51.34**
PBS-10	170	49.11	48.93	48.86	48.98	48.83	48.83	48.93	48.91	**48.74**	**49.06**	**49.24**	**49.44**

Well No.	**Well elev.**	**J-98**	**F-98**	**M-98**	**A-98**	**M-98**	**J-98**	**J-98**	**A-98**	**A-98**	**S-98**	**O-98**	**N-98**	**D-98**
W2D	343	**126.86**	**126.80**	**126.57**	**126.48**	**126.14**	**126.04**	**125.98**	**125.89**	125.68	125.74	125.62	125.67	125.93
W4E	303	**53.36**	**53.65**	**53.32**	**52.83**	**52.55**	**52.54**	**52.79**	**53.33**	53.47	53.94	54.54	54.82	55.59
WLT	281	**95.47**	**95.71**	**95.89**	**96.42**	-	-	-	-	-	-	-	-	-
B88-4	343	**14.04**	**12.96**	**8.76**	**10.78**	**11.56**	**12.18**	**12.87**	**12.76**	12.01	11.77	11.64	11.57	11.57
B88-5	299	**31.47**	-	-	-	**24.92**	**29.22**	**30.52**	**31.43**	31.74	-	-	-	-
B88-9	304	**37.74**	**37.95**	**37.32**	**35.08**	**34.02**	**34.52**	**34.9**	**35.04**	35.02	34.69	35.41	35.82	36.12
PBS-1	180	**87.31**	**87.34**	**85.86**	**86.91**	**79.48**	-	**87.1**	**86.28**	87.29	87.31	88.23	88.64	88.99
PBS-2	156	-	-	-	-	-	-	-	-	-	-	-	-	-
PBS-3	216	**94.73**	**94.76**	**94.56**	**94.65**	**95.03**	**94.98**	**94.78**	**94.74**	94.79	94.83	94.66	94.67	94.76
PBS-4	249	**76.56**	**76.53**	**76.18**	**76.08**	**75.94**	**76.04**	**76.21**	**76.04**	76.06	76.28	76.38	76.69	77.04
PBS-5	288	**51.70**	**53.24**	**52.35**	**54.54**	**53.08**	**58.66**	**60.2**	**60.04**	58.15	55.9	52.28	51.74	51.61
PBS-6	310	**48.49**	**48.44**	**47.45**	**45.86**	**44.92**	**46.18**	**46.81**	**46.91**	46.89	47	47.13	47.27	47.39
PBS-7	299	**13.97**	**14.74**	**7.39**	**6.03**	**9.26**	**7.03**	**8.03**	**8.72**	9.33	9.92	10.53	11.23	11.91
PBS-9	185	**51.76**	**51.89**	**50.12**	**48.94**	**48.67**	**48.21**	**48.09**	**48.08**	47.87	47.89	47.89	48.02	48.24
PBS-10	170	**49.49**	**48.76**	**49.42**	**49.64**	**49.64**	**49.69**	**49.83**	**49.84**	49.66	49.78	49.76	49.97	50.02

Bold entries represent 1997-98 study period.

Wellhead elevations are presented in feet above mean sea level and water level measurements are in feet below mean sea level.

See Figure 6 for well locations.



- Groundwater monitoring well
- Well in which groundwater levels rise within 1-3 months following rainfall.
- Multi-stage, pneumatic piezometer

Figure 11. Monitoring well locations in Portuguese Bend landslide. (See Table 13 for well data.)

(51 to 182 m^3/day). Unfortunately, the weir was non-functional during the months of January and February 1998 so no samples were collected during that time. A graph of the available discharge measurements versus time is shown in Figure 12 with the apparent maximum discharge occurring during the month of April.

Response of Groundwater

The response of groundwater levels to rainfall can be observed by examining hydrographs (plots of groundwater elevation versus time) of the Portuguese Bend monitoring wells (Figure 13). Several of the wells (PBS-3, PBS-10, WLT, PBS-4, and W2D) show no apparent increase in groundwater levels following the wet portion of the 1997-98 study period. Other wells (PBS-9, B88-9, PBS-6, and W4E) show modest and gradual increases of several feet which occur within or immediately-following the three months of peak rainfall in the area. Wells PBS-1, PBS-7, B88-5, and B88-4 show sharper increases of 1.5 to 3 meters (5 to 10 feet) within one to two months following peak rainfall (Figure 13). These four wells are in close proximity to major slide boundaries with PBS-1 located near the southeastern margin and the others near the head scarp (Figure 11). Well PBS-5 shows a trend which cannot be easily correlated with rainfall patterns. However, rises in groundwater levels in this well correspond to periods of time in which nearby sump wells were not actively pumping.

Wells located progressively inward from the boundaries show slower response to rainfall with the innermost wells showing no significant response. It appears then, that despite the presence of smaller fissures in the interior of the landslide area, most of the

TABLE 14. DISCHARGE MEASUREMENTS AT KELVIN CANYON SPRING

Date	Readings (seconds)			Average	gal/sec	gpm	m^3/day
11-Sep-97	27	25	27	26	0.2	11	62
09-Oct-97	26	25	25	25	0.2	12	65
20-Oct-97	23	24	23	23	0.2	13	70
23-Oct-97	27	30	29	29	0.2	10	57
04-Nov-97	28	27	28	28	0.2	11	59
17-Nov-97	35	31	31	32	0.2	9	51
16-Mar-98	13	12	13	13	0.4	24	129
17-Mar-98	14	14	14	14	0.4	21	117
23-Mar-98	9.4	9.7	9.6	10	0.5	31	171
26-Mar-98	9.6	8.3	9	9	0.6	33	182
30-Apr-98	10.5	10.4	10.3	10	0.5	29	157
14-May-98	12.9	12.8	13	13	0.4	23	127
01-Jun-98	12.9	12.5	12.8	13	0.4	24	128
15-Jun-98	12.9	12.3	12.9	13	0.4	24	129
13-Jul-98	15.6	15.3	15.9	16	0.3	19	105
27-Jul-98	14.7	15.4	15	15	0.3	20	109
18-Aug-98	16.3	16.7	17.2	17	0.3	18	98

(measurements taken in 5-gallon bucket)

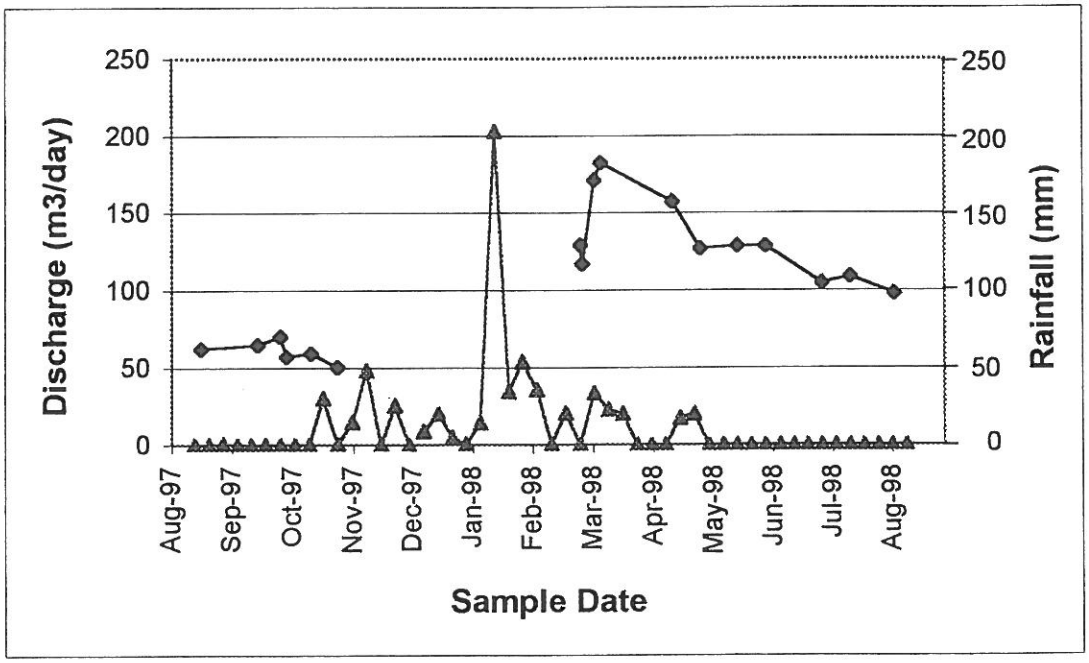


Figure 12. Graph of discharge measurements at Kelvin Canyon spring during the study period. Diamonds = spring discharge; triangles = rainfall. Spring discharge shows a peak ~ 2 months following peak rainfall indicating fairly rapid response of groundwater system to rainfall recharge.

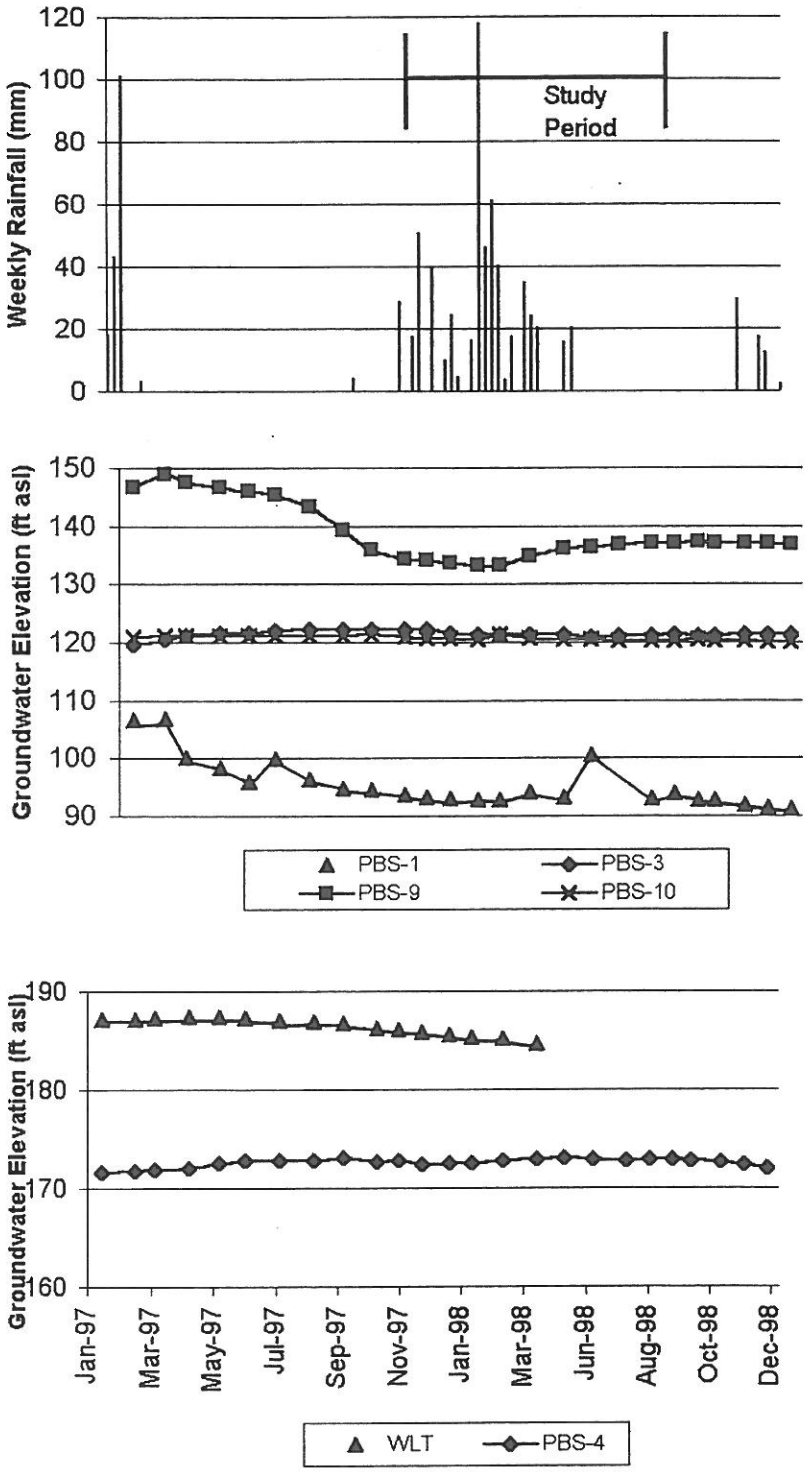


Figure 13. Comparison of groundwater levels in the Portuguese Bend landslide with rainfall measurements collected during the study period. Groundwater elevations in well PBS-1 show a 1 to 2-month delayed response to rainfall.

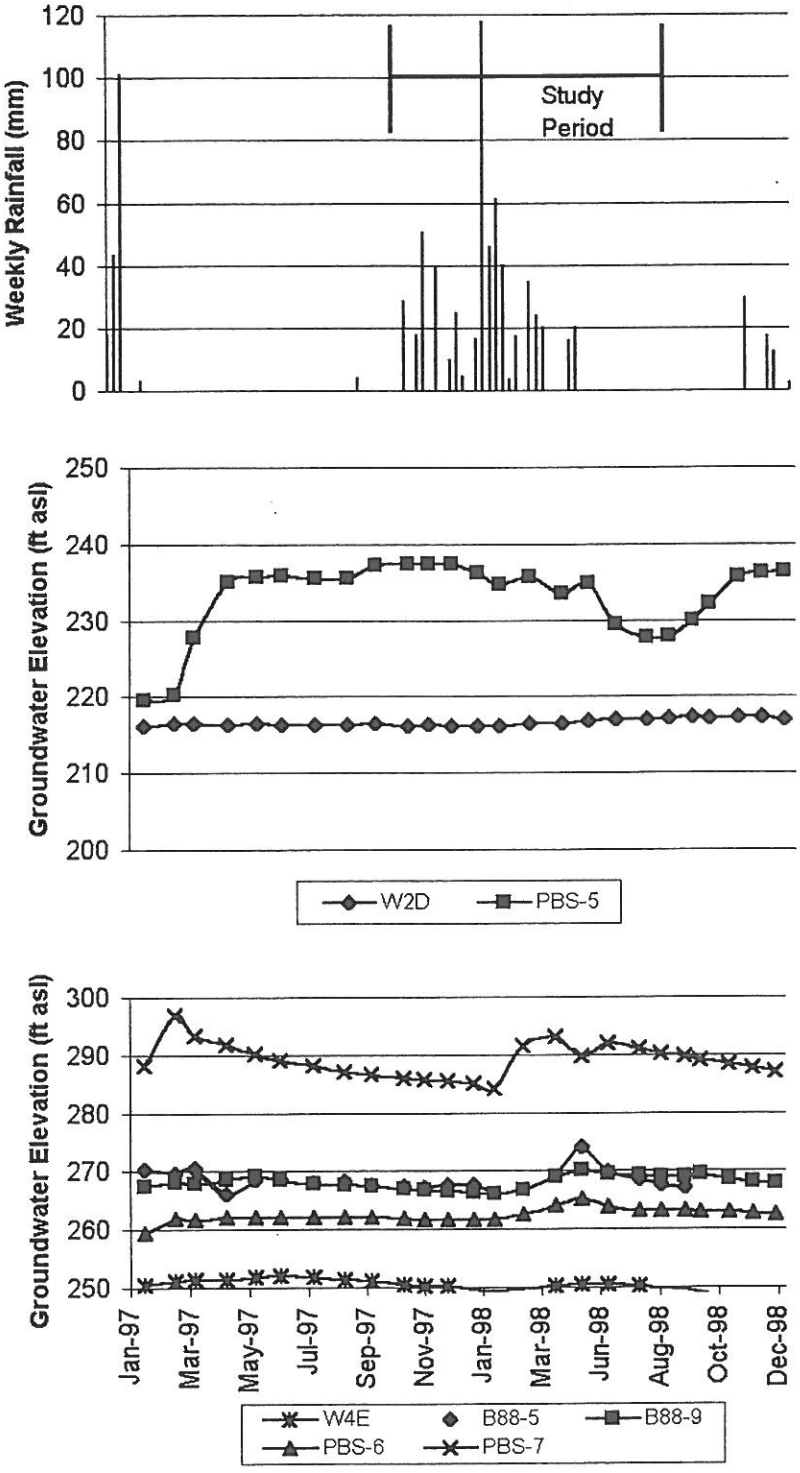


Figure 13 (cont'd). Comparison of groundwater levels in the Portuguese Bend landslide with rainfall measurements collected during the study period. Groundwater levels in wells B88-5, B88-9, PBS-6 and PBS-7 show a delayed response to rainfall.

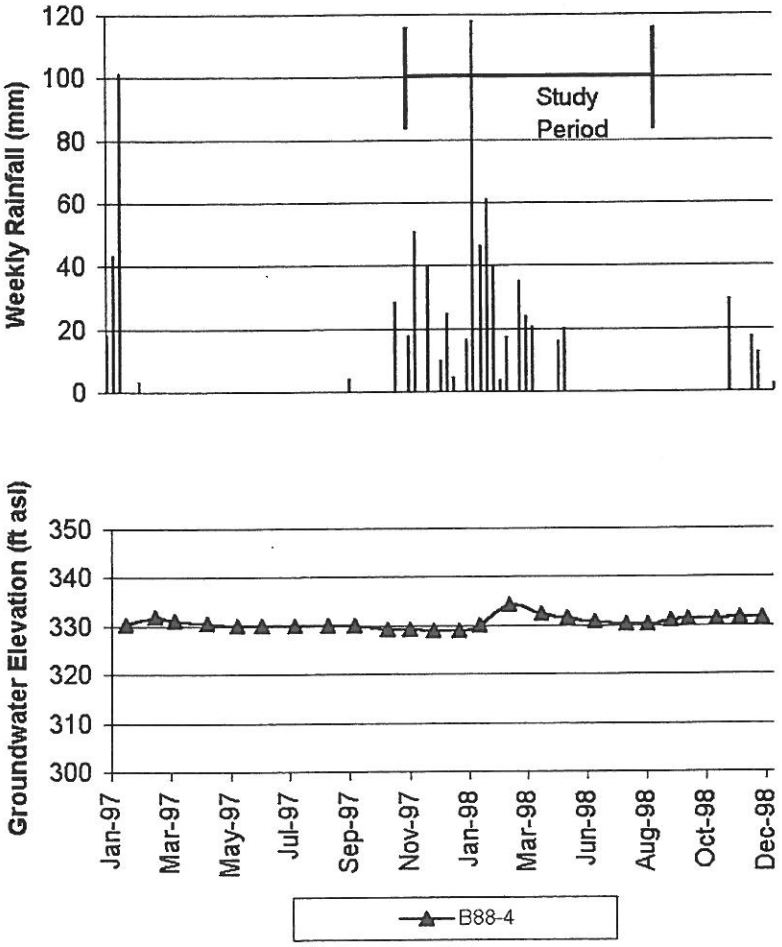


Figure 13 (cont'd). Comparison of groundwater levels in the Portuguese Bend landslide with rainfall measurements collected during the study period. Groundwater levels in well B88-4 show a delayed reponse to rainfall of ~ 1 month.

rapid recharge occurs via the larger, bounding landslide scarps. This phenomenon was also observed by Ehlig and Yen (1997).

Annual Storage for 1997-98

The predicted change in storage in each of the groundwater basins during the 1997-98 study year was estimated in the previously-discussed groundwater budget calculations. These calculations contain uncertainties in the estimation of evapotranspiration, subsurface outflow, and flow along the graben. However, the validity of the predicted change in storage can be evaluated by comparison with actual observed changes in groundwater levels during the same time period. Because functional groundwater monitoring wells are virtually absent in the Altamira Canyon basin, the only available groundwater level measurements are those from Portuguese Bend.

The average groundwater level change throughout the Portuguese Bend basin during the study year was +0.07 m. Assuming a porosity of 0.35 (representative of silty to clayey lithologies) over the basin area of 2.5×10^6 m^2, the observed change in groundwater storage during the study year was a gain of 0.6×10^5 m^3. This value falls within the predicted range of values of -0.16 to 0.98 ($\times 10^5 m^3$) obtained from the groundwater budget calculations. The observation that the predicted storage closely approximates the observed storage suggests that the uncertainty in the selected evapotranspiration and subsurface runoff estimates used in the budget calculations was small.

Long-term Groundwater Budget

A long term budget was calculated by examining input and output values for the water year 1995-96. This year was chosen because annual rainfall in the area was 12.74 inches, closely approximating the long-term average rainfall for the area of 12.9 inches. Based on budget calculations for the 1995-96 year, the Altamira Canyon basin is predicted to experience a loss in storage of ~ -2.4 x 10^5 m^3 (Table 15) and the Portuguese Bend basin is predicted to experience a loss of ~ -0.8 to 0 (x $10^5 m^3$) (Table 16). This range in Portuguese Bend basin compares favorably to the observed storage loss of -0.4 x 10^5 m^3 during 1995-96. Again, lack of monitoring wells in the Altamira Canyon basin prohibits comparison with actual observed groundwater level changes.

TABLE 15. LONG-TERM GROUNDWATER BUDGET FOR ALTAMIRA CANYON BASIN.

Subsurface Budget Component	Volume (10^5 m^3)	Volume (acre-ft)	% Contribution
Input – Recharge/Infiltration	0.4	32	~ 43
Domestic water	0.5	41	~ 57
Total input	**0.9**	**73**	
Output – Subsurface outflow	0.04	3	< 1
Pumping from wells	3	243	~ 91
Flow along head graben	0.3	24	~ 9
Total output	**3.3**	**270**	
Predicted change in storage:	***-2.4 x 10^5***	***-197***	

TABLE 16. LONG-TERM GROUNDWATER BUDGET FOR PORTUGUESE BEND BASIN.

Subsurface Budget Component	Volume (10^5 m^3)	Volume (acre-ft)	% Contribution
Input – Flow along graben	0.3	24	~ 77
Domestic water	0.09	7	~ 23
Total input	**0.4**	**31**	
Output – Subsurface outflow	0.09 – 0.93	7 – 76	< 1
Pumping from wells	0.3	24	~ 91
Total output	**0.4 – 1.2**	**31 – 97**	
Predicted change in storage:	***-0.8 to 0***	***-66 to 0***	
Observed change in storage:	*-0.4*	*-32*	

A significant difference between the long-term budget and the study year (El Nino) budget is the percentage of recharge which comes from domestic water. During the 1997-98 study year, domestic water constituted ~ 14 to 21% of recharge to the Altamira Canyon basin. During an average rainfall year, domestic water makes up ~ 57% of the recharge. The remaining ~ 43% of recharge is provided through canyon fissure recharge during storm runoff and some surface infiltration.

In the Portuguese Bend basin, ~ 6 to 8% of the input to groundwater was contributed by domestic water recharge during the 1997-98 study year. By contrast, ~ 23% of the recharge in an average rainfall year (1995-96) was domestic water. This estimate was based evapotranspiration calculations which indicated little to no recharge via infiltration or fissure flow. The amount of recharge expected via fissures and infiltration is difficult to constrain in the Portuguese Bend area. If significant fissure recharge did occur during an average rainfall year, the domestic water contribution would be less than the predicted 23%.

Response of Landslide Mass

The relations between rainfall, groundwater levels, and landslide movement in the landslide areas have been fairly well documented (Merriam, 1960; Easton, 1973; Ehlig,

1986; Proffer, 1992; Ehlig, 1992). The Abalone Cove landslide exhibits little overall movement, mostly in the form of creep in the upper portion and near the beach. Previous studies have examined recharge by observing the response of groundwater (rise of water levels in wells) to rainfall (Proffer, 1992). Wells in the upper portion of the Altamira Canyon basin typically exhibit a delayed response to rainfall, extending from one to eight months. Some wells within the Abalone Cove landslide area were observed to have rapid responses due to the movement of water down open fissures.

Movement of the Portuguese Bend landslide occurs constantly but increases in the rate of movement have been observed in conjunction with rainfall events. Easton (1973) observed movement of the Portuguese Bend landslide during two storms in November and December, 1970. Each storm produced nearly a doubling of the rate of landslide movement. He also observed that the response of the landslide movement to even small amounts of rainfall (5 to 10 mm) was almost immediate (within a few hours). Figure 14 illustrates the relationship between rainfall occurrence and landslide movement of a survey monument located within the Portuguese Bend landslide (Ehlig, 1992).

This fluctuating response of persistent landslides to rainfall events has been observed in other areas. Baum and Reid (1995) studied a smectite-rich landslide in Hawaii, observing that water movement through the slide mass is limited by the fairly impermeable slide base. In Hawaii, where rainfall occurs frequently, the slide mass remained fairly saturated year round. During periods of rainfall, pore pressures within the landslide increased significantly within one to two days following the onset of rainfall. The result was a diffusive propagation of pore pressure waves through the slide

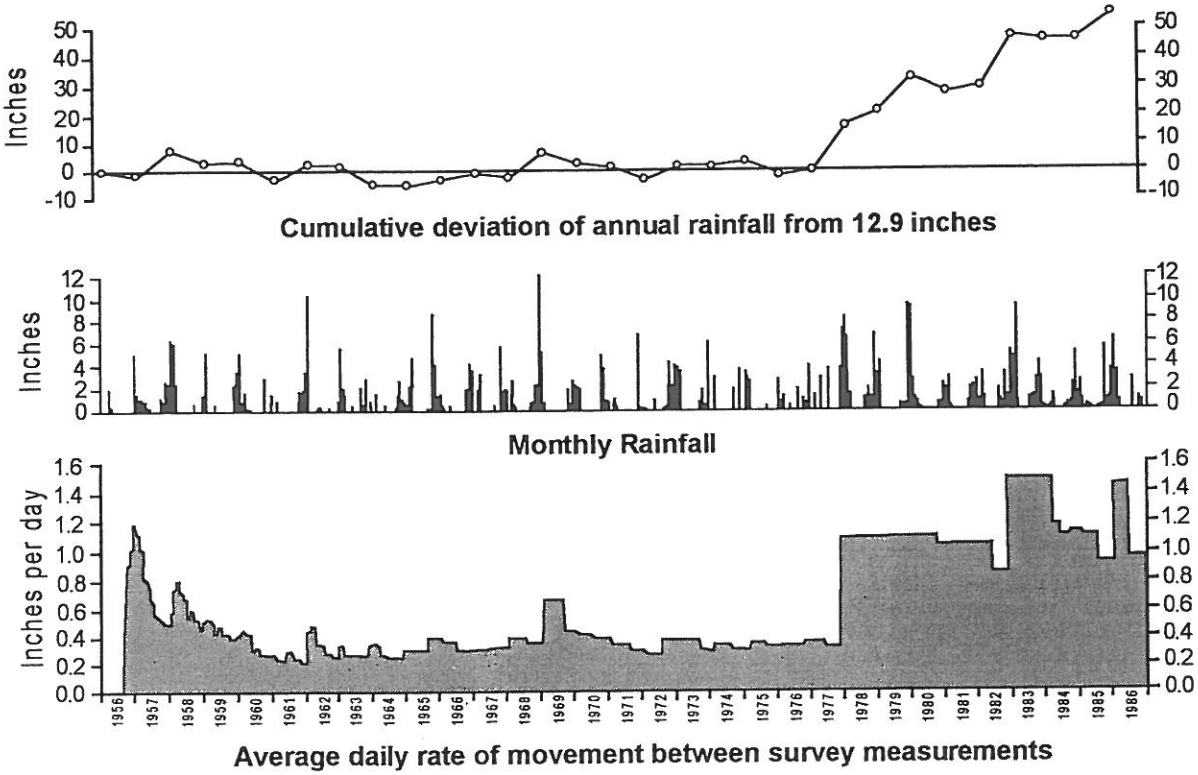


Figure 14. Graph showing relationship of rainfall to movement of the Portuguese Bend landslide between 1956 and 1986 (modified from Ehlig, 1992). Movement of the landslide is closely correlated to increases in rainfall.

mass to the slip surface, triggering landslide movement (Baum and Reid, 1995). Similar findings were reported in a study by Iverson and Major (1987) who observed that single rainstorms produced short-period pore pressure waves that attenuated before reaching the slide base, while seasonal rainfall cycles produced long-period waves that modified pore pressures at the base of the landslide. These pore pressure effects are significant in an already saturated slide mass such as the Portuguese Bend landslide.

The clay-rich nature of the slide mass at Portuguese Bend creates conditions of high porosity but low permeability, allowing for retention of water for long periods of time. The water table within the Portuguese Bend landslide area typically occurs above the slide plane, creating an average of 40 feet (12 m) of saturated material above the slide base (Ehlig and Yen, 1997). Thus internal slide conditions are present for a pore pressure response to winter season rainfall events.

While increased pore pressure seems a likely explanation for movement of the Portuguese Bend landslide, there is a question of potential pressure from beneath the slide base. It has been reported in previous studies that groundwater flow occurs entirely within the slide mass where the Portuguese Tuff serves as a barrier to vertical groundwater movement (Ehlig, 1979). To further investigate the potential for flow across the basal rupture surface, Ehlig and Yen (1997) installed multi-stage pneumatic piezometers in three locations within the landslide area (Figure 11). Two piezometers located in the northern portion of the landslide measured a higher piezometric level above the rupture surface than below, indicating negligible downward flow across the rupture surface. By contrast, the most southerly, downgradient piezometer measured

approximately ten feet of hydraulic head beneath the rupture surface and none above, indicating potential for upward flow of water and/or associated hydraulic pressure on the underside of the rupture surface. These findings were preliminary but significant in assessing the potential driving forces for landslide movement (Ehlig and Yen, 1997). The extent of the upward trend is unclear and further work would be required to constrain its influence.

F. SUMMARY

In general, groundwater in the study area flows from the upper part of the topographic basin to the ocean where it has, in the past, been observed seeping from the toe of the slides during low tides. Since the inception of groundwater pumping, the seepage has not been observed (P.L. Ehlig, personal communication, August 1999).

The two groundwater bodies are essentially independent with the exception of a small subsurface graben connecting the western edge of the Portuguese Bend landslide with the upper margin of the Abalone Cove landslide. Groundwater flow between the Portuguese Bend landslide and the Abalone Cove landslide along this trough has been observed (P.L. Ehlig, personal communication, August 1999).

In both basins, analyses of water budgets indicates the majority of water entering the subsurface comes from rainfall via infiltration or direct recharge through surface fissures. For the study year, only a modest percentage (~ 14–21% in Altamira Canyon and 6–8% in Portuguese Bend) comes from domestic water influx. However, this study year witnessed a rainfall amount (~ 24 inches) that was approximately double the decadal

average of 12.9 inches, and these domestic water influx estimates increase at least two-fold over the long term.

The percentage of recharge contributed by infiltration versus surface fissure flow is difficult to assess. Aside from flow down the head scarp fissure within Altamira Canyon, it is likely that recharge via infiltration in the upslope areas is the more dominant process in the Altamira Canyon basin. The Abalone Cove landslide is smaller in area and its movement has resulted in less disruption of the overall ground surface in the form of fissures. The surface area of the basin is also more developed, resulting in more overland runoff from asphalt and concrete ground coverings. Both of these factors would decrease the amount of water which could rapidly recharge to the subsurface via fissure flow.

The opposite is expected in the Portuguese Bend basin where extensive disruption of ground surface has produced multiple subslides and numerous surface fissures. The opportunity for rapid recharge is greater but the relative contribution of fissure recharge versus upgradient infiltration and inflow is difficult to constrain. Where rapid recharge does occur, it appears to be most prevalent along the larger, bounding landslide scarps.

Based on water budget calculations for the 1997-98 study year, the Altamira Canyon basin groundwater budget appears to experience a net loss in storage ranging from -1.48×10^5 m^3 to -0.16×10^5 m^3 (-120 to -13 acre-ft). Predicted change in storage in the Portuguese Bend basin ranges from -0.16×10^5 m^3 to 0.98×10^5 m^3 (-13 to 79 acre-ft). The range is, in large part, due to the difficulty in constraining the evapotranspiration factor. In addition, subsurface outflow may fluctuate and is difficult

to determine. It appears, by comparison of the predicted storage values with those actually observed, that the uncertainties are rather small.

Groundwater plays a significant role in the persistent, long-term movement of the Portuguese Bend landslide. Although a few wells show a rapid response to rainfall in the area, most wells show a small, delayed or negligible response. Increases in overall landslide movement during high rainfall years could be explained by increases in pore pressure at depth. The potential for upward hydraulic pressure from beneath the slide plane requires further investigation because of its implications for landslide movement, even in areas with no apparent response to rainfall.

CHAPTER III

GEOCHEMISTRY

A. MAJOR ION CHEMISTRY

The objective of the geochemical portion of the research was to employ both geochemical and isotopic techniques to constrain the contributions of various source waters to the overall groundwater body in the study area. In addition, important information was obtained on the sources of groundwater composition and on the approximate residence time of water within the groundwater system. Combined, this information presents a picture of the dynamics of groundwater recharge and movement, allowing consideration of the effects of groundwater on landslide movement.

Rainfall

Two rainwater samples were collected during the 3 February 1998 storm event and analyzed for major ion composition, the results of which are listed in Table B-3 of Appendix B. There is a large difference in the two results, reflecting a rainout effect. A weighted average of these data was obtained by multiplying the data by the percentage of the storm they represent. These weighted values, along with the average data from Kadera (1997), are plotted in Figure 15. K, SO_4, and HCO_3 were below detection limits. Both sets of rainfall data parallel the seawater pattern (diluted ~ 5,000 to 10,000 times), suggesting a strongly marine influence for rainfall in the study area. As a result of this influence, rainfall chemistry is dominated by Na and Cl.

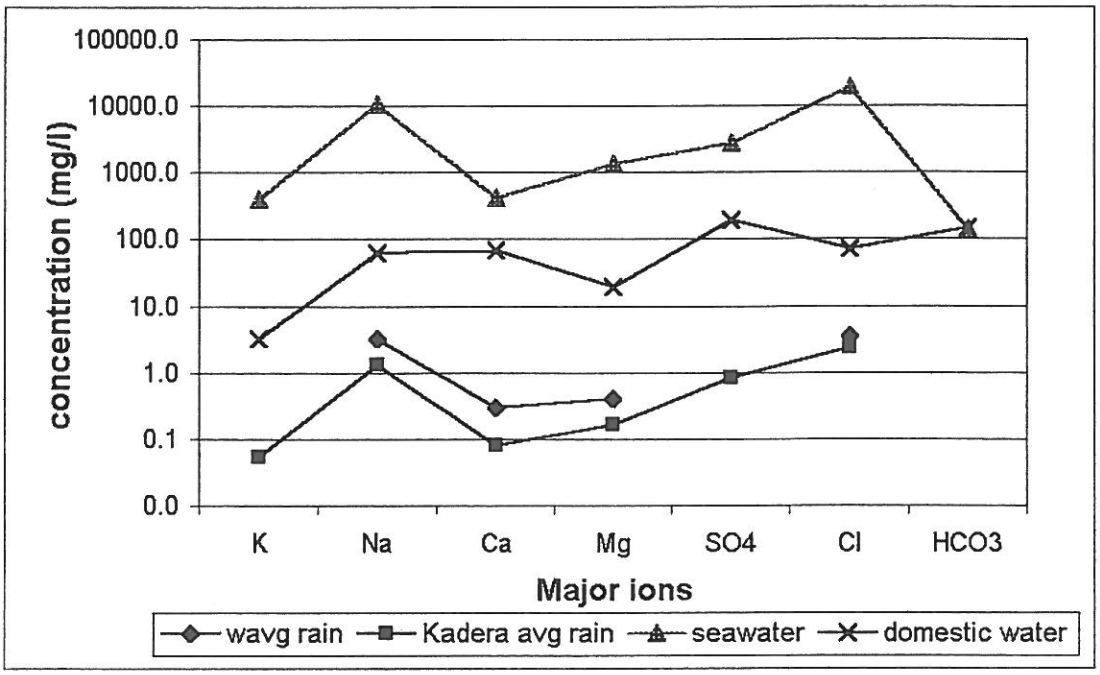


Figure 15. Fingerprint diagram of major ion chemistry of rainfall and domestic water in the study area and seawater. Rainfall composition closely resembles a diluted version of seawater suggesting a marine source for precipitation.

Storm Runoff

Runoff samples were collected from two areas during two separate rainfall events and analyzed for major ion concentrations (see Table B-2). Samples collected during the January 1998 event were relatively small in volume and only one sample from each area had sufficient volume to be analyzed for the major ion concentrations. Samples from the February 1998 storm were collected at intervals throughout the storm. All the runoff samples contain greater concentrations of ions than those reported for rainfall, about three times greater for Na, ten times greater for Mg, and fifty times greater for Ca. These increases in concentration probably reflect interaction with surface material during runoff through the canyon.

Domestic Water

Four water samples were collected over the study period and the results of chemical analyses are provided in Table B-2. According to Mr. David Delsigne, of the California Water Service, domestic water provided to homes in the study area is obtained from the Metropolitan Water District and is composed of an approximate 50-50 mix of water from the Colorado River aqueduct and from the northern California State Water Project. This approximate mix has been maintained over the past eight years.

With the exception of sample DW2-12-1, which has an extraordinarily high Na concentration, all the samples are similar in composition. The Na concentration of DW2-12-1 is nearly seven times the average of the other three samples. The Na measurements on that sample were repeated several times with similar results. However, this sample is so far outside the standard deviation of the sample population, that it was

disregarded for this interpretive analysis. Average domestic water values are plotted on the fingerprint diagram in Figure 15. This plot reveals that the average domestic water chemical composition is significantly different from that of seawater and rainwater.

Groundwater

Major element ion concentrations in groundwater are helpful for distinguishing various water types and potential water-rock interactions. Based on preliminary observations, the groundwater in the study area occurs as two distinguishable bodies underlying the two prominent drainage basins. Limited interaction between the two bodies occurs along the head graben of the Abalone Cove landslide.

Groundwater samples were collected on a monthly basis from 21 pumping wells throughout the study area (Figure 7). All sampled wells were equipped with a faucet near the wellhead. Most wells were continuously pumping and water was allowed to flow from the faucet for approximately 1 to 2 minutes prior to the collection of a sample. If a well was not continuously pumping, it was turned off for a period of time to allow for water to accumulate in the well. The period of time ranged from 5 minutes to several hours depending on the well.

Water samples were also collected on a bi-monthly basis from Kelvin Canyon spring (Figure 7). Spring samples were collected from two areas: the middle of a small surface stream, and from seepage emerging from between sedimentary layers in the side wall of the canyon. While both sets of samples were analyzed, it is assumed that the sidewall samples are the most direct measurement of subsurface water and more indicative of groundwater composition. The isotopic and chemical composition of

surface water can vary as a result of interaction with surface materials and evaporative processes in the atmosphere.

All groundwater samples were collected in a plastic beaker and measurements of temperature and conductivity were taken immediately. Temperature and conductivity measurements were taken for each sample at the time of collection using a portable conductivity meter. Samples to be analyzed for major ions and nitrates were filtered through 0.45 μm syringe filters and placed in a cooler of ice. Upon returning to the lab, samples to be analyzed for cations were acidified with 600 μl of 6N HCl. Nitrate samples were transferred to a freezer at the lab and the remaining water samples were refrigerated.

Average annual values of temperature and conductivity for the wells and the spring were calculated and are presented in Table 17. Temperatures ranged from 21°C at well WW11 and Kelvin Canyon spring to 27°C at well EB. In general, average temperatures in the study area tend to increase downgradient with the highest temperatures occurring near the ocean. The exception to this trend is beach well CB with an average annual temperature of 23°C. Annual average conductivity values range from 3,913 μmhos at well WW11 to 9,433 μmhos at well W6K. Well CB also exhibits a high average conductivity of 9,375 μmhos.

The major cations of calcium, magnesium, sodium, and potassium were analyzed by the author at the University of Southern California (USC) using atomic absorption spectroscopy (AAS). An air/acetylene flame was used to analyze sodium and potassium, while calcium and magnesium were analyzed using a nitrous oxide/acetylene flame. All

TABLE 17. SUMMARY OF AVERAGE CHEMICAL AND PHYSICAL DATA FROM GROUNDWATER SAMPLES

Sample No.	Well elev.[1]	Temp. (°C)	Cond (µmhos)	Ca^{2}	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2[3]	NO_3	TDI[4]	$\delta^{18}O$[5]	^{3}H[6]	elev. of well bottom[1]	elev. of slide base[1]	avg. daily prod.[7]	Comments
KCS	770	21	3420	18	9	20	1	7	36	9	588	0	101	-5.7	1.2	-	osl	-	
LCC1	415	23	4486	26	16	18	1	13	43	7	482	0	125	-6.3	na	267	osl	58	
UN	404	23	4378	22	11	25	0	13	42	9	606	0	123	-5.8	1.8	224	osl	178	
WW13	386	22	4189	22	15	23	0	13	39	8	606	0	121	-6.1	3.2	273	osl	344	
WW12	383	23	4757	22	20	21	1	13	47	7	544	0	131	-6.3	na	257	osl	81	
SG	364	23	4245	23	15	23	0	13	41	9	629	0	124	-6.0	na	164	osl	43	
SB	364	23	4150	23	11	25	0	12	41	9	708	0	121	-5.9	na	184	osl	160	
WW8	350	23	4332	23	11	27	0	16	39	8	540	0	125	-6.0	na	unk	osl	8	
WW11	315	21	3913	20	12	20	0	14	36	8	482	0	111	-6.2	na	199	osl	70	
WW3	279	24	4228	23	14	22	0	11	43	7	537	0	120	-6.0	na	unk	117	23	
WW4	221	22	4398	25	17	25	0	11	47	8	506	0	133	-5.9	1.2	137	140	24	
WW2A	170	26	4302	22	16	21	1	9	44	7	529	0	120	-6.4	na	unk	10	19	
EB	86	27	8192	4	69	20	2	28	62	9	535	0	194	-6.0	<0.8	-59	-20	31	sulfide smell, some seawater influence
CB	64	23	9375	19	38	85	1	33	108	7	369	0	292	-6.1	3.7	-69	< -80	221	some seawater influence
W6A	**386**	**22**	**4689**	**28**	**16**	**23**	**0**	**15**	**45**	**7**	**582**	**0**	134	**-5.7**	**na**	**226**	**unk**	**39**	
N	**377**	**23**	**5124**	**25**	**18**	**26**	**0**	**16**	**50**	**6**	**563**	**1**	143	**-5.9**	**3**	**unk**	**233**	**5**	
FW	**373**	**23**	**5177**	**29**	**17**	**28**	**0**	**20**	**49**	**7**	**594**	**1**	151	**-6.3**	**na**	**261**	**unk**	**12**	
W973	**355**	**23**	**5564**	**27**	**23**	**33**	**1**	**18**	**53**	**11**	**372**	**0**	166	**-5.4**	**na**	**unk**	**unk**	**3**	
PTG	**184**	**25**	**5623**	**21**	**27**	**24**	**1**	**9**	**55**	**7**	**626**	**0**	144	**-6.5**	**na**	**unk**	**unk**	**7**	
W6K	**181**	**25**	**9433**	**27**	**24**	**125**	**0**	**24**	**118**	**3**	**77**	**4**	324	**-6.0**	**8.1**	**71**	**~ 51**	**5**	yellow color, possible animal waste influence
ISE	**179**	**26**	**8400**	**34**	**20**	**53**	**0**	**42**	**49**	**5**	**355**	**16**	219	**-5.7**	**4.6**	**7**	**~ 0**	**1**	possible fertilizer influence
FSW	**167**	**25**	**6010**	**31**	**22**	**27**	**0**	**24**	**51**	**6**	**427**	**2**	164	**-6.6**	**na**	**50**	**~ 60**	**2**	
DW	-	-	-	3	7	2	0	2	4	2	59	0	20	-11.3	6.5	-	-	-	

Average values for domestic water (DW) are also included for comparison. Entries in **bold** are from the Portuguese Bend basin. (unk = unknown value)

Notes:

[1] Wellhead elevations expressed at feet above mean sea level (ft asl).

[2] Major ion concentrations expressed as milliequivalents per liter (meq/l).

[3] SiO_2 concentrations expressed as micromoles per liter (µM/l)

[4] TDI = total dissolved ions in meq/l.

[5] $\delta^{18}O$ concentrations expressed in parts per thousand (‰)

[6] Tritium concentrations expressed as tritium units (TU) where 1 TU = 1 ^{3}H per 10^{18} hydrogen atoms

[7] Average daily well production is expressed in m^3 per day

samples were diluted to within the detection range with a 1,500 ppm cesium ionization suppressant. Chloride analyses were also conducted at USC using coulometric titration. All the above results (except where noted) are within 3% uncertainty. Exceptions are within 10% uncertainty and were typically the result of small sample size or low ion concentration.

Nitrate and SiO_4 were analyzed by the Upper Ocean Process Lab operated by Dr. Burt Jones at USC. The analyses were performed using a continuous-flow analyzer according to the methods described in the 1996 Joint Global Ocean Flux Study, Report 19 (SCOR, 1996). Sulfate and bicarbonate analyses were conducted by M.J. Schiff & Associates, Inc. of Upland, California.

Results of chemical analyses of groundwater samples for major ions are included in Table B-1 in Appendix B. The yearly averages for the major ions are listed in Table 17 and were plotted on a trilinear Piper (1944) diagram (Figures 16 and 17), along with plots of the average concentrations of domestic water and rainwater samples collected during the study period. Average seawater composition (Goldberg et al., 1971) is also plotted on Figures 16 and 17. Comparison of the resulting plot with the classification scheme in Figure 18 reveals that the majority of the groundwater in the study area is dominated primarily by SO_4 but, with the exception of wells EB and CB, contains no dominant cation type. Groundwater in wells EB and CB is dominated by Na and Mg, respectively. Total dissolved ion concentrations range from 3,435 to 9,163 milligrams per liter (mg/l).

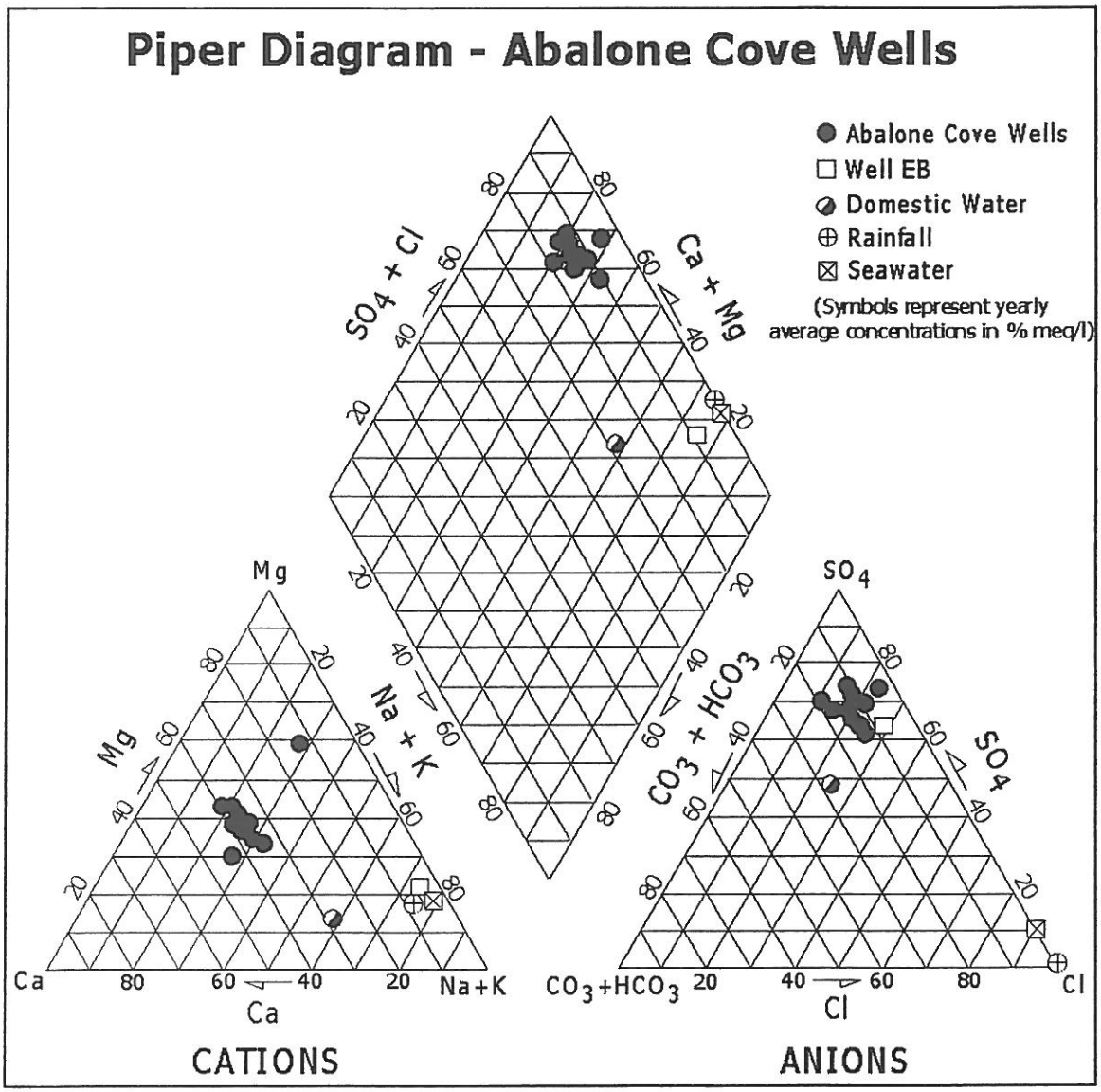


Figure 16. Piper tri-linear diagram for wells located in the Abalone Cove landslide. Groundwater is classified as a sulfide-type and is relatively constant in composition. Well EB is the exception and plots in the vicinity of seawater and rainfall compositions.

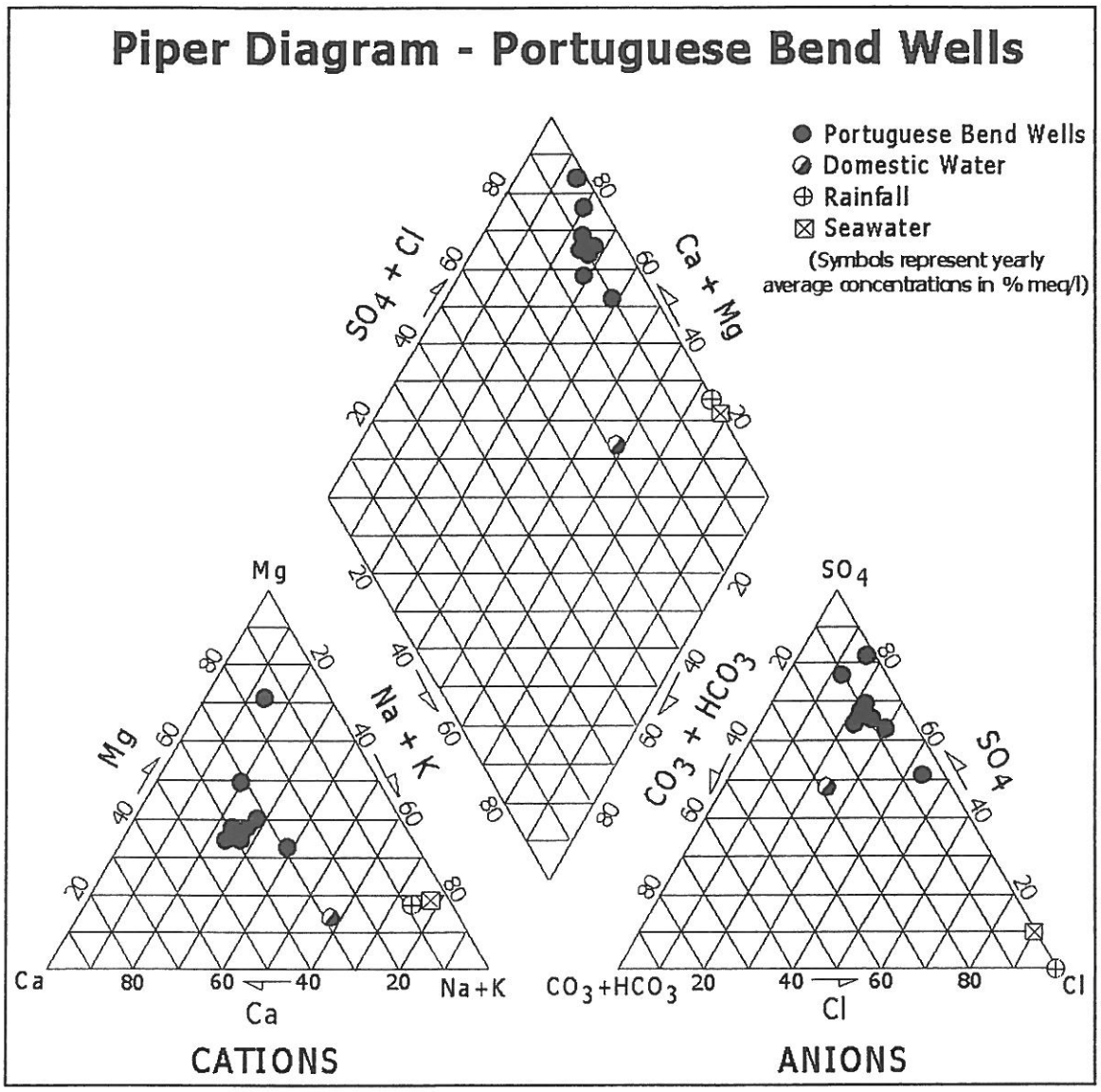


Figure 17. Piper tri-linear diagram for wells located in the Portuguese Bend landslide. Groundwater is classified as sulfide-type and exhibits a wider range in composition than groundwater within the Abalone Cove landslide area.

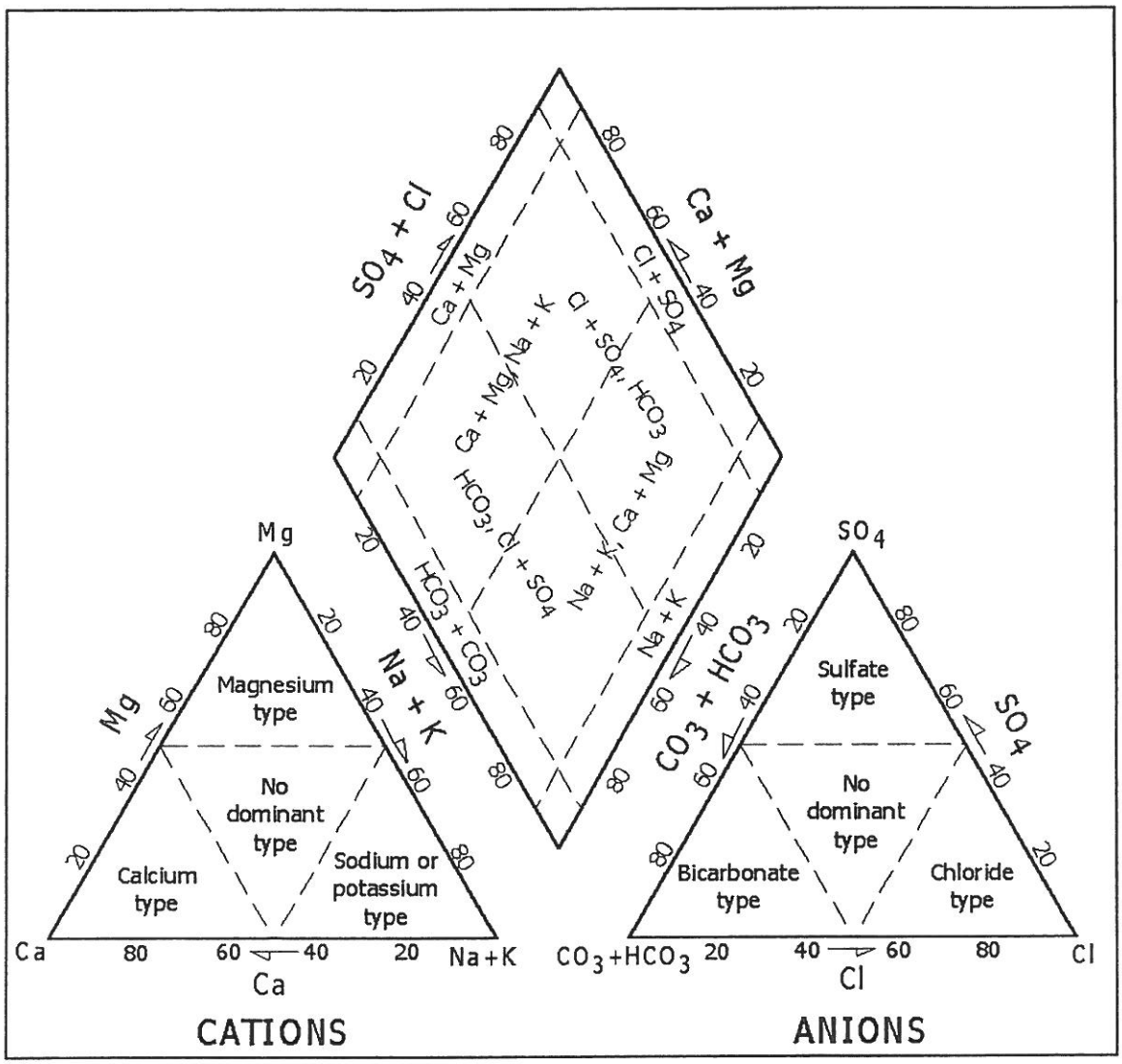


Figure 18. Hydrochemical classification system for natural waters.

Similarities and differences in chemical composition can also be seen in fingerprint diagrams of major ions (Figure 19). The Altamira Canyon wells show ion concentrations are fairly tightly clustered. The most variation occurs in the monovalent ions of Na, K, and Cl. The Portuguese Bend wells show minor differences, with the exception of well W6K, which has a higher Mg concentration. Of the two beach wells, CB resembles well W6K in composition and EB exhibits a pattern unlike any other.

Figure 20 shows the major ion concentrations of the beach wells compared to those of seawater. The cation concentrations in well EB are parallel but diluted patterns when compared to seawater. However, the anion concentration patterns are dissimilar, with seawater showing significantly high Cl concentrations compared to well EB.

The different, but very consistent, chemical composition in well EB, along with warmer average temperatures and a strong sulfide smell, suggest that groundwater in the vicinity of this well may reflect a source or body of water which is different from that tapped by the other wells in the area. Kadera (1997) used strontium isotope ratios and the higher temperatures in well EB to conclude that water in this well represented a hybrid mix of groundwater within the landslide, seawater, and water which circulated much deeper within the peninsula. Evidence of deeper, warm water circulation has been found elsewhere on the Palos Verdes peninsula in the form of coastal, hydrothermal springs.

The influence of seawater is also apparent in association with well CB. Well CB is a nested well, with an adjacent one-inch-diameter pipe (CBA) which extends to a depth below the Abalone Cove slide plane. As with well EB, which also terminates below the slide plane, the cation concentrations in well CBA show parallel, yet diluted patterns

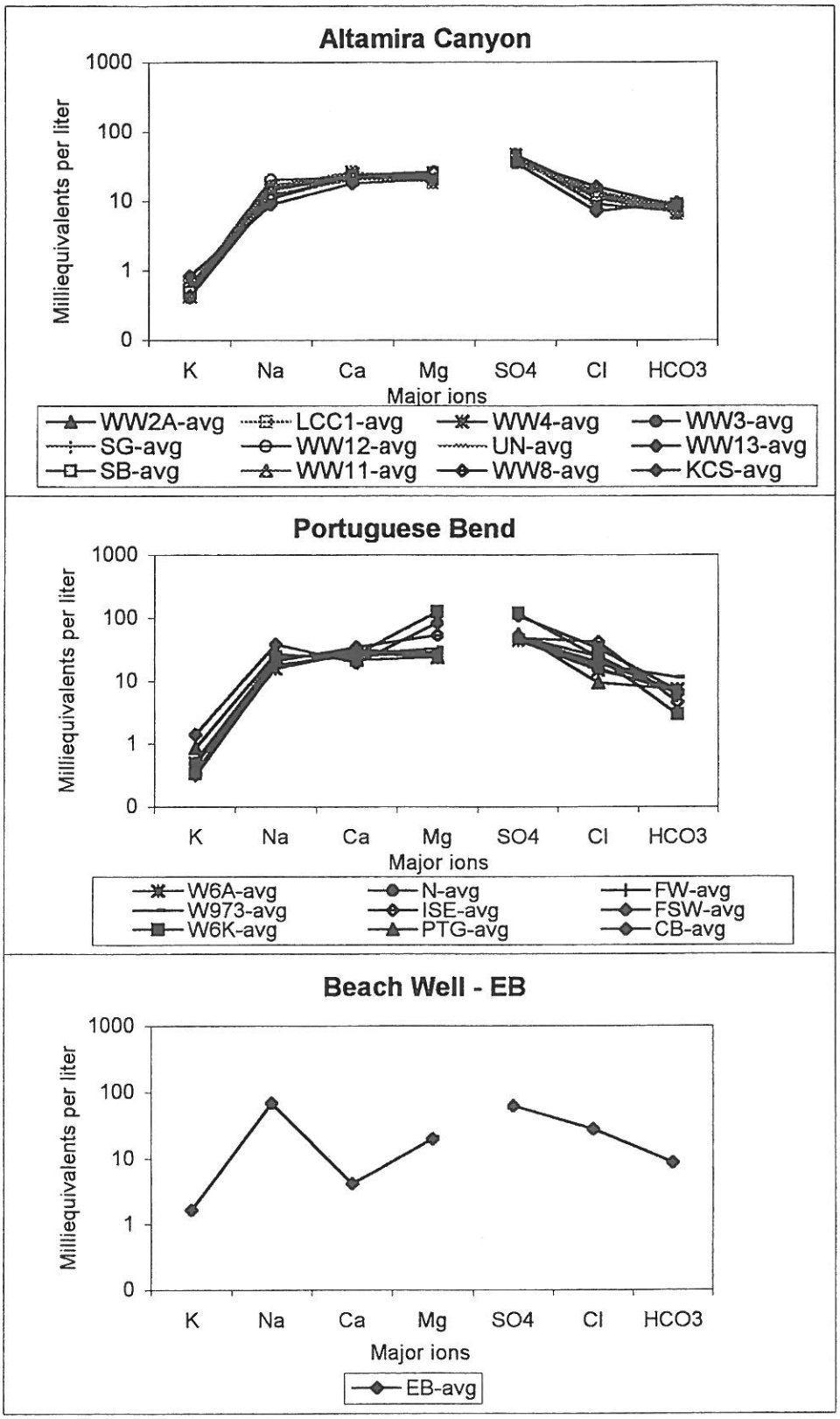


Figure 19. Fingerprint diagrams of groundwater data from study area. Variation in Portuguese Bend composition could be result of adsorption effects. Well EB composition suggests possible deep-circulating water source.

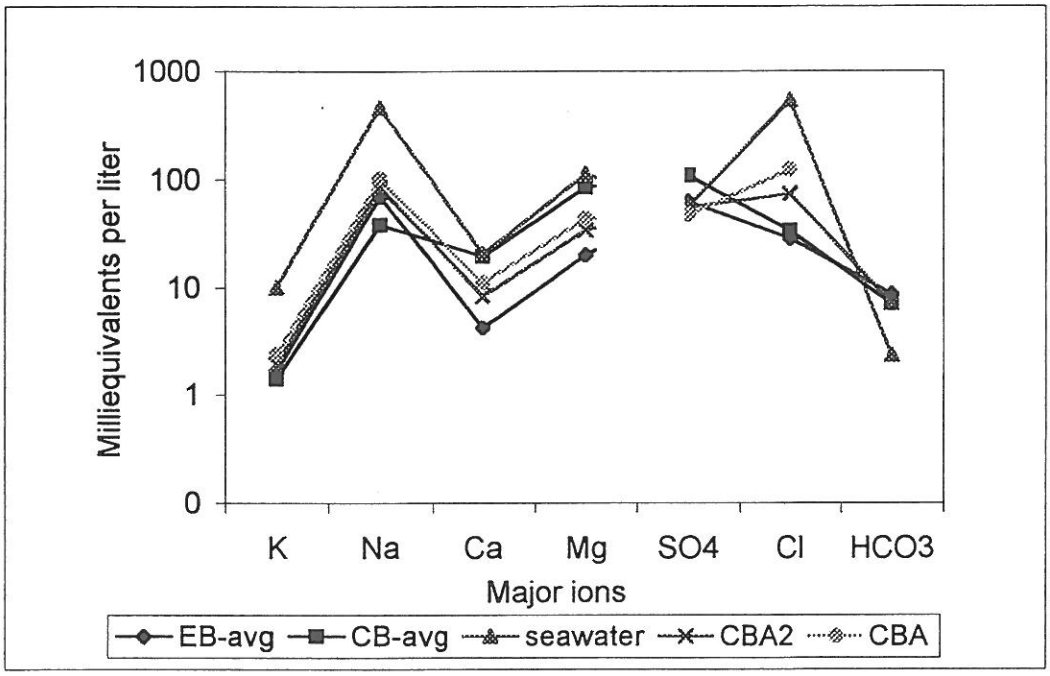


Figure 20. Fingerprint diagram of beach well and seawater major ion concentrations. Groundwater in well CBA may represent a transition mix between a lower seawater wedge and upper landslide water body. (Data on CBA and CBA2 from Kadera, 1997)

compared to seawater concentrations suggesting that water beneath the slide surface in the vicinity of this well has a seawater component. The anion concentrations of well CBA show similar SO_4 and HCO_3 concentrations compared to wells CB and EB, but show Cl concentrations intermediate between the more shallow beach wells (CB and EB) and seawater. Water collected from the CB well, which terminates above the slide plane, has a composition more reflective of the other wells in the Portuguese Bend basin. The bottoms of both wells CB and EB terminate at a depth below mean sea level (Table A-1).

The chemical behavior of chloride ions in groundwater tends to be fairly conservative (Hem, 1992). In the majority of the study area, chloride concentrations range from approximately 250 to 700 mg/l. Two areas of relatively high chloride concentration are observed surrounding wells EB and CB and well ISE near the coastline. Well ISE extends to a depth near mean sea level (~ 7 feet above mean sea level). The chloride concentrations in well ISE may result from a combination of seawater intrusion and evaporative recharge as will be discussed in the stable isotope section. The one exception to this chloride observation in coastal wells is well PTG, which along with well WW2A, exhibit the lowest chloride concentrations in the slide area. The lower chloride concentrations may reflect dilution by domestic water.

Nitrate analyses were performed on groundwater samples, and average values ranged from 0 mg/l at the beach wells (EB and CB) to 971 mg/l in well ISE. The average measured nitrate concentration in domestic water was 1 mg/l. The highest average nitrate concentration reported in the Altamira Canyon portion was 28 mg/l. The Portuguese Bend portion of the study area typically contained higher values, including

wells W6K and FSW with reported nitrate concentrations of 256 and 138 mg/l, respectively. Kelvin Canyon spring contained an average nitrate concentration of 4 mg/l. The presence of nitrate concentrations in many of the wells indicates probable domestic water influence. Nitrate is indicative of waste products and would be closely associated with septic system discharge. Wells FSW and W6K, which have higher nitrate concentrations than nearby wells are located in close proximity to a horse corral. The extremely high nitrate concentrations reported in well ISE are most difficult to explain. There are currently no buildings in the vicinity of the well. There are residences upgradient on the crest of the peninsula which are serviced by septic systems, but indications of domestic water input, specifically $\delta^{18}O$ values more negative than – 6.0, are not present in the well. According to local residents, well ISE is located in a former agricultural area near a former fertilizer storage location. It is possible that, during extensive regrading of the Portuguese Bend landslide, nitrate-laden soil was buried and is slowly leaching nitrates into the groundwater in the vicinity of well ISE.

With some exceptions, the major ion chemistry of water in any given well remained consistent (within 10% deviation from the mean) over the 12-month sampling period (see Table B-1). Analytical uncertainties can account for ~ 3% of the variations. The exceptions, in which more than two ions showed significantly greater than 10% variation, include wells CB and W6K. Well CB also shows unusual temperature variability. Fingerprint diagrams of these wells are shown in Figure 21. Well CB, located near the shoreline of Abalone Cove, showed fairly significant variation in Na, K and Cl over the study period, but only small variations in Ca, Mg, and SO_4. Well W6K

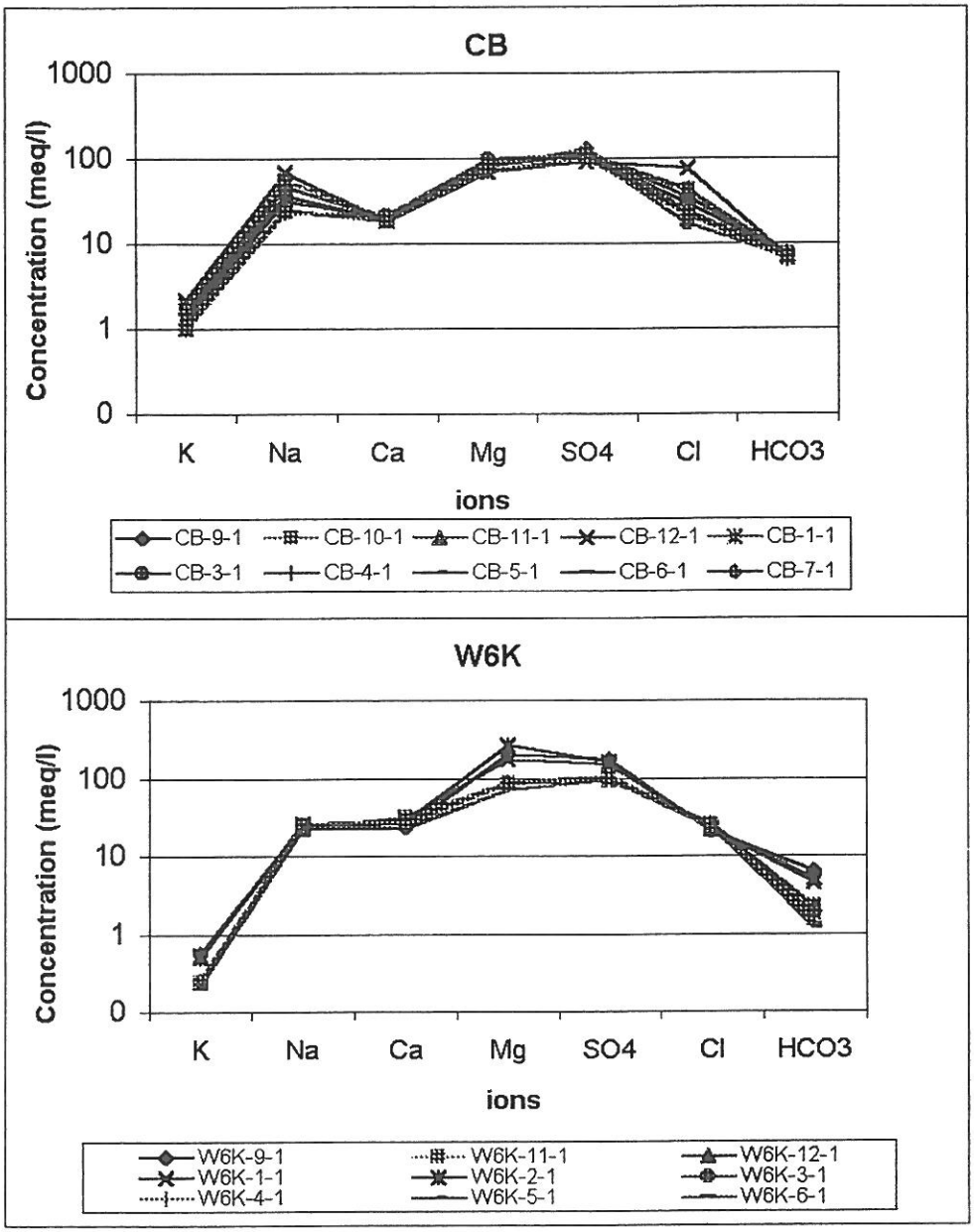


Figure 21. Fingerprint diagrams of major ion concentrations in wells CB and W6K over the sampling period. The fluctuations in Na and Cl in well CB may result from seawater intrusion. Well W6K appears to be influenced by two separate water sources.

(Figure 7) exhibits fingerprint patterns showing two fairly distinct types of water. One type, with higher concentrations of the above-mentioned ions, appeared during the months of September and the following January and February. The two types are distinguished by variations in K, which could be explained by decomposition of animal waste, and Mg, SO_4, and HCO_3, which could be caused by differential weathering of subsurface materials.

In order to better identify and discriminate among the potential influences on groundwater chemistry, multivariate factor analysis was conducted on the average major ion results for each well. This type of analysis results in a set of factors which can hopefully be used to explain interrelationships among a large number of variables. Figure 22 illustrates that results of the analysis, displaying the loadings of each variable on a specific factor. The loadings have numerical values between +1 and –1 and measure the extent to which each factor is associated with a particular variable. The closer the variable loading is to 1 (regardless of the sign), the greater the association of that variable to the factor. Factors were judged to be significant if their percent variance was greater than ten.

Kelvin Canyon spring is located in the upper portion of the Altamira Canyon drainage basin and would therefore be a likely candidate to represent groundwater at or near the recharge area for the basin. As a representation of recently-recharged rainfall, the spring water might be expected to most closely reflect the chemical composition of rainwater, although weathering may be important. As discussed earlier, rainfall

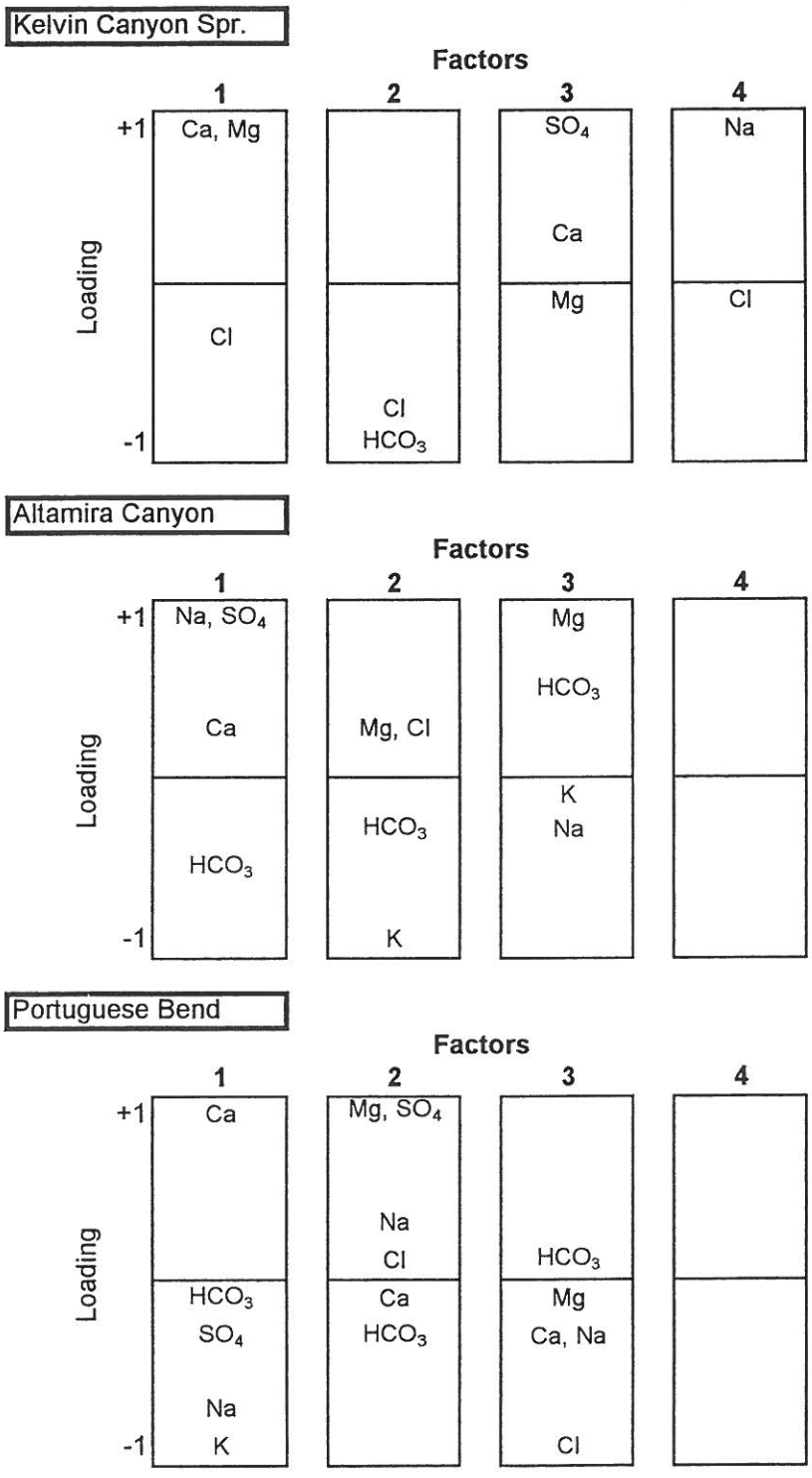


Figure 22. Factor loadings for major elements in water samples from the study area. Within each factor, the closer the variable (such as Na) is to 1 (regardless of the sign), the greater the association of that variable to the factor. See the text and Table 17 for an interpretation of the factors in each analysis.

composition reflects a marine source with the dominant ions being Na and Cl. The ion composition of water in Kelvin Canyon spring is enriched in K, Ca, Mg, SO_4, and HCO_3 relative to rainwater. Factor analysis of the spring water shows 4 dominant factors. Factors 1 and 2 show high loadings on Ca, Mg, and HCO_3 suggesting weathering of subsurface dolomite material which is prominent in the study area. Factor 3 has a high loading for SO_4 and an intermediate loading for Ca. There is abundant pyrite present in the lithologic units throughout the study area which can be oxidized to release SO_4 as sulfuric acid. Oxidation occurring in the presence of calcite would proceed according to the following reaction:

$$FeS_2 + 3.75O_2 + 1.5H_2O + 2CaCO_3 = Fe(OH)_3 + 2Ca^{2+} + 2SO_4^{2-} + 2CO_2,$$

or, if CO_2 does not escape and reacts further:

$$FeS_2 + 3.75O_2 + 3.5H_2O + 4CaCO_3 = Fe(OH)_3 + 4Ca^{2+} + 2SO_4^{2-} + 4HCO_3.$$

Weathering of dolomite is likely to release Mg as well as Ca. Factor 4 shows a high loading for Na, possibly derived from weathering of sodium montmorillonite in the subsurface.

As stated earlier, the groundwater within the study area can be classified as sulfate-type. The weathering reactions discussed above will proceed in the presence of oxygen. At ambient air temperatures experienced in the study area, the dissolved oxygen concentration expected in groundwater in equilibrium with the atmosphere would be ~ 200 μm (Truesdale et al., 1955). Based on the stoichiometric reaction, ~ 100 μm of SO_4 will be produced for each 200 μm of oxygen. Concentrations of SO_4 in groundwater of the study area range from ~ 18,000 to 59,000 μm. In order to produce the amount of

SO_4 measured in the groundwater, large volumes of oxygen must be supplied. This must reflect interactions of gas, water, and solids in the vadose zone.

Factor analysis of Altamira Canyon groundwater shows high loadings of Na and SO_4 with an intermediate loading of Ca on factor 1 suggesting pyrite oxidation with some possible exchange of Ca for Na. As mentioned earlier, Ca adsorption is most likely to occur in uphill, highly weathered areas. Factor 3 has a high loading for Mg, and an intermediate loading for HCO_3, once again supporting dolomite dissolution. Any variation present in ion concentrations in groundwater primarily effects the monovalent ions. This occurrence supports the process of adsorption in the study area because divalent ions are more easily adsorbed and therefore tend to vary less as a result of this buffering effect.

The Portuguese Bend samples are more varied in composition and the factors are much more difficult to interpret. Again there are high loadings on Ca, Mg, and SO_4 although not associated with the same factors. The high loading on K in factor 1 may be indicative of animal waste decomposition (there are numerous horses in the area) or past applications of fertilizer in the agricultural areas. This explanation is supported by significant concentrations of nitrate present in several Portuguese Bend wells.

Because the lithology underlying Portuguese Bend is similar to that underlying the Altamira Canyon basin, any differences in groundwater composition may reflect variations in weathering patterns. For example, the SO_4 concentrations in the Portuguese Bend area, which are even higher than those found in the Altamira Canyon basin, suggest one or more of several possible geochemical scenarios: 1) there is significant gas

exchange within the vadose zone; 2) there is potentially more material (i.e. pyrite) exposed in the subsurface; 3) more evaporative concentration has occurred; or 4) the residence time of water in the weathering zone is prolonged. The landslide activity has significantly disrupted the continuity of subsurface sedimentary units in the Portuguese Bend area creating the potential for more reactive surface area to be exposed to groundwater interaction. In addition, the low, and likely variable, permeability typical of disrupted, clayey landslide material would result in the potential for variable residence times of groundwater in the subsurface. A more detailed discussion of groundwater residence time is included in a subsequent section on tritium. Table 18 provides a summary of the factor analysis interpretation.

The weathering relationships discussed above are also illustrated in plots of individual ion concentrations from wells in the study area versus TDI (Figure 23). A positive correlation is seen between TDI and the ions of Na, Ca, Mg, and Cl. A strong positive correlation is observed between SO_4 and TDI as well as between conductivity and TDI. The HCO_3 concentrations show a negative correlation versus TDI. In all plots, except Mg, SO_4, and conductivity, ion concentrations from wells CB, EB, ISE, and W6K consistently plot separately from the trend exhibited by the rest of the wells.

B. STABLE ISOTOPE CHEMISTRY

As suggested by the hydrologic calculations, rainfall appears to be the primary source of recharge for the groundwater body in the study area. Recharge is inferred to occur via two primary processes: infiltration through the unsaturated zone and directly down fissures in the landslide body. The relative importance of these two processes can

TABLE 18. FACTOR ANALYSIS INTERPRETATION

Kelvin Canyon spring		
Factor No.	**Associated Elements***	**Interpretation**
1	Ca, Mg	weathering of subsurface dolomite
2	HCO_3	
3	SO_4	pyrite oxidation
4	Na	weathering of montmorillonite

Altamira Canyon groundwater		
Factor No.	**Associated Elements**	**Interpretation**
1	Na, SO_4	pyrite oxidation in presence of calcite; Ca released exchanges for Na
2	K	possible waste decomposition
3	Mg, HCO_3	dolomite dissolution

Portuguese Bend groundwater		
Factor No.	**Associated Elements**	**Interpretation**
1	K, Ca, Na	waste decomposition, weathering of montmorillonite
2	Mg, SO_4	pyrite oxidation, possible basalt weathering?
3	Cl	possible seawater intrusion

* Elements have their highest correlation with Factor 1, next highest with Factor 2, etc.

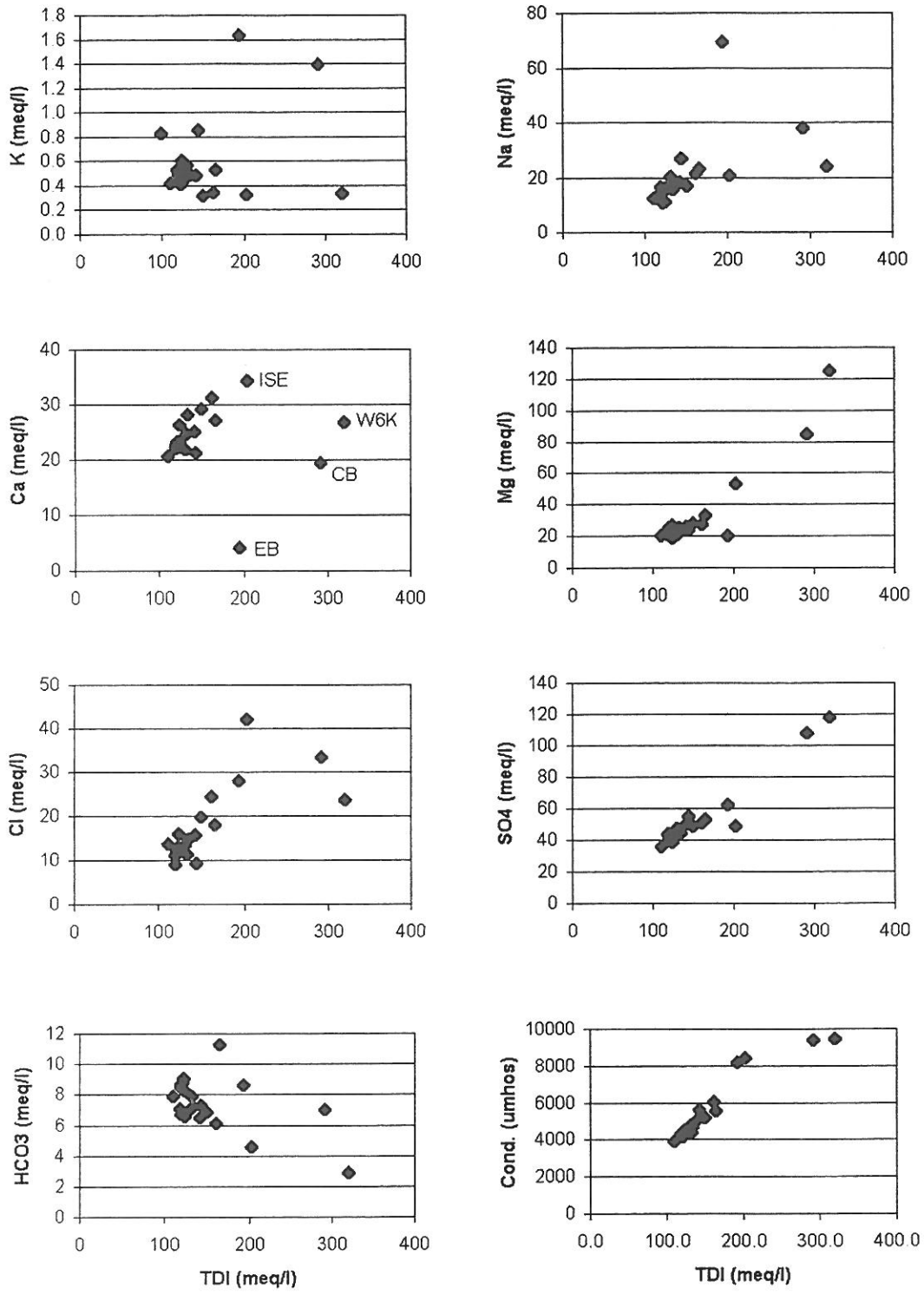


Figure 23. Yearly average concentrations of major ions and conductivity in groundwater plotted as a function of total dissolved ions. The correlations between Ca, HCO_3, Mg, and SO_4, and total dissolved ions (TDI) support weathering of subsurface dolomite and pyrite.

be evaluated using stable isotopes. Stable isotopes are excellent tracers of groundwater source and movement for two reasons: 1) the isotopes of oxygen and hydrogen are part of the water molecule and therefore will not act independently; and 2) in the environmental conditions of the study area, water isotopic composition can only be altered by evaporation or mixing with other waters.

Water samples to be analyzed for stable isotopes were collected directly into plastic vials with polyseal caps to prevent evaporation and stored at room temperature. Analyses of oxygen and hydrogen isotopes were conducted in the Water Resources Division laboratory at the United States Geological Survey (USGS) in Menlo Park, California. Analyses for $\delta^{18}O$ were conducted by equilibrating the water samples with CO_2 in a shaking water bath for 9 hours (Epstein and Mayeda, 1953) followed by analysis on a Finnigan MAT 251 mass spectrometer. Reproducibility is 0.05 per mil. Samples were analyzed for hydrogen isotope ratios (δD) on a Finnigan Delta E mass spectrometer using the methods described by Kendall and Coplen (1985). Reproducibility is 1.5 per mil. Isotopic results are reported relative to the Vienna Standard Mean Ocean Water standard.

Rainfall

This study was conducted during the 1997-98 El Nino event, one of the strongest on record. While this is beneficial in providing us with a worst-case scenario in studying the effects of rainfall on landslide movement, the question arises as to how representative the El Nino rainfall isotopic compositions are of typical rainfall years. To examine the possible isotopic variations in rainfall due to El Nino years, oxygen isotope records were

obtained from Santa Maria, California (IAEA/WMO, 1998). Eight full water-year (Sept-Sept) records were available and weighted annual $\delta^{18}O$ values are illustrated in Figure 24. As illustrated in the diagram, three significant El Nino events occurred during the subject years, with weighted $\delta^{18}O$ values of –5.4, –6.4, and –4.9 ‰. These particular years do not represent a significant deviation from the overall weighted average $\delta^{18}O$ value of rainfall of -5.4 ± 1.1 ‰ suggesting that El Nino rainfall events do not have significantly different isotopic averages.

During the study period, at least one rainfall sample was collected at Station BD for each storm event and analyzed for $\delta^{18}O$. As a result, ~ 94.5% of total measured rainfall at Station BD, located in the approximate center of the Altamira Canyon drainage basin, was sampled. Sample collection dates, rainfall amounts, and stable isotope analytical results are listed in Table 19. As stated earlier, rainfall occurred during the months from November 1997 through May 1998. Rainfall $\delta^{18}O$ values at Station BD ranged from –1.1 ‰ to –11.5 ‰ with an annual weighted average of –5.7 ‰. Table 20 lists the amount of rainfall and weighted monthly $\delta^{18}O$ values for each month during the study period.

Local variations in rainfall isotopic composition can occur as a result of seasonal trends, intrastorm and interstorm variations, and elevation changes (Dansgaard, 1964; Kendall and McDonnell, 1993). Seasonal trends are typically most apparent in temperate climates where rainfall occurs all year round and temperatures vary (Clark and Fritz, 1997). In the Mediterranean climate of the study area, rainfall primarily occurs during a winter rainy season, thereby reducing seasonality. There is significant isotopic variation

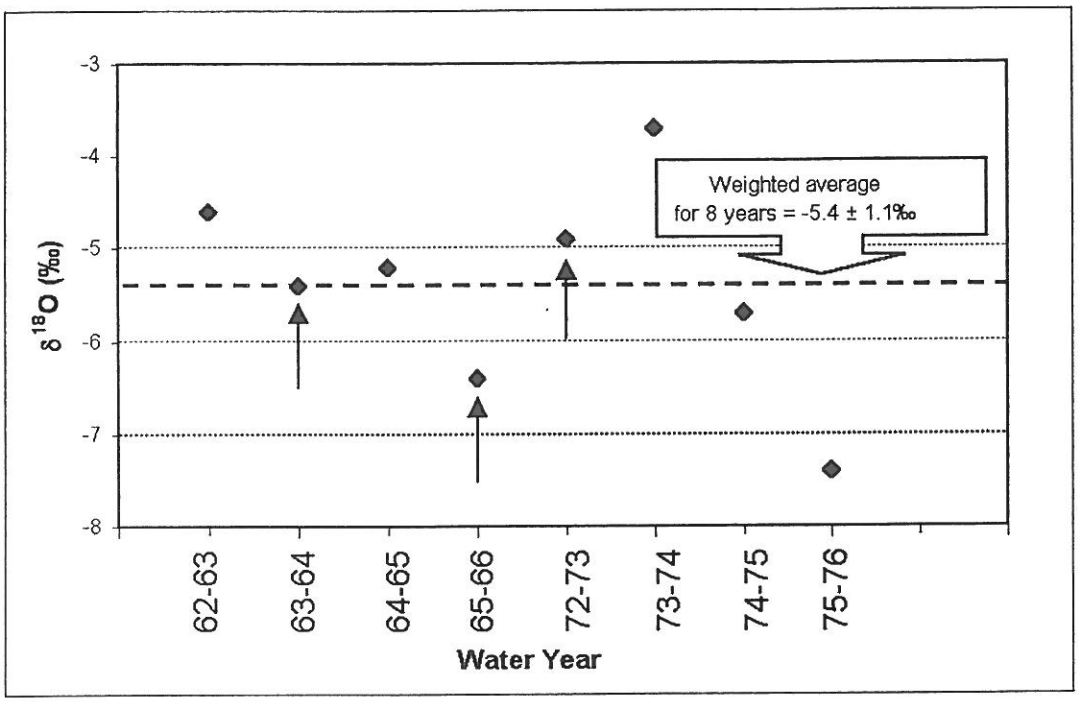


Figure 24. Stable isotope composition of rainfall in Santa Maria, California. El Nino years are indicated with arrows (WeatherNet4, 1999). El Nino events do not have significantly different isotope averages from non-El Nino events.

TABLE 19. CALCULATED ANNUAL WEIGHTED AVERAGE $\delta^{18}O$ VALUES FOR RAINFALL AT STATION BD

Sample No.	Date	gauge (mm)	$\delta^{18}O$ (‰)	weekly wgted $\delta^{18}O$
RD-1	13-Nov-97		-6.0	
RD-2	13-Nov-97	16	-5.4	
RD-3	14-Nov-97	12	-5.1	-5.5
RD-4	20-Nov-97	3	-2.2	-2.2
RD-5	26-Nov-97	12	-4.4	
RD-6	30-Nov-97	4.5	-7.1	-5.2
RD-7	06-Dec-97	20.5	-2.8	
RD-8	06-Dec-97	44	-6.6	cumulative for storm
RD-9	07-Dec-97	12	-5.6	-6.4
RD-10	19-Dec-97	37	-5.5	-5.5
RD-11	05-Jan-98	13	-5.4	-5.4
RD-12	10-Jan-98	24	-4.6	-4.6
RD-13	14-Jan-98	3	-2.7	-2.7
RD-14	19-Jan-98	5	-1.1	-1.1
RD-15	01-Feb-98	18	-4.0	-4.0
RD-16	02-Feb-98	14	-2.7	
RD-17	03-Feb-98	20	-6.3	collected at intervals
RD-18	03-Feb-98	24	-13.1	during same storm
RD-19	06-Feb-98	12	-4.4	
RD-20	08-Feb-98	32	-5.2	
RD-21	09-Feb-98	27	-5.0	-6.5
RD-22	16-Feb-98	47.5	-4.0	-4.0
RD-23	21-Feb-98	42	-11.5	
RD-24	23-Feb-98	25.5	-2.5	-8.1
RD-25	25-Feb-98	43	-5.3	-5.3
RD-27	31-Mar-98	38	-4.2	several rains
RD-28	01-Apr-98	22	-7.0	-7.0
RD-29	13-Apr-98	17.5	-6.6	-6.6
RD-30	05-May-98	17	-2.9	-2.9
RD-31	13-May-98	20	-5.3	-5.3
DCP-R1	04-Feb-98	*140*	*-6.3*	
DC-R1	04-Feb-98	*57*	*-8.6*	cumulative for storm
BD-R1	04-Feb-98	*62*	*-8.4*	at each location
		605		
Annual weighted rainfall $\delta^{18}O$ at Station BD:				**-5.7**
Percent of total rainfall sampled at Station BD:				**94.5**

Note:

Weighting of annual δ18O rainfall value determined from the following equation:

$$\delta^{18}O_A = \frac{\Sigma h_i \delta^{18}O_i}{\Sigma h_i}$$

where: h_i = event rainfall in millimeters and $\delta^{18}O_i$ = average event value in ‰.

TABLE 20. MONTHLY RAINFALL AND WEIGHTED AVERAGE $\delta^{18}O$ AT STATION BD

Month	Amount of rainfall (mm)	Average $\delta^{18}O$ (‰)
September	0	-
October	0	-
November	47.5	-5.1
December	93.0	-6.0
January	45.0	-4.3
February	305.0	-6.1
March	38.0	-4.2
April	39.5	-6.8
May	37.0	-4.2
June	0	-
July	0	-
August	0	-

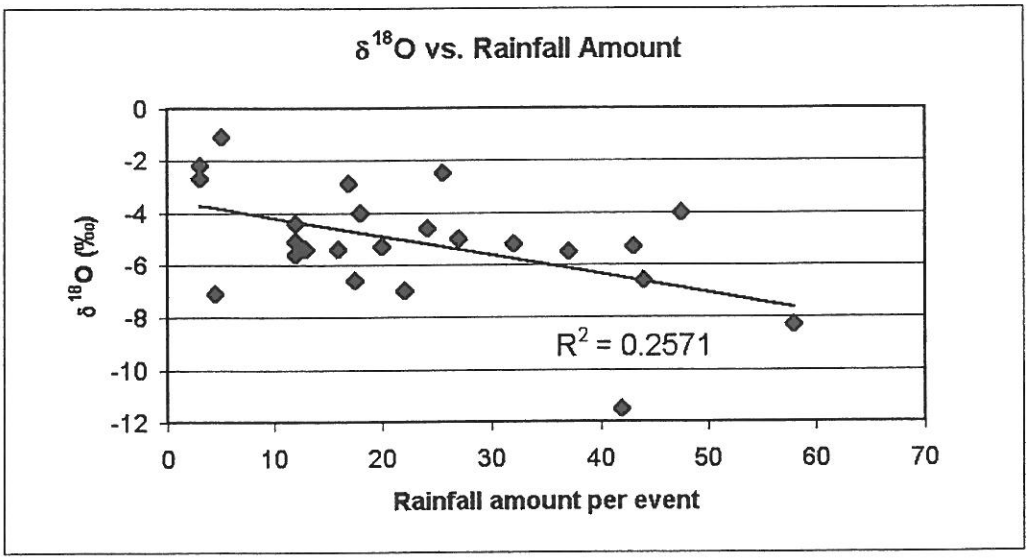


Figure 25. Correlation of $\delta^{18}O$ with amount of rainfall in each event. In general, rainfall $\delta^{18}O$ values show a rainout effect, becoming lighter with increasing amounts of precipitation.

between individual storms within the study area (Table 19), and no apparent correlation relating isotopic composition to time of year (Table 20). Rainfall $\delta^{18}O$ values appear to get more negative with increasing amounts of rainfall, but the correlation is weak (Figure 25). In addition, there is a negative correlation between $\delta^{18}O$ and timing of rainfall within an event. Specifically, the earliest rainfall within a given storm event is typically heavier in $\delta^{18}O$, with oxygen isotopic values becoming lighter as the storm progresses. This trend is also apparent in storm runoff $\delta^{18}O$ measurements (Table B-2). The majority of storm events dropped between 10 and 50 mm of rain and had $\delta^{18}O$ values ranging from – 4 ‰ to – 7 ‰.

Because of the topographic change within the study area (a total of about 366 meters from shoreline to crest), the potential orographic effect on rainfall isotopic composition must be considered. During placement of the rain gauge network, stations were selected to evaluate the effect of altitude during storm activity. Station DCP was located at the top of the study area at an elevation of approximately 360 meters (1,180 feet) asl, while station DC was located near the bottom at an approximate elevation of 50 meters (162 feet) asl. Station BD (~ 131 meters asl) was located near the middle of the study area and was the location selected for collection of a complete set of storm samples (every storm event).

Isotopic values typically become progressively lighter with increasing elevation (Dansgaard, 1964). In two studies in similar coastal settings (Clark, 1987; and Fontes et al., 1977), the observed change in isotopic composition was between –0.1 and –0.155 ‰ per 100 meters, respectively. By applying this isotopic gradient to the elevation change

in the study area relative to station BD, the effect of isotopic change with elevation can be predicted to range from –5.6 ‰ at station DC to –6.1 ‰ at station DCP (Table 21).

During the 3 February 1998 storm event, samples were collected at all three stations to observe the actual isotopic difference with elevation. Contrary to expectations, the rainfall isotopic composition became heavier with increasing altitude. Because of the unexpected results during the 1998 storm, additional samples were collected during the 1999 winter rainy season in an attempt to clarify the $\delta^{18}O$-altitude relationship. During the first 1999 sampled event, the isotopic values again became heavier with increasing altitude (DC = -6.8; BD = -2.4, and DCP/RM = -2.5 ‰). During the second event, the values showed no trend at all (DC = -6.7, BD = -3.4, DCP/RM = -8.6 ‰)(Figure 26). It appears then, that there is no apparent and/or predictable isotopic elevation effect in the study area. This may be attributable to the varied storm paths and rainfall patterns which are prevalent on the peninsula (D. Gales, personal communication, August 1998).

Selected rainfall samples representing different storm events in different months and of different magnitude were analyzed for δD. δD results from these samples are listed in Table 22 and range from -90 to 0 ‰. δD results are plotted versus $\delta^{18}O$ in Figure 27 to produce a local meteoric water line (LMWL) with an slope of $\delta D = 7.77\ \delta^{18}O + 11.36$. The use of a LMWL is preferable to comparison of samples with a global meteoric water line because the LMWL is composed of local rainfall and more closely reflects the environmental conditions present in the study area.

TABLE 21. ESTIMATES OF POTENTIAL ELEVATION EFFECTS ON $\delta^{18}O$ COMPOSITION OF RAINFALL

Weighted avg δ18O at station BD:	**-5.7**			
At station DCP	Δ $\delta^{18}O$/100m	m elev	totl change	range $\delta^{18}O$
potential $\delta^{18}O$-altitude change based on: Clark (1987)	-0.1	229	-0.2	**-5.9**
Fontes et al. (1977)	-0.155	229	-0.4	**-6.1**
At station DC	Δ $\delta^{18}O$/100m	m elev	totl change	range $\delta^{18}O$
potential altitude change based on: Clark (1987)	-0.1	82	-0.1	**-5.6**
Fontes et al. (1977)	-0.155	82	-0.1	**-5.6**

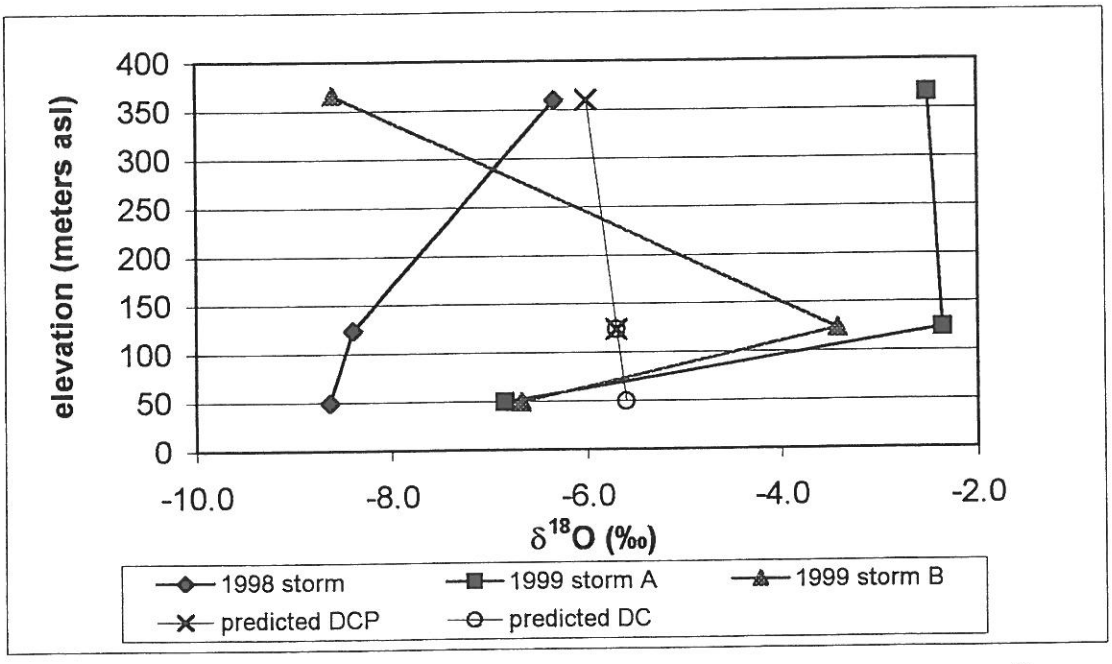


Figure 26. Graph of $\delta^{18}O$ versus elevation within the study area. Measured rainfall $\delta^{18}O$ values vary from the trend predicted based on elevation change in the area.

TABLE 22. $\delta^{18}O$ and δD CONCENTRATIONS FOR SELECTED SAMPLES

Sample	δ18O	δD
RD-2	-5.4	-31
RD-4	-2.2	-5
RD-9	-5.6	-36
RD-12	-4.6	-23
RD-14	-1.1	0
RD-17	-6.3	-31
RD-18	-13.1	-90
RD-23	-11.5	-80
RD-28	-7.0	-46
RD-31	-5.3	-27
DW1-10-1	-11.2	-98
WW2A-11-1	-6.5	-49
LCC1-11-1	-6.4	-43
FW-12-1	-6.7	-41
W973-11-1	-5.4	-41
W973-3-1	-4.8	-33
ISE-9-1	-5.0	-44
ISE-3-1	-5.9	-43
FSW-11-1	-6.5	-49
W6K-11-1	-6.1	-38
W6K-2-1	-5.7	-42
KCS-12-1	-5.8	-39
KCS-4-1b	-5.7	-33
KCS-6-1b	-5.5	-29
PTG-10-1	-6.2	-41
PTG-4-1	-6.6	-39
seawater	0	0

Concentrations in parts per thousand (‰)

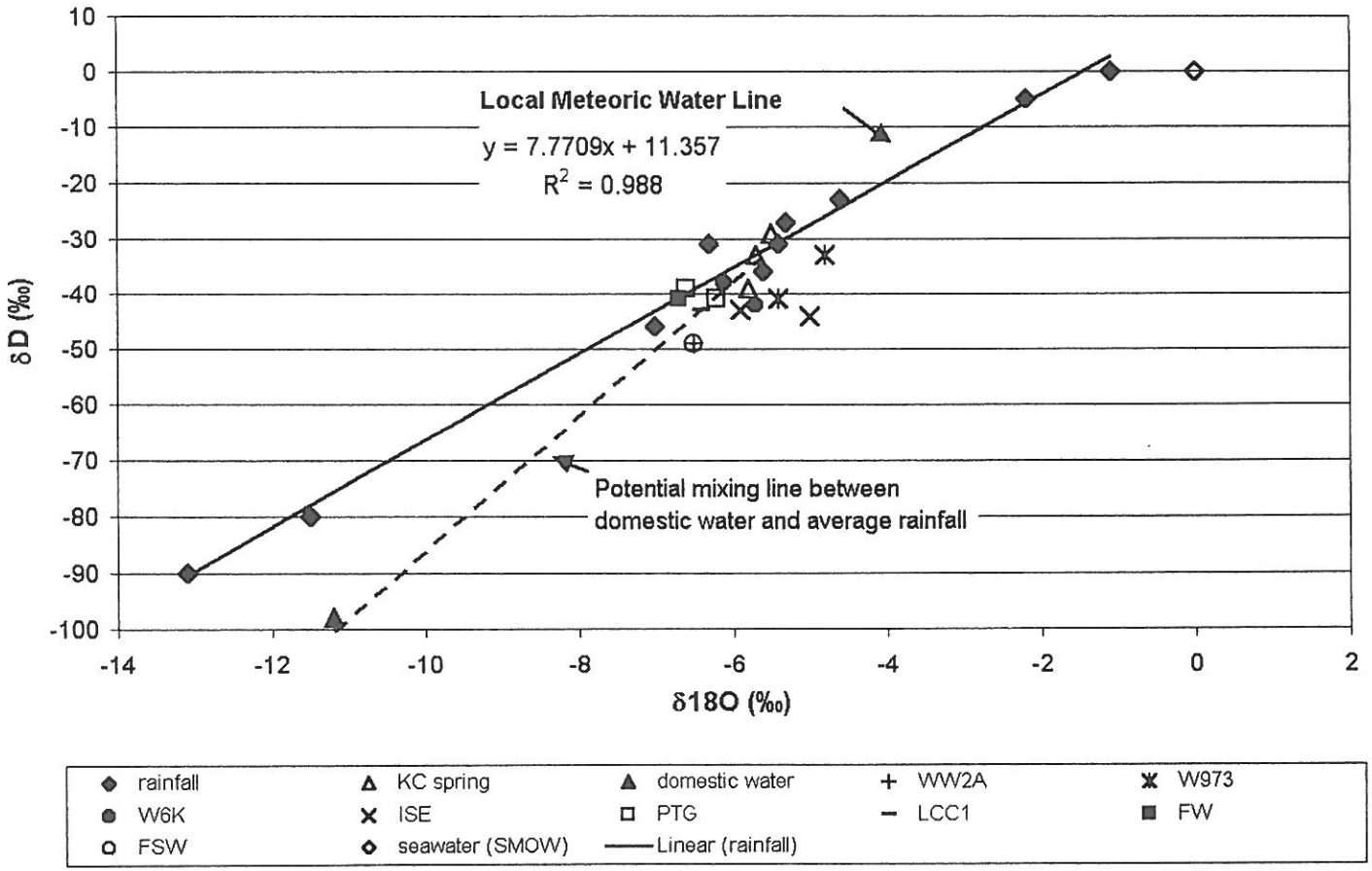


Figure 27. Stable isotope compositions of selected groundwater, rainfall, and domestic water samples. Kelvin Canyon spring samples plot on the meteoric water line suggesting that spring water reflects rainfall recharge with little evaporation in subsurface. Samples which plot to right of line indicated either evaporation (i.e. W973 and ISE) or possible mixing with domestic water. (Uncertainties are 0.05 per mil for $\delta^{18}O$ and 1.5 per mil for δD)

Storm Runoff

Storm samples from both the January and February rainfall events were analyzed for $\delta^{18}O$ with values ranging from –2.8 to –12.5 ‰ (see Table B-2). In general, $\delta^{18}O$ values in runoff samples became lighter as the storm event progressed, reflecting the patterns seen in precipitation.

Domestic Water

Four domestic tapwater samples were collected from two homes in the area. The samples were analyzed for $\delta^{18}O$ and ranged from –11.4 to –10.7 ‰. Sample DW1-10-1 was analyzed for deuterium with a reported value of –98.3 ‰. DW1-10-1 plots significantly below the LMWL in Figure 27.

Groundwater

Monthly groundwater samples were analyzed for $\delta^{18}O$ and selected samples were analyzed for δD. The $\delta^{18}O$ values for each sample location are listed in Table B-1. δD results are listed in Table 22 and groundwater samples with both $\delta^{18}O$ compositions and δD values are plotted in Figure 27. Several groundwater samples, including those from Kelvin Canyon spring, plot along or close to the LMWL. Other samples, including FSW, WW2A, ISE, and W973, plot below the LMWL.

Yearly average $\delta^{18}O$ values of groundwater in the study area range from –6.6 to –5.4 ‰ (Table 17). The average $\delta^{18}O$ composition at Kelvin Canyon spring is –5.7 ‰ and, in general, $\delta^{18}O$ values for groundwater in the Altamira Canyon basin become isotopically lighter as you enter developed areas downgradient within the study area. In addition, average $\delta^{18}O$ values in wells located in or adjacent to the canyons appear to

deviate less from the Kelvin Canyon spring $\delta^{18}O$ value than wells located farther from the canyons.

Rainfall recharge within the study area can occur by direct infiltration through the vadose zone or by movement down surface fissures. Each route will potentially affect the influence that rainfall variability has on groundwater isotopic composition. In some semi-arid to arid regions, groundwater isotopic composition can closely resemble the mean composition of rainfall as a result of fairly rapid recharge through preferential flow channels (Mathieu and Bariac, 1996). This direct recharge of rainfall to the groundwater body via surface fissures also provides an opportunity for an unequal contributions of various rainfall events to occur, potentially resulting in a groundwater isotopic composition that varies from the overall weighted average of rainfall.

Direct infiltration places water in the vadose zone where evapotranspiration is by far one of the most dominant mechanisms of removal of water, with important implications for groundwater recharge. While the process of transpiration is non-fractionating, direct evaporation of water from the soil zone can result in alteration of groundwater isotopic composition by fractionation (Clark and Fritz, 1997). The potential effect that the evaporative portion of this process had on groundwater isotopic composition in the study area was considered.

With the exception of arid climates, seasonal variations in rainfall are typically attenuated during passage through the vadose zone, resulting in groundwater isotopic values that closely approximate those of weighted annual rainfall (Clark and Fritz, 1997). This attenuation occurs because of the flow of water via differential flow paths in porous

subsurface materials. In arid regions, evaporation is prominent on both the surface and in the vadose zone. As a result, there is an isotopic enrichment of soil water in the vadose zone. As successive recharge pulses of soil water progress through the vadose zone to recharge the groundwater body, the groundwater will exhibit a $\delta^{18}O$-δD composition which will plot below but parallel to the local meteoric water line (Allison et al.,1984).

The spring in Kelvin Canyon provides a unique opportunity to access "groundwater" in the recharge area. The average $\delta^{18}O$ for the spring water was –5.7 ‰ and the δD was –34 ‰, closely matching the weighted average values for annual rainfall in the study area. These similar values suggest that the groundwater issuing at Kelvin Canyon spring is recharged from infiltration of rainwater with virtually no fractionating evaporation in the vadose zone. This interpretation is supported by the observation that the isotopic composition of several spring water measurements plot roughly on the local meteoric line (Figure 27). Evaporative fractionation would result in heavier $\delta^{18}O$ and δD values in water, with the resulting sample composition plotting to the right and below the meteoric water line. This trend was not observed in the Kelvin Canyon spring samples.

Upgradient sources of water to the spring were explored but ruled out. Immediately upgradient from the stream the developed properties are serviced by sewer systems. One developed area, northeast and upgradient of the study area, remains on septic systems. Any mixture of water in the spring from upgradient domestic sources is likely to be reflected in lighter $\delta^{18}O$ values, possible elevated nitrate concentrations, and younger tritium ages in the spring than are currently found.

The potential for recharge of groundwater through fissures is greatest in the active slide areas of the study area. This type of surface fissure recharge is most likely to occur once runoff begins overland and through the canyons. As mentioned in the section on water budgets, single storm events with rainfall totals > 20 mm were most likely to produce excess runoff and the potential for fissure recharge. In a fairly steady rainfall event, runoff typically occurs after about 20 to 30 minutes of rainfall. It is likely that the water with the heavier isotopic values is involved in initial saturation of ground and contributes little to runoff. The calculated weighted $\delta^{18}O$ average for these events, and therefore fissure recharge water, is –6.2 ‰.

Assuming recharge from either infiltration or fissure recharge, the groundwater isotopic composition would then be expected to range from –5.7 to –6.2 ‰. It is likely that both methods of recharge play a role and that groundwater isotopic composition reflects a balance between the two values.

An examination of the groundwater isotopic values in individual wells reveals some interesting observations. Several wells (WW2A, LCC1, WW12, FW, FSW, and PTG) have annual $\delta^{18}O$ averages more negative than –6.2 ‰. Several wells with annual $\delta^{18}O$ averages within the –5.7 to –6.2 ‰ range stated above have monthly values lighter than –6.2 ‰. These isotopically-lighter values suggest that groundwater in some areas is influenced by an isotopically-depleted source or that mixing does not perfectly homogenize the groundwater reservoir that may be episodically recharged. As mentioned before, the residences in the area are serviced by septic systems. In addition, groundwater recharge in urbanized areas can be increased by leaking pipes and irrigation.

As discussed previously, landscape irrigation is less likely to contribute significantly to recharge because of high summertime evaporation potential and the potential for undetected leaking from water supply pipes has been greatly lessened by the placement of the pipes above ground where leaks can be detected quickly and easily. Because septic system discharge places water directly into the subsurface and therefore into the groundwater body, the need for evaluation of this potential source is great. Domestic water $\delta^{18}O$ values averaged -11.3 ± 0.1 ‰ during the study period. Because the groundwater isotopic composition (-5.7 ‰) flowing into the housing area is so close to the range of rainfall-recharged isotopic values stated above (-5.7 to –6.2 ‰), it is difficult to distinguish between groundwater inflow and rainfall sources. Combining those two sources as one and using mass balance calculations, the percentage of recharge within the Altamira Canyon groundwater basin attributable to domestic water input can be estimated. Table 23 lists the stable isotope endmembers used and the general mass balance equations.

In order to use mass balance calculations to estimate domestic water contribution, steady-state conditions must be met. These steady state conditions would be reached if the groundwater body in Altamira Canyon was homogeneous and had a residence time of less than 50 years. The area has been developed for approximately 50 years and a residence time of water less than that would allow for complete mixing of domestic water into the groundwater body. However, if residence time of the groundwater body is longer than 50 years, it is unlikely that domestic water would be completely mixed into the

TABLE 23. STABLE ISOTOPE MASS BALANCE PARAMETERS.

Stable isotope endmembers ($\delta^{18}O$ in ‰):

Domestic water	-11.3
Rainfall/subsurface water	-5.7 to –6.2
Groundwater in Altamira Canyon wells	-5.8 to –6.4
Groundwater in Portuguese Bend wells	-5.4 to –6.6

General mass balance equations:

$$Q_T = Q_D + Q_R$$

$$Q_T\delta_T = Q_D\delta_D + Q_R\delta_R$$

where Q_T, Q_D, and Q_R represent total % of groundwater in wells, domestic water, and rainfall/groundwater inflow, respectively, and δ_T, δ_D, and δ_R represent their respective $\delta^{18}O$ values.

Results:

Domestic water contributed ~ 4 to 13 % of recharge to groundwater in Altamira Canyon and ~ 0 to 16 % of recharge in Portuguese Bend.

system (therefore indicating non-steady-state conditions) and the fraction of domestic water contribution predicted by mass balance calculations would be low.

Average isotopic compositions in the Altamira Canyon basin wells range from –5.8 to –6.4 ‰. Based on stable oxygen isotope mass balance calculations, the percentage of domestic water involved in groundwater recharge ranges from 4 to 13 %, comparable to the 14 to 21 % range obtained from the 1997-98 water budget calculations, but significantly lower than the long-term (average year) expected contribution of ~ 57%. These results imply that, during the El Nino study year, domestic water input played a small role in groundwater recharge. However, the significantly lower percentages obtained via the mass balance calculations suggest that conditions in the groundwater body are probably not steady-state. This conclusion can be tested by calculating the residence time of water in the Altamira Canyon basin.

An approximation of residence time can be obtained by estimating the volume of groundwater in the basin and dividing it by the rate of input of water to the groundwater body. However, the accuracy of this calculation is hindered by several limitations. Within the landslide, the slide plane provides a reasonable lower boundary for the saturated zone. However, the lower limit of the saturated zone in areas topographically higher than the landslide is undefined and difficult to determine. The thickness of the saturated zone throughout the basin can be approximated by extending the average saturated thickness in the landslide over the entire basin area. Because it is not uncommon for a saturated zone to thin out as it approaches the lateral boundaries of a basin, this extrapolated thickness would represent a maximum value. The porosity of the

subsurface material is also unknown and can be approximated based on likely subsurface lithologies. A porosity of 0.35 is typical for silty/clayey soils and was chosen for the calculation. The groundwater basin boundaries are also assumed to coincide with the boundaries of the surface drainage basin.

Keeping in mind the limitations discussed above, a first-order approximation of groundwater residence time in the Altamira Canyon basin was calculated. The resulting age was ~ 135 years and was based on an average saturated thickness of 10.4 meters (~ 34 feet), a porosity of 0.35, and a basin area of 3.3 km^2. This residence time is longer than the 50 years supporting the likely presence of non-steady-state conditions in the Altamira Canyon basin. Residence time estimates were also calculated using tritium concentrations and will be discussed in that particular section of this dissertation.

Average isotopic compositions in the Portuguese Bend wells range from –5.4 to –6.6 ‰. Using the same mass balance technique and assumptions from above, the estimated amount of groundwater recharge provided by domestic water input in the Portuguese Bend groundwater basin ranges from 0 to 16 %. Again, these values correspond closely with the 6 to 8 % range obtained in water budget calculations and are slightly less than the long-term, average estimate of ~ 23%. Hydrological parameters are even less constrained in the Portuguese Bend basin, making quantitative estimates of residence time difficult.

In the Portuguese Bend basin, average groundwater $\delta^{18}O$ values in the wells remain close to rainfall, or slightly lighter in developed areas. Well W973 is an

exception; with an yearly average concentration of –5.4 ‰, it is slightly heavier isotopically than other groundwater well samples and heavier than average rainfall (-5.7 ‰). Heavier groundwater isotopic values could be obtained in several ways: 1) evaporative fractionation prior to or during recharge, 2) mixing with heavier water from another source, and/or 3) recharge with a higher percentage of isotopically-heavier rainfall. No other sources of isotopically-heavier water have been identified in the study area, and the rainfall events with heavier isotopic compositions tend to be smaller in amount or at the beginning of storms. Therefore, options 2 and 3 seem unlikely. Because little natural surface drainage remains in the area, much of the Portuguese Bend landslide area has surface depressions and, according to Perry Ehlig (personal communication, August 1999), a significant amount of water received during rainfall events and concentrated canyon runoff sits in these depressions prior to infiltration into the ground. This collection of water prior to infiltration could allow for evaporative fractionation of the water, with the remaining heavier portion serving as recharge to the groundwater body in the vicinity of well W973. The occurrence of evaporative fractionation prior to recharge is supported by the plotting of W973 samples below but parallel to the meteoric water line (Figure 27). Recharge by direct rainfall infiltration, and subsequent dilution of groundwater, is also supported by the observation that ion concentrations and conductivity in well W973 generally decrease following the start of the rainy season. Rainfall contains less dissolved ions than groundwater and a decrease in groundwater TDI might indicate dilution by infiltrating precipitation. Well ISE also plots below the LMWL. $\delta^{18}O$ values in this well were heavier in the dryer initial part of

the study period (September through January), suggesting potential evaporative recharge conditions. However, the $\delta^{18}O$ composition became lighter following periods of rainfall. This suggests fairly rapid recharge of rainfall to the well, an observation supported by a corresponding rise in groundwater levels in nearby monitoring wells.

Several other wells (WW2A, FSW, LCC1, PTG, and W6K) also plot below the meteoric water line, but might be best explained as resulting from mixing of domestic water with average rainfall composition as indicated by the mixing line shown on Figure 27.

$\delta^{18}O$ values in well N change to become significantly lighter from March to April and remain so through the end of the 1997-98 study period. This difference indicates an apparent change in source contribution during the latter part of the study period with an increase in domestic water contribution. This may be an indication of flow along the previously-discussed head graben of the Abalone Cove landslide which is currently conducting water from the more developed Abalone Cove landslide to the Portuguese Bend landslide (P.L. Ehlig, personal communication, August 1999).

C. TRITIUM

Tritium, the radioactive isotope of hydrogen with a half-life of 12.43 years (Unterweger et al., 1980), can be used to estimate relatively young groundwater ages. During the 1960s, testing of nuclear bombs released significant amounts of tritium into the atmosphere (Figure 28). As this tritium rained out and recharged groundwater, a tritium spike could be identified in groundwater recharged during this time period. Today, groundwater with tritium concentrations greater than 15 probably contains some

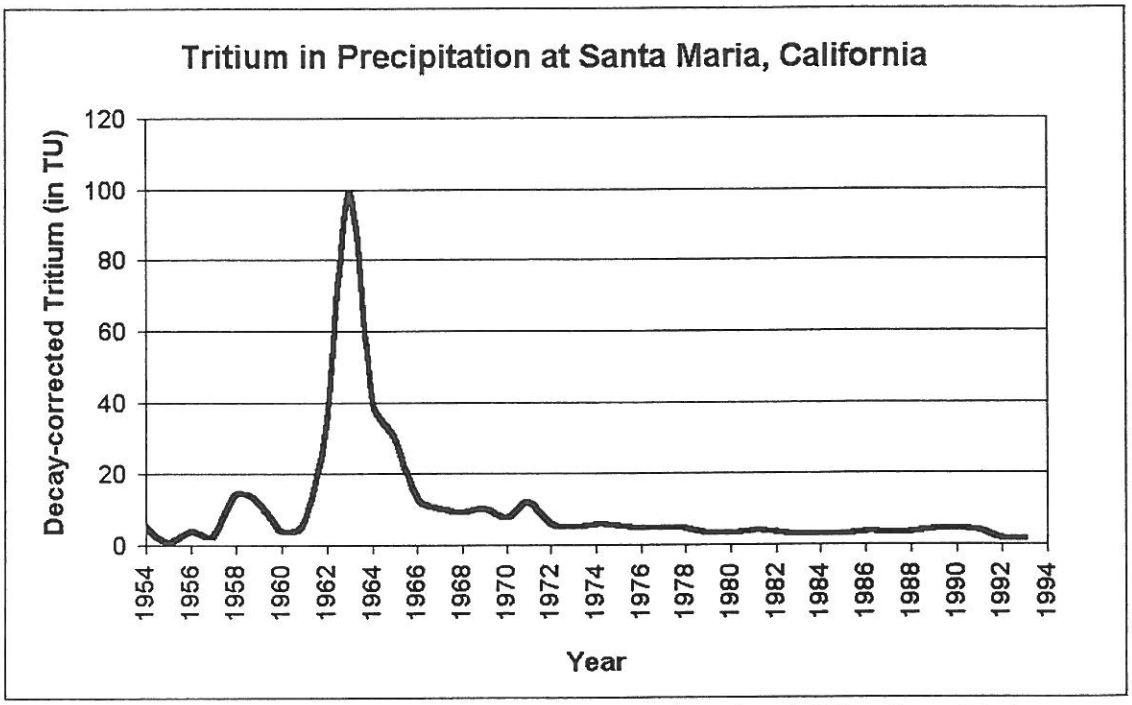


Figure 28. Graph of decay-corrected tritium concentrations in rainfall at Santa Maria, California from 1954 through 1993. The data are corrected to 1998 values. The peak records the influx of tritium resulting from testing of nuclear bombs.

bomb component in its composition. Even for younger waters a quantitative interpretation of groundwater age can be made if the tritium input values and the dynamics of mixing in the recharge zone are known.

Water samples to be analyzed for tritium were collected directly into 500 ml HDPE bottles and stored at room temperature. Tritium samples were analyzed at the Environmental Isotope Laboratory at the University of Waterloo, Canada. The samples were enriched approximately 15 times by electrolysis (Taylor, 1977) and then counted using a liquid scintillation counting technique (Drimmie et al., 1993). The detection limit for enriched samples is 0.6 ± 0.8 TU.

Rainfall

Two rainfall samples were collected after the initial study period (during March 1999) and analyzed for tritium concentration. Reported tritium values for samples RT1 and RT2 were 2.0 and 2.8 tritium units (TU), respectively (see Table 24). Tritium values for rainfall samples are illustrated on Figure 29. These values are similar to decay-corrected values of 2 TU determined (using the Ottawa correlation) for Santa Maria, California, a location with a similar coastal setting to the study area (J. Izbicki, personal communication, Dec. 1998). Figure 28 shows a graph of the tritium concentrations at Santa Maria over an approximate 40-year period.

Domestic Water

One domestic water sample (H1) was collected in March 1999 and analyzed for tritium. As stated earlier, the domestic water supply to the study area is a mixture of northern California and Colorado River water. Sample H1 had a reported tritium value of

TABLE 24. RESULTS OF TRITIUM ANALYSES ON GROUNDWATER RAINFALL, AND DOMESTIC WATER SAMPLES

		Sample Collection Dates			
	Sample Type	Sep-97	Feb-98	May-98	Mar-99
N	well	2.4		3.5	
WW4	well	0.9		1.5	
CB	well	3.2		4.2	
UN	well	1.5		2.1	
W6K	well	5.8		10.4	
ISE	well	4.2		4.9	
WW13	well	3.2			
EB	well	<0.8			
KCS	spring		1.2		
KCW	well				3.7
RT1	rainfall				2.0
RT2	rainfall				2.8
H1	domestic water				6.5

(Results are reported in tritium units (TU) with an average uncertainty of $\pm$ 0.6)

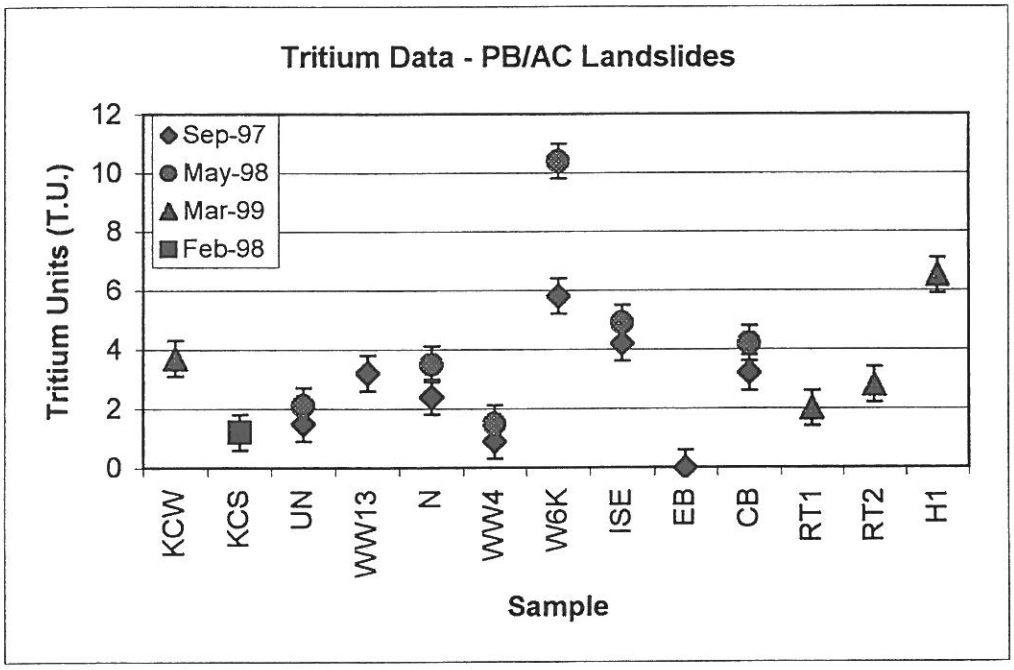


Figure 29. Graph of tritium data from locations in study area. Samples are plotted from left to right in order of decreasing elevation. Error bars represent $\pm$ 0.6 TU uncertainty. Wells with ages from ~ 2 to 8 TU suggest a modern age (< 5 to 10 years), possibly influenced by mixing with domestic water. Well EB shows age greater than ~ 45 years.

6.5 TU (Figure 29). Tritium concentrations in the Pacific northwest and the northern interior of the continental U.S. are typically higher than those found in the south (Michel, 1989). These concentrations are produced by the latitudinal dependence of stratospheric exchange of water vapor and a decreasing influence of oceanic water vapor exchange as air masses move inland. As a result, water supplied from those areas would be expected to have higher tritium concentrations that those measured in local rainfall.

Groundwater

Several groundwater samples were analyzed for tritium and selected samples were analyzed from two different months during the study period. The results of these analyses are reported in Table 24 and a graph of the values is presented in Figure 29. Tritium concentrations in groundwater ranged from < 0.8 to 10.4 TU and without exception, in wells sampled more than once, the values appear to have increased from September 1997 to May 1998. However, with the exception of well W6K, which showed an increase from 5.8 TU in September to 10.4 TU in May, the increases are within analytical uncertainty and could essentially represent similar values.

In the study area, the lack of known tritium input values for past years limits a more quantitative approach. The spring at Kelvin Canyon has a reported tritium concentration of 1.2 TU. Assuming no mixing during recharge, an estimated age range of the spring water can be obtained by using tritium input rainfall values from Santa Maria, California and the following decay equation:

$$t = -17.93 \{\ln (a_t{}^3H / a_o{}^3H)\}$$

where t = the age in number of years, $a_t{}^3H$ = the measured tritium value in groundwater, and $a_o{}^3H$ = the input tritium value of rainfall.

The low tritium concentration rules out the presence of a "bomb" tritium spike and therefore constrains the time of recharge to before the mid-1950s or after the 1970s. Decay calculations yield potential age estimates for spring water of ~ 9 or 45-50 years. The spring occurs naturally as the result of flow along sedimentary bedding planes, with flow emerging where the canyon wall intersects the strata. It is reasonable to assume that flow along the bedding planes will occur more rapidly than through the relatively less-permeable strata on either side. Although there is no clear way to further constrain the age estimate, the potential for more rapid flow through the subsurface along bedding planes and the proximity of the spring to the recharge area in the upper portion of the basin lend support to the shorter residence time of ~ 9 years. Even shorter residence times (less than a decade) can be ruled out with several lines of evidence. If the spring represented rapidly-recharging water, the tritium values would mirror rainfall values and the stable isotopic and chemical composition of the spring water would fluctuate with rainy season precipitation. Although the flow from the spring increased in response to increased periods of rainfall, the chemical composition and $\delta^{18}O$ concentrations remained remarkably constant throughout the study period. It appears then that groundwater in the upper portions of the study area has a minimum residence time of approximately a decade resulting in attenuation of tritium signals and other geochemical parameters in the spring water. The increase in spring flow following rainy periods most likely represents flow

pulses of older, well-mixed water being pushed by increasing pore pressure from episodic upgradient recharge.

As groundwater flow continues downgradient, there would be an expected increase in age, yielding tritium concentrations below the detection limit. However, this trend is not observed in the lower portions of the Altamira Canyon basin. Instead, tritium concentrations vary throughout the basin (from < 0.8 to 4.2 TU). In wells along Altamira Canyon (UN and WW4), tritium concentrations resemble those found in Kelvin Canyon spring (Figure 29). These similar tritium concentrations, as well as fairly uniform ion and isotope compositions, suggest a more rapid passage of groundwater downgradient within Altamira Canyon, possibly through more permeable alluvial material. The presence of this alluvial material is supported by the larger volumes of water removed by pumping from wells located in close proximity to the canyon (Figure 7 and Table 8).

In wells located away from the canyon, where groundwater compositions are more varied and pumping rates drop off, it is reasonable to assume that groundwater is flowing through less permeable materials and therefore may have a longer residence time. These wells (i.e. WW2, CB, and SG) are typically located in developed areas of Altamira Canyon where mixing of various water sources prohibits direct use of decay equations for age determination.

When it is difficult to obtain quantitative age values, for instance if mixing of multiple sources is possible, qualitative interpretations can be made using the following guidelines (Clark and Fritz., 1997):

<0.8 TU	Submodern – recharge prior to 1952
0.8 to ~ 4 TU	Mixture between submodern and recent recharge
5 to 15 TU	Modern (<5 to 10 years)
15 to 30 TU	Residual "bomb" tritium present; and
> 30 TU	Considerable component of recharge from 1960s or 1970s.

In wells away from Altamira Canyon, tritium concentrations range from 3.2 to 4.2 TU (Table 24). These values fall within the qualitative range of 0.8 to ~ 4 TU suggesting mixture between submodern (> ~ 45 years) and recent recharge (i.e. domestic water or rainfall). Approximations of groundwater residence time based on reservoir volume and input rates (see stable isotope section) yielded an estimated age of ~ 135 years. Considering the potential for lithologic heterogeneities within the basin, the mixing relationships present, and the uncertainties in the calculations, it is likely that groundwater residence time in the Altamira Canyon basin falls somewhere between the decade-old water at Kelvin Canyon spring and the > 135-year age approximated from hydrologic parameters, perhaps on the order of several decades.

The one exception to wells sampled in the lower portion is well EB (Figure 7). The measured tritium concentration in this well is < 0.8, suggesting that recharge of water currently found in this well occurred prior to the 1950s. This qualitative estimate, along with the unique geochemical signature and warmer temperatures, supports the idea that water in the vicinity of this well may represent deeper circulation patterns of water within the peninsula.

In the Portuguese Bend basin, with the exception of well W6K, tritium concentrations range from 2.4 to 4.9 TU (Table 24) suggesting a mixture of submodern water with recent recharge. Well W6K has tritium concentrations ranging from 5.8 to 10.4 TU which fall within a modern age range of < 5 to 10 years.

D. SUMMARY

In general, the chemical compositions of the groundwater bodies in both basins are dominated by sulfate with no apparent dominant cation. The ion concentrations between wells in the Altamira Canyon basin are less varied than those wells in the Portuguese Bend basin.

With few exceptions, the groundwater composition of the study area reflects the weathering of dolomitic rocks, driven by the oxidation of pyrite and accompanied by some cation exchange. Differences in the compositions between the two basins likely reflects the enhanced weathering environment present in the Portuguese Bend basin as a result of continued landslide movement.

During the study period, recharge to the groundwater body within the Altamira Canyon basin appears to be the result of fissure flow within the canyon, with contributions from infiltration of rainfall in the upper portions of the basin and domestic water within the Abalone Cove landslide area. Groundwater appears to have a residence time of several decades and responds fairly quickly to rainfall as a result of pore pressure waves. Recharge within the Portuguese Bend basin occurs primarily through infiltration from surface depressions or flow down surface fissures with minor contributions from domestic water.

There appears to be a component of water which circulates deeper within the peninsula, manifesting itself in the unique geochemical properties in well EB. This deeper water circulation could have an influence on landslide movement and presents a topic for further study.

CHAPTER IV

CONCLUSIONS

The correlation between rainfall and landslide movement in the Portuguese Bend landslide area has been clearly documented (Ehlig, 1992). The purpose of this study was to clarify the sources and mechanisms of recharge to the groundwater systems in the area and discuss the potential effects of groundwater dynamics on landslide movement. This investigation was completed by using geochemical and isotopic methods to complement more traditional hydrologic techniques of investigation. The results of the research suggest that geochemical and isotopic techniques provide additional information which can prove valuable in interpreting hydrologic systems.

The groundwater dynamics of a landslide area are influenced by the sources of water to the area, the residence time of the water in the area, the interaction of water with other sources of water and with the surrounding lithologies, and the movement of water through the area. The extensive groundwater dewatering and monitoring program in the Portuguese Bend and Abalone Cove landslides provided a unique opportunity to examine groundwater in great detail and over a significant period of time. The conclusions from this study are presented below:

- **Recharge to the groundwater body in Altamira Canyon basin during the 1997-98 study year (El Nino period) was accomplished via fissure flow within the canyon (49-75%), with contributions from infiltration of rainfall in the upper portions of the basin (4-37%), and domestic water influx (14-21%). This contrasts with recharge expected during a normal rainfall year, when domestic**

water constitutes over 50% of input to the groundwater system with canyon fissure recharge and infiltration making up the remainder.

The contribution of domestic water is readily apparent in the lighter $\delta^{18}O$ concentrations in the lower elevation wells in developed areas. Influence of residential septic systems is also indicated by the increase in nitrate concentrations in groundwater within the developed areas.

- **During the study year (1997-98 El Nino period), recharge to the groundwater body in the Portuguese Bend basin was provided by infiltration and fissure recharge (66-73%) with minor contributions from subsurface graben inflow (21-26%) and domestic water influx (6-8%). In contrast, long-term recharge (as evidenced by a normal rainfall year) is anticipated to occur primarily through contributions from domestic water (~ 23%) and graben inflow.**

It is difficult to distinguish between the amounts of water contributed by fissure recharge versus infiltration. Longer-term recharge estimates could be better refined by constraining the amount of water recharging down fissures during storms and the volume of water moving along the graben.

- **In both landslides, groundwater response to rainfall occurs within one to three months following periods of higher rainfall. It appears that this response is not the actual movement of water through the groundwater system (which could take decades), but rather a propagation of hydraulic pore pressure through the groundwater system.**

This increased flow is manifested as larger volumes of discharge at Kelvin Canyon spring in the Altamira Canyon basin and as periodic rises in groundwater levels in portions of the Portuguese Bend basin. The most rapid groundwater level response in wells in the Portuguese Bend landslide occurs near landslide boundaries or surface fissures. Elevations in pore pressure which extend to the landslide base would be expected to intensify during winter rainy periods and indeed, during periods of high rainfall, landslide movement increases. The effectiveness of the dewatering wells in the Abalone Cove landslide area is evident by the lack of landslide movement response even in periods of heavy rainfall such as those experienced in this El Nino study year. Although small amounts of creep are occurring, the Abalone Cove slide has been fairly stable over the past few years.

A decades-long residence time of groundwater is supported by several lines of evidence. Groundwater emerging at the spring possessed a fairly consistent geochemical and isotopic composition over the 1997-98 study year, suggesting that groundwater represented in the spring had remained in the subsurface long enough for storm or seasonal variations to become attenuated. The tritium value reported in the spring yielded an age of approximately nine years. In addition, the groundwater in the spring also exhibited a major ion chemical composition which differed from average rainfall, suggesting that time had passed to allow interaction with and dissolution of subsurface materials.

Residence time of groundwater in the Altamira Canyon basin may vary somewhat. Lower-elevation wells near the canyon (i.e. WW4, UN, and SB) may be

receiving water from upslope areas via passage through alluvial material within the canyon. Water flowing through this material would be expected to move more quickly and have less interaction with domestic water. This hypothesis is supported by the observation that wells near the canyon have similar $\delta^{18}O$ and tritium values to those found in Kelvin Canyon spring. In contrast, wells located farther from the canyon have a more varied chemical composition and $\delta^{18}O$ values indicative of domestic water influence. Tritium concentrations in these wells suggest a mixture of submodern (> ~ 45 years) water and recent recharge. Qualitative assessment of groundwater residence time in Portuguese Bend reveals an estimated age ranging from recent (< 5 – 10 years) to submodern.

- **There may be a component of water which circulates deeper within the peninsula. The presence of deeper circulating water could have important implications for landslide movement, potentially exerting hydraulic pressure from beneath the landslide plane.**

  This deeper circulation pattern may be reflected in well EB which exhibits a warmer average temperature than those in other wells, a tritium age of greater than > 45 years, a strong sulfide smell, and a geochemical signature that is unique from any other well in the study area. It appears to have some seawater influence, but its longer residence time and warmer temperatures suggest a possible association with a deeper-circulating water source. If there is a source of deeper water circulating upward, there is the potential for upward pore pressure to be applied on the underside of the Abalone Cove slide plane. This interpretation would require further work to

confirm. Other unique wells may also reflect combinations of water and recharge conditions that in general do not reflect the overall conditions of the study area.

- **Movement of the Portuguese Bend landslide increases following periods of rainfall (Ehlig, 1992). During the study year, there was an observed gain in groundwater storage of ~ 0.7 x 10^5 m^3 (57 acre-ft). In a normal rainfall year, there was an measured loss in storage of ~ - 0.4 x 10^5 m^3 (32 acre-ft) with landslide movement continuing even during periods of little to no rainfall.**

The weathering and mechanical breakdown in the landslide mass has produced fine-grained clay material which impedes the easy flow of groundwater. This results in lower groundwater recharge as evidenced by the lower groundwater recovery rates measured in dewatering wells within the landslide. This lower recharge rate hinders attempts to slow landslide movement by pumping groundwater. As a result, the landslide moves continuously, even during periods between rainfall seasons. The lower permeability results in a slide mass that is fairly saturated year-round, as evidenced by consistent groundwater levels in most monitoring wells. An already saturated slide mass is quick to respond to periods of rainfall with an increase in hydraulic head, in turn producing increased pore pressure which can result in increased landslide movement. Because of the low permeability of landslide material the recovery of the groundwater system to pre-rainfall levels is a slow process requiring several months, and allowing a high potential for landslide movement to extend for a significant period after precipitation events.

This persistent movement could also be aided by the continuous erosion of material supporting the toe of the landslide and/or hydraulic pressure acting on the underside of the landslide base.

The conclusions of this investigation are significant in recognizing and constraining the dominant mechanisms of recharge to the groundwater bodies of these two landslides. However, the specifics of the relationship of groundwater to landslide movement are still unclear. It is possible that groundwater exerts pressure on the slide planes from both above and below. Figure 30 presents a simple model of possible groundwater influence in the landslides of the study area. The potential for hydraulic pressure on the underside of the slide planes in both landslides has not been fully investigated, but has important implications for the mitigation of landslide movement. In addition, it is important to recognize that the residence time of groundwater within the groundwater body appears to be on the order of decades, and further supports the concept that the relationship between groundwater dynamics and landslide movement may be the result of pore pressure propagation and not the actual movement of groundwater through the saturated materials.

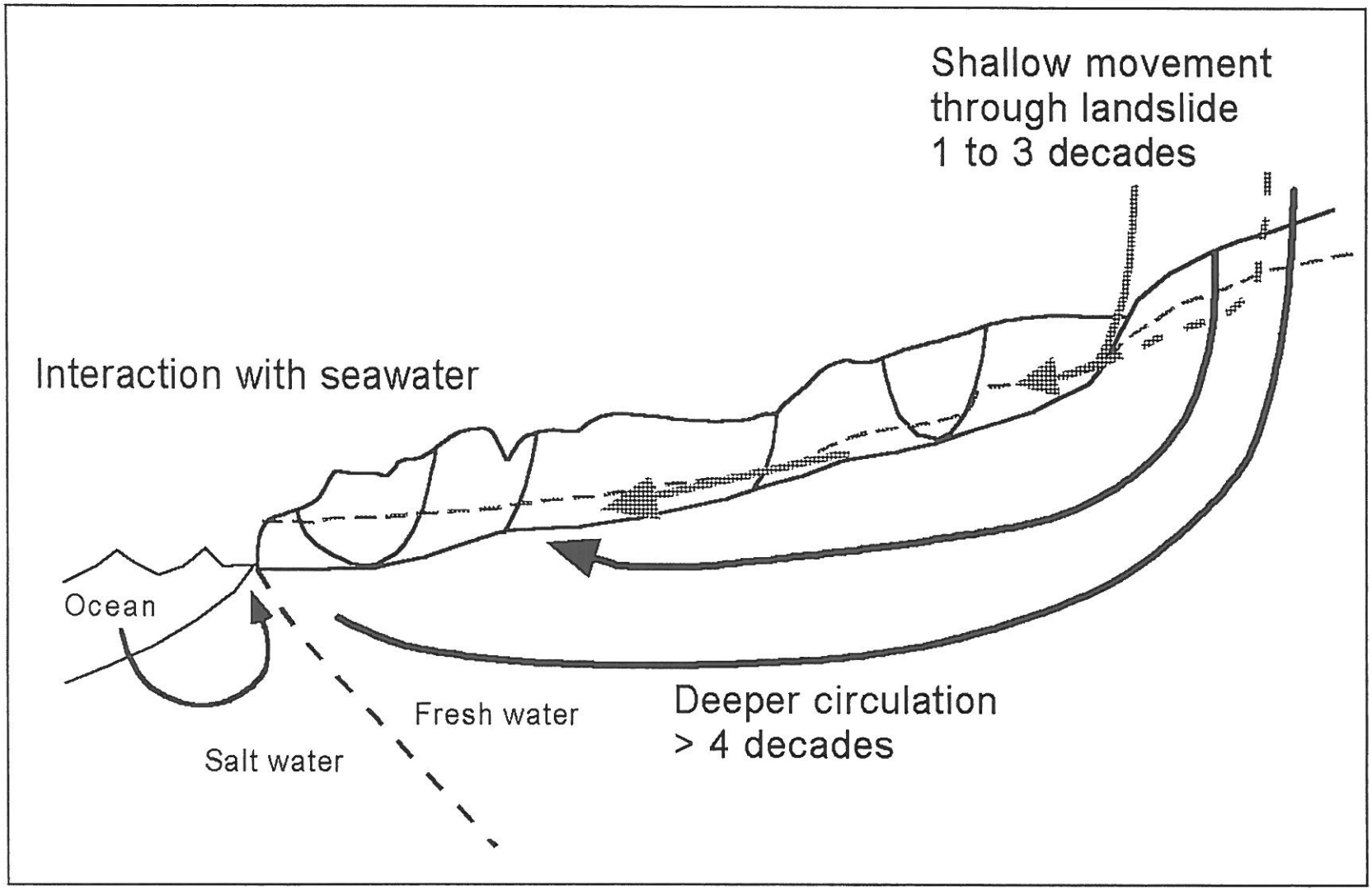


Figure 30. Model showing possible groundwater flow paths within the stuy area.

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TABLE A-1. WELL CONSTRUCTION DETAILS FOR DEWATERING AND MONITORING WELLS

Well No.	Location[1]	Type[2]	Long.(E)	Lat.(N)	Casing Diameter (in.)	Total Depth (ft bgs)	Screen Interval (ft)	Elev. top of well (ft asl)	Elev. bot. of well (ft asl)	Elev. of slide base (ft asl)
EB	AC	PW	4174465	4017965	6	145	125-105	86	-59	-20
CB	AC	PW	4174123	4017982	6	133	113-53	64	-69	< -80
WW2A	AC	PW	4174722	4018965	6	unk	unk	170	unk	10
LCC1	OAC	PW	4173514	4020337	6	148	unk	415	267	osl
WW4	AC	PW	4175284	4018914	unk	84	unk	221	137	140
WW3	AC	PW	4174945	4019372	unk	unk	unk	279	unk	117
SG	OAC	PW	4175303	4019870	6	200	160-140	364	164	osl
WW12	OAC	PW	4174290	4020874	6	126	unk	383	257	osl
UN	OAC	PW	4175849	4020933	6	180	140-120	404	224	osl
WW13	OAC	PW	4175024	4020674	6	113	unk	386	273	osl
SB	OAC	PW	4175570	4020603	6	180	160-120	364	184	osl
WW11	OAC	PW	4175696	4019915	6	116	unk	315	199	osl
WW8	OAC	PW	4176311	4020265	unk	unk	unk	350	unk	osl
W6A	PB	PW	4176975	4020030	6	160	150-80	386	226	unk
N	PB	PW	4177539	4019795	unk	unk	unk	377	unk	233
FW	PB	PW	4177153	4019995	6	112	unk	373	261	unk
W973	PB	PW	4177587	4020235	unk	unk	unk	355	unk	unk
ISE	PB	PW	4178680	4018028	6	172	?172-152	179	7	~sea level
FSW	PB	PW	4177425	4018265	6	117	105-75	167	50	~60
W6K (2 wells)	PB	PW	4177051	4018245	6	A = 120 B = 110	unk	181	A = 61 B=71	~ 51
PTG	OPB	PW	4175850	4017654	unk	unk	unk	184	unk	unk
W2D	PB	MW	4177050	4019400	2	150	unk	343	193	unk
W4E	PB	MW	4177935	4019412	4	unk	unk	303	unk	219
WLT	PB	MW	4177206	4018809	6	114.5	unk	281	166.5	164
B88-4	PB	MW	4177677	4020278	2	23	unk	343	320	281
B88-5	PB	MW	4178530	4019770	6	43	unk	299	256	254
B88-9	PB	MW	4178305	4019723	6	70	unk	304	234	233
PBS-1	PB	MW	4178700	4018018	2	180	unk	180	0	4
PBS-2	PB	MW	4177724	4018166	2	115	95-75	156	41	60
PBS-3	PB	MW	4177839	4018412	2	216.5	unk	216	-1	96
PBS-4	PB	MW	4177855	4018818	2	100	90-70	249	149	152
PBS-5	PB	MW	4177948	4019248	2	100	80-60	288	188	201
PBS-6	PB	MW	4178109	4019632	4	100	90-70	310	210	222
PBS-7	PB	MW	4178274	4019938	2	141.6	unk	299	157	269
PBS-9	PB	MW	4179010	4018552	2	90	70-50	185	95	98
PBS-10	PB	MW	4178218	4018350	unk	212	unk	170	-42	44
B96-12	PB	MW	4178393	4019950	2	14	unk	294	280	283

Notes:

[1] Location of well with respect to landslides (ex. OAC = outside Abalone Cove landslide, PB = Portuguese Bend).

[2] Type of well, either pumping or monitoring (ex. PW = pumping well).

unk = value unknown

osl = outside slide limit

asl = above mean sea level

APPENDIX B

GEOCHEMICAL DATA

TABLE B-1. GEOCHEMICAL AND ISOTOPIC DATA FOR GROUNDWATER SAMPLES

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
EB-9-1	03-Sep-97	28	8100	72	1738	237	64	1032	3019	539	-	-	-6.0
EB-10-1	09-Oct-97	27	8500	92	1611	243	66	1158	2815	520	29	0	-6.0
EB-11-1	13-Nov-97	26	8200	89	1509	248	62	1014	2861	505	-	-	-6.0
EB-12-1	10-Dec-97	27	8900	83	1541	241	62	1137	2704	520	28	0	-5.9
EB-1-1	16-Jan-98	26	8050	95	1629	254	67	1081	2662	520	-	-	-5.9
EB-1-2	16-Jan-98	26	8050	81	1645	252	67	1064	2966	508	30	0	-6.1
EB-2-1	13-Feb-98	27	8200	88	1678	255	62	1005	3033	476	**37**	0	-6.0
EB-3-1	16-Mar-98	25	8100	91	1643	243	67	833	3176	520	**34**	0	-5.9
EB-4-1	16-Apr-98	28	8500	82	1627	246	63	901	3358	517	**36**	1	-6.0
EB-5-1	15-May-98	27	8400	74	1483	219	63	951	2941	639	**34**	0	-6.0
EB-6-1	24-Jun-98	28	7900	83	1526	225	62	902	2888	520	31	0	-6.0
EB-7-1	22-Jul-98	28	7400	73	1497	233	61	835	3515	542	31	0	-6.0
	20-Aug-98	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Average		27	8192	84	1594	241	64	993	2995	527	32	0	-6.0
Samp. St. Dev.		1	370	8	81	11	2	110	252	39	3	0	0.1
% Deviation		3	5	9	5	5	4	11	8	7	10	124	1

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
CB-9-1	03-Sep-97	24	10500	390	1052	1112	67	1224	5489	466	-	-	-5.7
CB-10-1	09-Oct-97	24	10500	406	1265	1084	74	1489	5139	449	30	0	-6.2
CB-11-1	13-Nov-97	24	10200	398	1051	1159	56	1539	5283	410	22	0	-6.3
CB-12-1	10-Dec-97	26	13100	356	1561	842	83	2642	4392	434	23	0	-5.7
CB-1-1	16-Jan-98	24	8500	367	553	1004	40	811	5181	405	21	0	-6.0
	13-Feb-98	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CB-3-1	16-Mar-98	21	8200	439	539	1180	39	593	5362	422	**25**	1	-6.4
CB-4-1	16-Apr-98	21	7950	391	528	850	38	758	4773	386	**23**	0	-5.9
CB-5-1	15-May-98	21	8800	389	734	1162	48	818	4980	432	17	0	-6.1
CB-6-1	24-Jun-98	22	8700	380	847	984	58	1050	5229	447	19	0	-6.4
CB-7-1	22-Jul-98	23	7300	367	575	940	43	852	6076	425	20	0	-6.3
	20-Aug-98	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Average		23	9375	388	871	1032	55	1177	5190	428	22	0	-6.1
Samp. St. Dev.		2	1711	24	355	127	16	604	444	23	4	0	0.3
% Deviation		8	18	6	41	12	29	51	9	5	17	205	4

TABLE B-1 (cont'd). GEOCHEMICAL AND ISOTOPIC DATA FOR GROUNDWATER SAMPLES

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
WW2A-9-1	03-Sep-97	28	4650	420	368	236	20	335	2009	403	-	-	-6.2
WW2A-10-1	09-Oct-97	28	4500	449	362	238	21	340	2098	388	-	-	-6.6
WW2A-11-1	14-Nov-97	26	4410	443	371	249	19	342	2069	442	39	5	-6.5
WW2A-12-1	10-Dec-97	27	4260	454	368	247	20	353	2044	386	38	8	-6.4
WW2A-1-1	16-Jan-98	27	4400	458	380	257	21	351	2031	417	34	7	-6.5
WW2A-2-1	13-Feb-98	26	4420	459	404	273	21	332	2038	481	**27**	6	-6.5
WW2A-3-1	16-Mar-98	26	4380	468	384	257	22	284	1757	422	**27**	7	-6.5
WW2A-4-1	16-Apr-98	27	4410	457	399	257	21	334	2024	417	**26**	9	-6.4
WW2A-5-1	15-May-98	24	4320	441	393	289	22	308	2129	474	29	7	-6.4
WW2A-6-1	24-Jun-98	25	4100	442	389	266	22	**309**	2108	417	26	5	-6.5
WW2A-7-1	22-Jul-98	25	3980	441	363	265	21	272	2315	459	38	6	-6.4
WW2A-7-2	22-Jul-98	25	3980	429	371	255	20	272	2249	456	35	6	-6.5
WW2A-8-1	20-Aug-98	26	4110	396	347	222	20	336	2341	420	32	7	-6.4
Average		26	4302	443	377	255	21	321	2093	429	32	7	-6.4
Samp. St. Dev.		1	204	19	16	17	1	29	150	31	5	1	0.1
% Deviation		4	5	4	4	7	4	9	7	7	17	17	1

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
LCC1-9-1	03-Sep-97	25	4840	553	386	233	24	472	2162	364	-	-	-6.3
LCC1-10-1	09-Oct-97	24	4520	587	385	233	25	472	2129	347	25	12	-6.3
LCC1-11-1	13-Nov-97	21	4510	576	391	239	23	473	2110	410	27	13	-6.4
LCC1-12-1	10-Dec-97	22	4680	567	393	234	24	482	2090	339	32	21	-6.2
LCC1-1-1	16-Jan-98	23	4520	514	356	220	25	478	1782	400	30	21	-6.3
LCC1-2-1	13-Feb-98	22	4540	540	383	230	23	481	2121	437	**34**	21	-6.3
LCC1-3-1	16-Mar-98	22	4570	507	355	211	24	453	2030	422	**40**	22	-6.3
LCC1-4-1	16-Apr-98	23	4610	517	380	217	24	457	2192	339	**27**	22	-6.3
LCC1-5-1	15-May-98	24	4400	500	379	247	24	463	2143	312	**22**	23	-6.4
LCC1-5-2	15-May-98	24	4400	520	379	245	25	461	2066	351	**26**	23	-6.2
LCC1-6-1	24-Jun-98	23	4330	484	351	199	21	477	2021	447	31	23	-6.3
LCC1-7-1	22-Jul-98	22	4150	555	383	230	22	438	2332	515	27	24	-6.4
LCC1-8-1	20-Aug-98	23	4250	438	307	179	24	337	1935	491	27	24	-6.4
Average		23	4486	528	371	224	24	457	2086	398	29	21	-6.3
Samp. St. Dev.		1	182	41	24	19	1	38	131	63	5	4	0.1
% Deviation		5	4	8	6	9	5	8	6	16	16	19	1

TABLE B-1 (cont'd). GEOCHEMICAL AND ISOTOPIC DATA FOR GROUNDWATER SAMPLES

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
WW4-9-1	03-Sep-97	24	4700	496	400	291	20	423	2239	459	-	-	-5.9
WW4-10-1	09-Oct-97	19	4060	472	364	274	19	450	2061	425	-	-	-5.9
WW4-11-1	14-Nov-97	22	4730	526	404	317	18	422	2304	498	-	-	-6.0
WW4-12-1	10-Dec-97	22	4550	535	403	321	18	417	2360	456	35	9	-5.9
WW4-1-1	16-Jan-98	22	4500	532	401	327	20	423	-	-	31	10	-5.9
WW4-2-1	13-Feb-98	21	4310	510	401	331	18	432	2232	503	**37**	21	-5.6
WW4-3-1	16-Mar-98	21	4330	513	402	324	19	349	2306	508	**32**	16	-6.1
WW4-4-1	16-Apr-98	22	4380	494	372	322	18	393	2309	481	**28**	17	-6.0
WW4-4-2	16-Apr-98	22	4380	489	392	321	18	388	2194	474	**28**	16	-5.9
WW4-5-1	15-May-98	23	4470	452	367	305	19	360	2258	476	25	11	-6.0
WW4-6-1	24-Jun-98	22	4320	498	403	317	20	404	1700	498	30	10	-5.8
WW4-7-1	22-Jul-98	23	4240	389	300	240	19	339	2554	510	29	9	-6.0
WW4-8-1	20-Aug-98	22	4210	497	370	297	18	406	2430	493	30	9	-6.0
Average		22	4398	492	383	307	19	401	2246	482	30	13	-5.9
Samp. St. Dev.		1	190	39	30	26	1	34	211	25	4	4	0.1
% Deviation		5	4	8	8	8	4	8	9	5	12	34	2

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
WW3-9-1	15-Sep-97	26	4400	451	332	253	18	365	2045	351	-	-	-5.9
WW3-10-1	09-Oct-97	24	4280	472	340	268	18	401	2085	412	-	-	-5.9
WW3-11-1	13-Nov-97	23	4300	467	330	270	16	395	2111	415	38	5	-6.0
WW3-12-1	10-Dec-97	24	4330	484	343	281	17	403	2037	420	31	4	-5.9
	16-Jan-98	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	13-Feb-98	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
WW3-3-1	16-Mar-98	22	4230	453	340	268	18	388	1921	425	**39**	5	-6.1
WW3-4-1	16-Apr-98	23	4280	465	346	275	17	400	2059	427	**19**	5	-5.9
	15-May-98	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	24-Jun-98	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
WW3-7-1	22-Jul-98	23	3900	410	296	240	16	362	2216	417	34	6	-6.0
WW3-8-1	20-Aug-98	24	4100	418	320	253	16	400	2234	415	33	6	-5.9
Average		24	4228	452	331	264	17	389	2089	410	32	5	-6.0
Samp. St. Dev.		1	158	26	16	14	1	17	101	24	7	1	0.1
% Deviation		5	4	6	5	5	5	4	5	6	22	12	1

TABLE B-1 (cont'd). GEOCHEMICAL AND ISOTOPIC DATA FOR GROUNDWATER SAMPLES

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
SG-9-1	03-Sep-97	25	4520	464	356	269	18	455	1958	549	-	-	-6.1
SG-9-2	03-Sep-97	25	4520	475	359	268	17	463	1802	559	-	-	-6.0
SG-10-1	09-Oct-97	24	4330	462	355	280	16	423	1925	544	-	-	-6.1
SG-11-1	13-Nov-97	21	4320	448	352	286	15	456	1903	542	40	9	-5.9
SG-12-1	10-Dec-97	22	4260	495	355	289	15	465	1923	559	38	10	-5.8
SG-1-1	16-Jan-98	22	4090	499	356	288	16	452	1838	549	43	9	-5.7
SG-2-1	13-Feb-98	22	3880	441	338	261	14	416	1721	520	**40**	9	-5.9
SG-3-1	16-Mar-98	22	4330	532	376	305	17	479	1906	530	**39**	8	-6.1
SG-4-1	16-Apr-98	23	4220	466	355	272	16	449	1949	537	**28**	10	-6.0
SG-5-1	15-May-98	24	4280	420	355	274	16	468	1906	564	30	10	-6.1
	24-Jun-98	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
SG-7-1	22-Jul-98	23	4120	458	326	267	14	480	2126	608	43	11	-6.0
SG-8-1	20-Aug-98	24	4160	442	368	285	16	453	2253	571	40	10	-6.0
SG-8-2	20-Aug-98	24	4160	379	321	251	14	473	2167	559	36	10	-6.0
Average		23	4245	460	352	277	16	456	1952	553	38	9	-6.0
Samp. St. Dev.		1	173	38	15	14	1	19	148	22	5	1	0.1
% Deviation		5	4	8	4	5	7	4	8	4	13	7	2

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
WW12-9-1	15-Sep-97	24	5000	479	525	255	25	479	2260	393	-	-	-6.3
WW12-10-1	09-Oct-97	23	4910	468	513	266	24	493	2187	391	-	-	-6.3
WW12-11-1	13-Nov-97	21	4910	436	500	259	24	499	2087	449	30	24	-6.3
WW12-12-1	10-Dec-97	22	4880	509	560	289	25	508	2221	415	31	25	-6.3
WW12-12-2	10-Dec-97	22	4880	479	513	264	24	502	2258	398	-	-	-6.2
WW12-1-1	16-Jan-98	22	4800	448	483	254	23	507	2110	395	31	25	-6.1
WW12-2-1	13-Feb-98	22	4820	439	491	250	23	503	2236	425	**31**	25	-6.3
WW12-3-1	16-Mar-98	22	4800	402	436	233	23	481	2148	405	**30**	24	-6.3
WW12-4-1	16-Apr-98	23	4790	391	447	224	23	469	2310	378	**25**	24	-6.3
WW12-5-1	15-May-98	23	4600	384	413	247	20	409	2288	408	34	25	-6.3
WW12-6-1	24-Jun-98	24	4620	446	405	262	19	432	2158	508	38	30	-6.3
WW12-7-1	22-Jul-98	22	4400	371	315	217	16	434	2589	525	39	30	-6.2
WW12-8-1	20-Aug-98	23	4430	447	425	281	20	420	2559	527	39	29	-6.2
Average		23	4757	438	463	254	22	472	2262	432	33	26	-6.3
Samp. St. Dev.		1	188	41	65	21	3	36	154	53	5	3	0.1
% Deviation		4	4	9	14	8	12	8	7	12	14	10	1

TABLE B-1 (cont'd). GEOCHEMICAL AND ISOTOPIC DATA FOR GROUNDWATER SAMPLES

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
UN-9-1	03-Sep-97	25	4750	490	281	317	20	462	1930	515	-	-	-5.8
UN-10-1	09-Oct-97	24	4470	493	286	337	20	440	2017	476	-	-	-5.6
UN-10-2	09-Oct-97	24	4470	488	282	335	20	459	2004	503	44	6	-5.8
UN-11-1	13-Nov-97	22	4420	444	263	310	19	456	1915	542	35	9	-5.9
UN-12-1	10-Dec-97	22	4380	485	272	320	19	460	1993	486	38	9	-5.6
UN-1-1	16-Jan-98	22	4300	469	258	300	20	456	2010	513	40	9	-5.8
UN-2-1	13-Feb-98	22	4310	448	270	304	18	457	2029	574	**31**	9	-5.8
UN-3-1	16-Mar-98	22	4310	404	231	282	18	405	1964	532	**44**	9	-5.7
UN-4-1	16-Apr-98	22	4320	408	231	282	19	382	1990	503	**34**	9	-5.8
UN-5-1	15-May-98	22	4350	415	245	289	17	470	2018	515	**33**	11	-6.1
UN-6-1	24-Jun-98	23	4330	345	193	244	17	483	1881	596	37	12	-6.1
UN-7-1	22-Jul-98	23	4210	448	227	309	18	490	2210	596	34	13	-6.0
UN-8-1	20-Aug-98	24	4300	441	258	321	21	546	2312	622	31	13	-6.0
Average		23	4378	444	254	304	19	459	2021	536	36	10	-5.8
Samp. St. Dev.		1	133	43	27	25	1	39	117	46	5	2	0.2
% Deviation		4	3	10	11	8	7	9	6	9	13	21	3

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
WW13-9-1	03-Sep-97	24	4500	456	371	263	20	461	1864	488	-	-	-6.2
WW13-10-1	09-Oct-97	23	4170	450	350	273	20	471	1808	476	-	-	-6.1
WW13-11-1	13-Nov-97	21	4210	433	338	274	18	445	1956	505	34	12	-6.2
WW13-12-1	10-Dec-97	23	4220	468	351	276	19	451	1802	452	32	11	-6.2
WW13-1-1	16-Jan-98	22	4130	471	362	283	20	457	1817	478	36	12	-5.7
WW13-1-2	16-Jan-98	22	4130	411	311	242	18	463	1735	456	37	12	-6.2
WW13-2-1	13-Feb-98	21	4150	460	373	282	18	457	1795	554	**38**	12	-6.1
WW13-2-2	13-Feb-98	21	4150	431	343	261	18	457	1845	544	**40**	12	-5.6
WW13-3-1	16-Mar-98	22	4220	476	366	294	21	391	1816	547	**44**	13	-6.2
WW13-3-2	16-Mar-98	22	4220	448	346	277	20	407	1850	552	**42**	13	-6.2
WW13-4-1	16-Apr-98	21	4230	449	353	277	20	412	1926	505	**42**	13	-6.2
WW13-5-1	15-May-98	22	4110	410	357	269	20	457	1881	500	34	13	-6.3
	24-Jun-98	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
WW13-7-1	22-Jul-98	23	4080	451	329	280	20	490	2221	561	31	14	-6.3
WW13-8-1	20-Aug-98	23	4130	445	326	288	20	470	2225	620	28	14	-6.3
Average		22	4189	447	348	274	19	449	1896	517	36	13	-6.1
Samp. St. Dev.		1	101	20	18	13	1	27	149	48	5	1	0.2
% Deviation		4	2	5	5	5	5	6	8	9	13	8	3

TABLE B-1 (cont'd). GEOCHEMICAL AND ISOTOPIC DATA FOR GROUNDWATER SAMPLES

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
SB-9-1	03-Sep-97	26	4600	471	238	286	19	422	1890	483	-	-	-5.9
SB-10-1	09-Oct-97	23	4270	493	261	310	20	424	1894	466	-	-	-5.8
SB-11-1	13-Nov-97	21	4200	462	239	296	19	401	1956	520	-	-	-5.8
SB-12-1	10-Dec-97	22	4160	496	256	315	19	422	1860	493	44	8	-6.0
SB-1-1	16-Jan-98	22	4110	504	254	316	20	420	2694	495	48	8	-5.8
SB-2-1	13-Feb-98	22	4040	489	255	308	19	402	1850	476	**44**	8	-5.8
SB-3-1	16-Mar-98	22	4060	484	251	330	20	363	1861	569	**41**	9	-6.0
SB-4-1	16-Apr-98	21	4090	471	251	323	20	388	1850	471	**42**	11	-6.1
SB-5-1	15-May-98	22	4000	409	240	301	19	404	1862	508	**37**	12	-6.0
SB-6-1	24-Jun-98	23	4110	439	**243**	310	19	441	1803	574	46	19	-5.8
SB-6-2	24-Jun-98	23	4110	407	232	305	19	437	1786	605	39	19	-5.8
SB-7-1	22-Jul-98	23	4060	423	223	287	18	477	2072	620	46	20	-5.9
SB-8-1	20-Aug-98	23	4140	495	253	320	20	513	2106	642	40	19	-5.9
Average		23	4150	465	246	308	19	424	1960	532	43	13	-5.9
Samp. St. Dev.		1	152	34	11	13	0	38	240	62	3	5	0.1
% Deviation		5	4	7	4	4	3	9	12	12	8	41	2

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
WW11-9-1	03-Sep-97	24	4290	440	301	256	17	506	1761	486	-	-	-6.2
WW11-10-1	09-Oct-97	22	4020	436	283	254	17	518	1704	486	-	-	-6.1
WW11-11-1	14-Nov-97	22	3970	441	289	264	16	504	1683	454	26	24	-6.3
WW11-11-2	14-Nov-97	22	3970	458	298	267	16	512	1728	442	22	24	-6.1
WW11-12-1	10-Dec-97	22	4030	440	284	262	17	522	1647	427	21	24	-6.4
WW11-1-1	16-Jan-98	20	3810	391	269	239	16	520	1692	422	20	24	-6.0
WW11-2-1	13-Feb-98	21	3920	464	308	264	17	550	1782	383	**40**	24	-6.2
WW11-3-1	16-Mar-98	22	3980	390	284	239	16	504	1636	508	**45**	22	-6.1
WW11-4-1	16-Apr-98	21	3920	388	265	241	17	475	1688	459	**28**	21	-6.3
WW11-5-1	15-May-98	20	3790	324	248	208	14	420	1637	474	**30**	20	-6.2
WW11-5-2	15-May-98	20	3790	367	258	235	16	451	1612	520	32	20	-6.1
WW11-6-1	24-Jun-98	21	3760	356	258	230	15	426	1599	557	28	19	-6.1
WW11-7-1	22-Jul-98	21	3730	396	291	252	16	466	2030	564	30	19	-6.1
WW11-8-1	20-Aug-98	21	3800	457	310	254	18	390	2038	549	25	17	-6.0
Average		21	3913	411	282	248	16	483	1731	481	29	21	-6.2
Samp. St. Dev.		1	149	43	20	17	1	47	139	54	7	2	0.1
% Deviation		5	4	11	7	7	5	10	8	11	26	11	2

TABLE B-1 (cont'd). GEOCHEMICAL AND ISOTOPIC DATA FOR GROUNDWATER SAMPLES

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
WW8-9-1	04-Sep-97	23	4800	485	255	324	16	608	1888	469	-	-	-6.0
WW8-10-1	09-Oct-97	24	4490	470	255	323	18	606	1801	476	-	-	-6.0
WW8-11-1	14-Nov-97	22	4440	494	260	327	16	594	1942	478	25	26	-6.1
WW8-12-1	10-Dec-97	24	4480	490	256	334	17	605	1771	491	28	27	-6.0
WW8-1-1	16-Jan-98	22	4290	468	268	331	17	598	1810	461	-	-	-6.0
WW8-2-1	13-Feb-98	22	4340	497	270	323	16	607	1909	425	**39**	28	-5.8
WW8-3-1	16-Mar-98	24	4500	478	276	333	17	553	1820	574	**41**	29	-5.9
WW8-4-1	16-Apr-98	22	4250	483	263	336	18	497	1856	425	**36**	29	-6.1
WW8-5-1	15-May-98	22	4200	463	268	340	17	531	1836	500	33	26	-6.1
WW8-6-1	24-Jun-98	22	4140	394	228	294	15	498	1761	522	31	27	-6.2
WW8-7-1	22-Jul-98	23	4090	376	221	281	16	547	2029	576	33	29	-6.1
WW8-7-2	22-Jul-98	23	4090	448	263	332	16	530	2054	574	31	29	-6.1
WW8-8-1	20-Aug-98	23	4210	497	271	323	17	545	1831	576	28	29	-6.0
Average		23	4332	465	258	323	17	563	1870	504	32	28	-6.0
Samp. St. Dev.		1	204	39	16	17	1	42	92	56	5	1	0.1
% Deviation		4	5	8	6	5	5	7	5	11	16	5	2

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
W6A-9-1	04-Sep-97	24	4950	548	364	271	19	537	2155	456	-	-	-5.7
	Oct-97	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
W6A-11-1	14-Nov-97	22	4680	580	371	285	18	532	2140	461	31	22	-5.7
W6A-12-1	10-Dec-97	23	4710	567	358	288	19	534	2127	425	34	19	-5.8
W6A-12-2	10-Dec-97	23	4710	580	366	288	19	536	2197	469	36	21	-5.5
W6A-1-1	16-Jan-98	22	4620	500	293	254	19	531	2081	427	38	22	-5.5
W6A-2-1	13-Feb-98	22	4610	597	388	287	19	487	2191	347	**44**	24	-6.0
	16-Mar-98	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
W6A-4-1	16-Apr-98	22	4660	585	387	297	20	508	2180	452	**32**	23	-5.7
W6A-5-1	15-May-98	23	4570	534	365	298	20	512	2078	469	**29**	23	-5.6
	24-Jun-98	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	22-Jul-98	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	20-Aug-98	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Average		22	4689	561	362	283	19	522	2144	438	35	22	-5.7
Samp. St. Dev.		1	117	32	30	15	1	18	46	41	5	2	0.2
% Deviation		3	2	6	8	5	3	3	2	9	14	7	3

TABLE B-1 (cont'd). GEOCHEMICAL AND ISOTOPIC DATA FOR GROUNDWATER SAMPLES

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
N-9-1	04-Sep-97	25	5500	547	452	329	20	589	2312	378	-	-	-5.8
N-10-1	09-Oct-97	24	5300	557	452	343	20	587	2335	386	-	-	-5.8
N-11-1	14-Nov-97	22	5100	521	422	320	18	588	2341	400	22	36	-5.7
N-12-1	10-Dec-97	23	5300	532	433	334	20	594	2396	381	24	33	-5.9
N-1-1	16-Jan-98	23	5100	472	405	309	18	589	2365	393	25	34	-5.8
N-2-1	13-Feb-98	22	5100	523	430	324	18	606	2462	351	**46**	37	-5.8
N-2-2	13-Feb-98	22	5100	564	461	346	19	603	2411	361	**44**	36	-5.9
N-3-1	16-Mar-98	23	5050	524	451	338	19	459	2291	420	**43**	37	-5.7
N-4-1	16-Apr-98	24	5200	501	410	323	20	568	2353	354	**39**	37	-6.2
N-5-1	15-May-98	24	5100	446	375	309	19	554	2332	417	**39**	36	-6.3
N-6-1	24-Jun-98	24	5000	409	361	265	18	502	2370	449	33	36	-6.3
N-7-1	22-Jul-98	24	4860	412	352	277	16	468	2672	422	31	35	-6.0
N-8-1	20-Aug-98	24	4900	521	419	303	21	527	2728	425	27	33	-6.3
Average		23	5124	502	417	317	19	557	2413	395	34	35	-5.9
Samp. St. Dev.		1	171	52	36	24	1	51	135	30	9	1	0.2
% Deviation		4	3	10	9	8	7	9	6	8	26	4	4

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
FW-9-1	04-Sep-97	23	5500	624	410	345	13	712	2410	405	-	-	-6.2
FW-10-1	09-Oct-97	24	5200	492	373	317	13	695	2150	398	41	23	-6.4
FW-11-1	14-Nov-97	22	5200	618	395	347	11	692	2520	447	33	37	-6.3
FW-12-1	10-Dec-97	22	5400	598	376	345	12	696	2325	400	42	37	-6.7
FW-1-1	16-Jan-98	23	5100	609	398	357	13	693	2161	410	36	39	-6.2
FW-2-1	13-Feb-98	22	5000	633	408	362	11	677	2177	400	**36**	41	-6.4
	16-Mar-98	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
FW-4-1	16-Apr-98	23	5200	616	399	360	14	694	2328	391	**34**	47	-6.3
FW-5-1	15-May-98	24	5100	469	323	312	12	673	2152	232	41	48	-6.2
FW-6-1	24-Jun-98	24	5100	527	370	319	12	620	2227	466	32	46	-6.1
FW-7-1	22-Jul-98	23	5100	610	420	373	13	748	2521	520	28	47	-6.3
FW-8-1	20-Aug-98	24	5050	646	434	349	13	749	2755	508	33	47	-6.1
Average		23	5177	586	391	344	12	695	2339	416	36	41	-6.3
Samp. St. Dev.		1	151	60	30	20	1	35	196	76	5	8	0.2
% Deviation		3	3	10	8	6	6	5	8	18	13	18	3

TABLE B-1 (cont'd). GEOCHEMICAL AND ISOTOPIC DATA FOR GROUNDWATER SAMPLES

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
	Sep-97	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
W973-10-1	10-Oct-97	25	6200	562	569	460	26	609	2945	586	26	0	-6.1
W973-11-1	14-Nov-97	24	6200	548	603	465	27	593	3067	632	14	1	-5.4
W973-11-2	14-Nov-97	24	6200	542	597	466	27	591	3077	637	16	1	-5.7
	10-Dec-97	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
W973-1-1	16-Jan-98	22	5900	536	600	468	28	601	2889	588	21	6	-4.9
W973-2-1	13-Feb-98	21	5200	585	522	366	15	610	2440	661	**31**	4	-5.4
W973-3-1	16-Mar-98	23	5500	599	524	384	15	802	1963	779	**34**	11	-4.8
W973-4-1	16-Apr-98	23	5400	527	480	372	19	692	2381	588	**29**	7	-5.4
W973-5-1	15-May-98	23	5200	514	515	398	18	647	2307	732	**26**	2	-5.4
W973-6-1	24-Jun-98	24	5200	438	416	312	16	538	2138	788	18	3	-5.5
W973-7-1	22-Jul-98	23	5200	535	502	384	17	656	2455	754	11	6	-5.5
W973-8-1	20-Aug-98	23	5000	580	514	358	16	663	2129	810	20	5	-5.4
Average		23	5564	542	531	403	20	637	2526	687	22	4	-5.4
Samp. St. Dev.		1	470	43	58	54	6	69	401	87	7	3	0.4
% Deviation		4	8	8	11	13	27	11	16	13	33	75	7

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
ISE-9-1	05-Sep-97	28	9300	672	481	669	13	1529	2281	271	-	-	-5.0
ISE-10-1	10-Oct-97	28	9200	706	476	660	13	1552	2192	281	15	973	-5.6
	Nov-97	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	10-Dec-97	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
ISE-1-1	16-Jan-98	24	8300	709	493	627	14	1569	2319	256	17	848	-5.5
ISE-2-1	13-Feb-98	22	8000	718	490	666	12	1537	2151	293	**32**	1027	-5.8
ISE-3-1	16-Mar-98	25	8800	705	510	636	13	1483	2029	276	**24**	1035	-5.9
ISE-4-1	16-Apr-98	27	8500	697	495	696	12	1482	2306	268	**25**	1058	-5.6
ISE-5-1	15-May-98	27	8200	641	444	613	12	1378	2308	286	**22**	1046	-5.7
	24-Jun-98	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
ISE-7-1	22-Jul-98	24	7600	667	449	641	12	1371	2806	281	12	760	-5.7
ISE-8-1	20-Aug-98	25	7700	649	403	624	13	1482	2584	286	23	1019	-6.0
Average		26	8400	685	471	648	13	1487	2331	278	21	971	-5.7
Samp. St. Dev.		2	608	28	33	27	1	71	234	11	6	109	0.3
% Deviation		8	7	4	7	4	5	5	10	4	29	11	5

TABLE B-1 (cont'd). GEOCHEMICAL AND ISOTOPIC DATA FOR GROUNDWATER SAMPLES

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
FSW-9-1	05-Sep-97	27	6500	643	517	333	15	890	2526	312	-	-	-6.6
	Oct-97	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
FSW-11-1	14-Nov-97	25	6200	651	503	333	14	904	2401	327	37	131	-6.5
	10-Dec-97	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
FSW-1-1	16-Jan-98	26	6200	665	504	322	15	922	2322	847	-	-	-6.5
FSW-2-1	13-Feb-98	26	6200	641	512	453	13	909	2228	317	**24**	146	-6.6
FSW-3-1	16-Mar-98	26	6400	623	520	334	14	868	2427	317	**24**	150	-6.5
FSW-4-1	16-Apr-98	23	5800	615	488	319	13	894	2505	303	**22**	141	-6.6
FSW-5-1	15-May-98	22	5700	574	499	307	13	802	2399	320	**23**	148	-6.6
FSW-6-1	24-Jun-98	26	5900	578	467	305	13	755	2348	315	25	123	-6.6
FSW-7-1	22-Jul-98	24	5600	654	515	333	13	831	2752	322	23	132	-6.6
FSW-8-1	20-Aug-98	25	5600	596	424	296	12	877	2549	337	27	131	-6.7
Average		25	6010	624	495	334	14	865	2446	372	26	138	-6.6
Samp. St. Dev.		1	331	32	29	44	1	53	146	167	5	10	0.1
% Deviation		6	6	5	6	13	6	6	6	45	18	7	1

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
W6K-9-1	05-Sep-97	30	12200	469	584	2480	22	724	8444	383	-	-	-6.0
	Oct-97	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
W6K-11-1	14-Nov-97	22	8600	616	505	1051	10	898	5142	137	4	188	-6.1
W6K-12-1	10-Dec-97	22	8400	532	516	1080	9	914	4474	134	4	227	-6.1
W6K-1-1	16-Jan-98	24	10200	610	542	2140	21	784	7108	273	-	-	-6.0
W6K-2-1	13-Feb-98	23	12200	571	597	3170	19	761	7716	312	**12**	324	-5.7
W6K-3-1	16-Mar-98	23	8300	565	569	1018	9	823	4496	112	**4**	255	-6.1
W6K-4-1	16-Apr-98	24	8200	518	588	1008	10	911	4495	90	**2**	253	-6.0
W6K-5-1	15-May-98	27	8300	445	518	852	9	909	4580	73	**2**	287	-6.1
W6K-6-1	24-Jun-98	27	8500	469	565	840	9	806	4617	78	5	254	-5.9
	22-Jul-98	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	20-Aug-98	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Average		25	9433	533	554	1516	13	837	5675	177	5	255	-6.0
Samp. St. Dev.		3	1682	63	34	856	6	73	1609	115	3	43	0.1
% Deviation		10	18	12	6	56	43	9	28	65	72	17	2

TABLE B-1 (cont'd). GEOCHEMICAL AND ISOTOPIC DATA FOR GROUNDWATER SAMPLES

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
PTG-9-1	05-Sep-97	27	6000	444	700	285	38	324	2813	412	-	-	-6.4
PTG-10-1	10-Oct-97	26	6100	444	661	292	37	346	2771	447	36	11	-6.2
PTG-11-1	14-Nov-97	24	5800	425	598	275	34	341	2919	461	32	19	-6.5
PTG-12-1	10-Dec-97	26	5800	424	602	274	34	355	2666	415	36	20	-6.2
PTG-1-1	16-Jan-98	24	5500	451	605	274	35	355	2700	422	37	16	-6.5
PTG-2-1	13-Feb-98	25	5500	439	633	391	33	355	2564	425	**39**	22	-6.6
PTG-3-1	16-Mar-98	25	5700	423	585	280	31	324	2584	474	**44**	24	-6.6
PTG-3-2	16-Mar-98	25	5700	442	615	289	33	345	2646	464	**44**	23	-6.6
PTG-4-1	16-Apr-98	25	5600	439	632	299	33	341	2648	430	**38**	21	-6.6
PTG-5-1	15-May-98	25	5300	354	486	249	32	284	2634	444	**44**	21	-6.8
PTG-6-1	24-Jun-98	26	5500	353	697	230	28	271	1907	474	34	17	-6.2
	22-Jul-98	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PTG-8-1	20-Aug-98	26	5300	439	530	300	33	282	2952	476	30	8	-6.5
PTG-8-2	20-Aug-98	26	5300	-	-	-	-	-	-	-	-	-	-6.5
Average		25	5623	423	612	286	34	327	2650	445	38	18	-6.5
Samp. St. Dev.		1	259	34	62	39	3	31	265	24	5	5	0.2
% Deviation		3	5	8	10	14	8	9	10	5	13	27	3

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
KCS-10-1	10-Oct-97	22	3410	446	146	267	27	298	1502	478	35	2	-5.8
KCS-2-1	13-Feb-98	23	2790	445	154	365	25	304	1274	547	**40**	2	-5.7
KCS-4-1a	16-Apr-98	18	3780	536	183	337	24	298	2393	505	**41**	4	-5.7
KCS-6-1a	24-Jun-98	-	-	490	157	301	25	267	1979	466	34	2	-5.8
KCS-8-1a	20-Aug-98	20	3400	450	119	284	26	250	1991	537	30	3	-5.9
KCS-12-1	10-Dec-97	20	3120	347	216	238	31	285	1325	493	34	2	-5.8
KCS-4-1b	16-Apr-98	20	3600	390	242	268	32	255	1752	613	**42**	5	-5.7
KCS-6-1b	24-Jun-98	22	3580	343	186	235	33	239	1850	569	31	4	-5.5
KCS-8-1b	20-Aug-98	21	3380	354	182	251	32	231	1962	630	34	5	-5.6
Average		21	3420	359	207	248	32	253	1722	576	35	4	-5.7
Samp. St. Dev.		1	223	21	28	15	1	24	278	61	5	1	0.1
% Deviation		5	7	6	13	6	2	9	16	11	13	28	2

Shaded samples were collected from center of spring surface stream.

TABLE B-2. GEOCHEMICAL AND ISOTOPIC DATA FOR DOMESTIC WATER (DW) AND SURFACE RUNOFF SAMPLES

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
DW1-10-1	10-Oct-97	-	-	80	85	24	3	80	165	137	3	1	-11.2
DW2-12-1	10-Dec-97	-	-	75	422	23	4	78	204	154	4	1	-10.7
DW3-6-1	24-Jun-98	-	-	61	48	20	2	55	171	149	-	-	-11.4
DW4-7-1	22-Jul-98	-	-	51	55	11	3	73	220	137	3	1	-11.3
Average		-	-	64	63	18	3	69	185	141	3	1	-11.3
Samp. St. Dev.		-	-	15	19	7	0	13	30	7	0	0	0.1
% Deviation		-	-	23	31	37	15	19	16	5	6	27	3

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
SB126-1	26-Jan-98	-	-	20	13	8	3	29	41	49	-	-	-2.8
SB126-2	26-Jan-98	-	-	-	-	-	-	-	-	-	-	-	-9.2
SB126-3	26-Jan-98	-	-	-	-	-	-	-	-	-	-	-	-8.7
SB126-4	26-Jan-98	-	-	-	-	-	-	-	-	-	-	-	-8.7
N126-1	26-Jan-98	-	-	13	0	1	3	15	17	10	-	-	-3.4
N126-2	26-Jan-98	-	-	-	-	-	-	-	-	-	-	-	-9.4
N126-3	26-Jan-98	-	-	-	-	-	-	-	-	-	-	-	-8.8
SB23-1	03-Feb-98	-	-	20	20	7	1	29	43	36	-	-	-4.0
SB23-2	03-Feb-98	-	-	18	17	5	1	**18**	27	41	-	-	-5.5
SB23-3	03-Feb-98	-	-	15	15	5	0	**11**	33	37	-	-	-9.1
SB23-4	03-Feb-98	-	-	23	21	8	1	**17**	55	56	-	-	-9.2
SB23-5	03-Feb-98	-	-	30	27	12	0	**16**	73	71	-	-	-9.1
SB23-6	03-Feb-98	-	-	20	18	7	1	**10**	42	49	-	-	-12.5
SB23-7	03-Feb-98	-	-	31	25	11	1	20	83	66	-	-	-11.9
SB23-8	03-Feb-98	-	-	45	29	15	1	**22**	129	66	-	-	-11.4
N23-1	03-Feb-98	-	-	19	24	4	7	39	25	27	-	-	-3.7
N23-2	03-Feb-98	-	-	23	24	7	2	39	37	95	-	-	-6.7
N23-3	03-Feb-98	-	-	19	18	6	2	**16**	36	56	-	-	-9.8
N23-4	03-Feb-98	-	-	22	19	7	2	22	46	66	-	-	-9.4
N23-5	03-Feb-98	-	-	15	11	3	3	**7**	30	44	-	-	-11.6
N23-6	03-Feb-98	-	-	24	21	8	1	**15**	51	56	-	-	-11.8
N23-7	03-Feb-98	-	-	33	29	11	2	24	93	76	-	-	-11.7

Shaded sample excluded from calculations.

TABLE B-3. GEOCHEMICAL AND ISOTOPIC DATA FOR RAINFALL SAMPLES

Sample No.[1]	Date	Temp.[2]	Cond.[3]	Ca[4]	Na	Mg	K	Cl	SO_4	HCO_3	SiO_2	NO_3	$\delta^{18}O$ [5]
RD-1	13-Nov-97	-	-	-	-	-	-	-	-	-	-	-	-6.0
RD-2	13-Nov-97	-	-	-	-	-	-	-	-	-	-	-	-5.4
RD-3	14-Nov-97	-	-	-	-	-	-	-	-	-	-	-	-5.1
RD-4	20-Nov-97	-	-	-	-	-	-	-	-	-	-	-	-2.2
RD-5	26-Nov-97	-	-	-	-	-	-	-	-	-	-	-	-4.4
RD-6	30-Nov-97	-	-	-	-	-	-	-	-	-	-	-	-7.1
RD-7	06-Dec-97	-	-	-	-	-	-	-	-	-	-	-	-2.8
RD-8	06-Dec-97	-	-	-	-	-	-	-	-	-	-	-	-6.6
RD-9	07-Dec-97	-	-	-	-	-	-	-	-	-	-	-	-5.6
RD-10	19-Dec-97	-	-	-	-	-	-	-	-	-	-	-	-5.5
RD-11	05-Jan-98	-	-	-	-	-	-	-	-	-	-	-	-5.4
RD-12	10-Jan-98	-	-	-	-	-	-	-	-	-	-	-	-4.6
RD-13	14-Jan-98	-	-	-	-	-	-	-	-	-	-	-	-2.7
RD-14	19-Jan-98	-	-	-	-	-	-	-	-	-	-	-	-1.1
RD-15	01-Feb-98	-	-	-	-	-	-	-	-	-	-	-	-4.0
RD-16	02-Feb-98	-	-	-	-	-	-	-	-	-	-	-	-2.7
RD-17	03-Feb-98	-	-	0.4	6.7	0.8	0.0	7.8	0.0	0.0	-	-	-6.3
RD-18	03-Feb-98	-	-	0.2	0.4	0.1	0.0	0.0	0.0	0.0	-	-	-13.1
RD-19	06-Feb-98	-	-	-	-	-	-	-	-	-	-	-	-4.4
RD-20	08-Feb-98	-	-	-	-	-	-	-	-	-	-	-	-5.2
RD-21	09-Feb-98	-	-	-	-	-	-	-	-	-	-	-	-5.0
RD-22	16-Feb-98	-	-	-	-	-	-	-	-	-	-	-	-4.0
RD-23	21-Feb-98	-	-	-	-	-	-	-	-	-	-	-	-11.5
RD-24	23-Feb-98	-	-	-	-	-	-	-	-	-	-	-	-2.5
RD-25	25-Feb-98	-	-	-	-	-	-	-	-	-	-	-	-5.3
RD-27	31-Mar-98	-	-	-	-	-	-	-	-	-	-	-	-4.2
RD-28	01-Apr-98	-	-	-	-	-	-	-	-	-	-	-	-7.0
RD-29	13-Apr-98	-	-	-	-	-	-	-	-	-	-	-	-6.6
RD-30	05-May-98	-	-	-	-	-	-	-	-	-	-	-	-2.9
RD-31	13-May-98	-	-	-	-	-	-	-	-	-	-	-	-5.3
DCP-R1	04-Feb-98	-	-	-	-	-	-	-	-	-	-	-	-6.3
DC-R1	04-Feb-98	-	-	-	-	-	-	-	-	-	-	-	-8.6
BD-R1	04-Feb-98	-	-	-	-	-	-	-	-	-	-	-	-8.39

Notes for Table B-1:

[1] Sample numbers (ex. LCC1-9-1) represent well (LCC1)- month collected (Sept.) - sample number (1)

[2] Temperature measurements given in degrees centigrade

[3] Conductivity measuremei ts given in μmhos

[4] Major ion concentrations given in milligrams per liter. (All results within 3% uncertainty, except bold entries, which are within 10%).

[5] Oxygen isotope concentrations given in parts per thousand.

ns = no sample collected

- = sample not analyzed

Notes for Table B-2:

[1] Sample numbers (ex. SB126-1) represent sample location (SB), collection date (12/6), and sample number (1)

[2] Temperature measurements given in degrees centigrade

[3] Conductivity measurements given in μmhos

[4] Major ion concentrations given in milligrams per liter. (All results within 3% uncertainty, except bold entries, which are within 10%).

[5] Oxygen isotope concentrations given in parts per thousand.

ns = no sample collected

- = sample not analyzed

Notes for Table B-3:

[1] Sample numbers (ex. RD-1) represent rain gauge location (RD), and sample number (1)

[2] Temperature measurements given in degrees centigrade

[3] Conductivity measurements given in μmhos

[4] Major ion concentrations given in milligrams per liter. (All results within 3% uncertainty, except bold entries, which are within 10%).

[5] Oxygen isotope concentrations given in parts per thousand.

ns = no sample collected

- = sample not analyzed