4 Hydrogeology

This section presents a hydrogeologic conceptual model of the groundwater system underlying the quarry, proposed expansion area, and overall Liddell Spring recharge area. The primary components and boundaries of this system are as follows:

- A large block of granitic and metasedimentary rocks containing the weathered marble (i.e., karst) groundwater system tributary to Liddell Spring.
- The entire watersheds of Laguna and Reggiardo creeks upstream of the City of Santa Cruz diversions. These watersheds encompass all of the recognized karst sinks potentially tributary to Liddell Spring, as well as other nearby karst springs. Other than noted below, karst connections to adjacent watersheds to the east, west, and north appear lacking.
- Both large and small remnants of Santa Margarita Sandstone directly overlying the granitic and metasedimentary rocks, which are important areas of groundwater recharge tributary to the karst system. These may include sandstone areas that extend west into the adjacent Mill Creek watershed.
- A southern, downgradient boundary consisting of various geologic units that abut the apparent termination of the karst system. Exposed granitic rock along portions of this boundary may serve as a barrier to the continued downgradient flow of groundwater. Between Liddell Spring and Laguna Creek, karst groundwater may flow directly into exposures of Santa Margarita and Lompico sandstone along this boundary.

The remaining elements of the hydrogeologic conceptual model presented below are as follows:

- The nature and structure of the groundwater system's hydrogeologic units (Section 4.1).
- The conditions under which groundwater occurs within these units (Section 4.2).
- The water quality of groundwater, springflow, and stream baseflow as a supporting indicator of groundwater occurrence, movement, and recharge (Section 4.3).
- The vertical and horizontal movement of water and sediment through the subsurface, including pathways indicated by groundwater and springflow responses to precipitation and tracer tests (Section 4.4).
- The balance of estimated groundwater inflows and outflows (Section 4.5).

Based on this conceptual model, Section 4 concludes with an assessment of groundwater responses to past and current quarry activities (Section 4.6).

4.1 Hydrogeologic Units

The hydrogeologic units of primary importance in the vicinity of Bonny Doon Quarry include both water-bearing and non-water-bearing rocks. The primary aquifer units are the marble and Santa Margarita Sandstone. Units that act mostly as barriers to groundwater flow include the granitic rocks and schist.

Other geologic formations with some importance include the Lompico Sandstone, which borders portions of the karst system's downgradient boundary, and landslide deposits with an apparent hydraulic connection to Liddell Spring. Small remnants of Santa Cruz Mudstone overlying the Santa Margarita Sandstone are mostly above the water table. Downgradient exposures of Monterey Formation do not appear to contact the karst system.

4.1.1 Granitic Rocks

As discussed in Section 2, granitic rocks occur regionally in large bodies spanning several square miles, but also as smaller bodies intruded or faulted into juxtaposition with other rocks, or as dikes and sills a few feet to tens of feet thick injected along faults, joints, and bedding planes.

Because granitic rocks have little primary porosity and generally low permeability, their hydrogeologic relevance is mostly as barriers to groundwater flow. Exposures of granitic rock surround nearly the entire karst groundwater system, which helps to focus groundwater flow toward Liddell Spring.

Because of weathering and open fractures, the granitic rock may yield small quantities of groundwater to wells up to several hundred feet deep. Past inventories of private wells in the area include wells completed in granitic rocks up to 300 ft deep with yields up to 40 gpm and specific capacities up to 1 gpm per foot of drawdown (HEA, 1979; Johnson, 1984). Well yields are minimal where the weathered granitic mantle has been eroded away and/or where fractures are sparse or tightly closed.

4.1.2 Schist

Schist generally has low permeability and generally is not a major water-bearing unit. The schist's primary hydrogeologic importance is its association with marble inclusions. Bodies of marble occur throughout the schist and are more extensive than previously mapped. Marble may exist in the near- or sub-surface wherever schist is mapped or inferred.

The large outcrop of Santa Margarita Sandstone exposed across the Bonny Doon area north of the quarry overlies a subsurface contact between schist on the east and granitic rock to the west (Figure 20). Based on the distribution of surrounding schist outcrops, a large portion of the sandstone outcrop is probably underlain by schist, and, considering the number of marble outcrops observed in Laguna Creek, some marble as well.

The schist may transmit groundwater where sufficiently fractured or weathered. This may help explain the groundwater pathways between apparently isolated bodies of marble. Also, sinkholes may form in schist underlain by marble and karst springs may emerge from schist outcrops.

4.1.3 **Marble**

Bonny Doon Quarry is located within a block of faulted marble roughly 4,000 ft square (Figure 20). It is the largest block of marble evident in the immediate area, and regionally second in size to the body of marble at UCSC about 5 miles to the southeast. To the immediate north, the quarry marble extends an unknown distance under the Santa Margarita Sandstone. A smaller body of marble occurs in the Reggiardo Creek watershed to the immediate east, which is at least partially juxtaposed with the quarry block. Other apparently smaller bodies of faulted marble occur to the north-northeast along Laguna Creek. Tracer studies discussed later in this section suggest that these bodies are interconnected into a single karst groundwater system. The marble may be more extensive at depth and/or the individual bodies may be interconnected by fractures and marble interbeds within the schist. Areas of marble may directly underlie the large exposure of Santa Margarita Sandstone that occurs about a mile north of the quarry. To the west, marble in the San Vicente Creek watershed is separated hydraulically from Bonny Doon by more than a mile of intervening granitic rock. Although within the same body of schist, marble exposed in the Fall Creek watershed is more than a mile east of the Laguna Creek marble, across a major topographic divide, and probably hydraulically separate from the Bonny Doon karst system.

Marble has little primary porosity and very low permeability where unfractured and unweathered. Dissolution of the marble by slightly acidic percolating soil water and flowing groundwater results in substantial secondary porosity, including macropores such as caverns and conduits. These tend to form preferentially along fractures, leaving blocks of low permeability between fracture zones. Although zones of pervasive dissolution may develop with porous-media like properties, the concentration of groundwater flow along dissolution channels is self enhancing because the high-capacity channels tend to flatten the hydraulic gradient, leaving little gradient to drive groundwater through the remaining rock. Furthermore, slow moving groundwater in less permeable zones becomes saturated with dissolved rock, retarding further dissolution (White, 1969). As such, karst aquifers generally behave very differently than porous-media aquifers and are difficult to characterize using conventional aquifer concepts (e.g., water table, saturated zone, transmissivity).

As shown in Figure 20, a roughly diamond-shaped grid of major fracture zones cut through the quarry area. At least four major fracture zones trend northeast between Liddell Spring and the quarry property's northern boundary. Another four or more major fracture zones trend south-southeast between the western edge of the quarry and Reggiardo Creek. These major fracture zones are spaced roughly 1,000 ft apart on average, and range between 500 to 2,000 ft apart. Each fracture zone may consist of multiple fractures, and this grid of major fractures zones is bisected by numerous other fractures. As mapped, the northeast trending fracture zones appear generally continuous compared to south-southeast fractures that are relatively offset and discontinuous. Liddell Spring is located at the southern, downgradient tip of this grid.

As described in Section 2.6, sinkholes tend to align with these fracture zones, with the most prominent sinkholes occurring at major fracture intersections. Quarrying and structural mapping reveal the occurrence of buried sinkholes along the top of the marble beneath the Santa Margarita Sandstone (e.g., PELA, May 2005, Figure II-3). Swallow holes tend to form where streams pass onto the upgradient edge of marble outcrops. Covered in sediment, these form "sinking stream" reaches where aligned along and/or between fracture zones. As shown in Figure 20, sinking-stream reaches along Reggiardo and Laguna creeks intersect fracture zones leading toward the quarry and Liddell Spring. Karst springs tend to occur at the downgradient edge of marble outcrops, but also may emerge from other rocks downgradient of the exposed marble.

Solution-widened fractures are visible in the quarry walls, commonly forming continuous zones of solution channeling that extend from the original ground surface down several hundred feet to the quarry floor and below. Fractures cut across schist interbeds and igneous sills and dikes such that these rocks do not impede groundwater flow through the karst; SECOR (November 1997) found no evidence that interbedded schist has a major influence on groundwater flow. Fractures and conduits do become blocked for periods of time when bridged with sediment or collapsed marble. Of the four major fracture zones trending northeast through the immediate quarry area, two have exposed marble along the relatively deep swales that align with them, and two remain covered with Santa Margarita Sandstone (Figure 20). The deeper swales with exposed marble may indicate zones that have experienced greater amounts of karst collapse. As such, the two less collapsed fracture zones may contain the highest permeability pathways, consistent with our interpretation of recent tracer tests (Section 4.4.2).

Todd (January 1963) reviewed the logs of 25 borings in the quarry area to evaluate the marble's overall porosity. No voids were logged for 15 of the borings while voids comprised nearly 4 percent of the other 10 boring's cumulative depth, of which one quarter were filled with sediment. He estimated the marble's overall porosity at 2 percent.

We performed a similar review of 225 borings with known locations and elevations drilled for the quarry, some of which probably did not encounter any marble. Voids and porous zones were not logged for about 36 percent of the borings. The remaining borings had voids and intervals of enhanced porosity as summarized by the following table:

Inventory of Drillers' Descriptions of Porosity and Voids for 225 Quarry Borings	Total Logged Length (ft)	% of Total
<u>Drillers' Descriptions</u> 1. Void – open	840	1.6%
2. Void – filled	653	1.2%
3. Vuggy porosity – open	286	0.5%
4. Vuggy porosity – filled	107	0.2%
5. Broken/fractured stone	1,859	3.4%
6. Porous interbed with clay filled fractures	63	0.1%
7. No recovery	689	1.3%
8. Filled fracture	341	0.6%
9. Breccia	110	0.2%
Sum of All Void Descriptions	4,948	9.1%
Sum of Open Voids (1,3,7)	1,815	3.4%
225 boring logs	54,109	100%

Vugs are pea-sized or larger cavities characteristic of weathered limestone. Breccia refers to deposits of angular, broken rock fragments. “No recovery” refers to an interval drilled without recovering any cuttings, suggesting a void such as an open cavern was encountered. As expected, sediment fills a fairly large percentage of these macropores. Based on these results, the marble’s overall porosity may be as much as 5 percent.

We profiled the average occurrence of voids and enhanced porosity with depth for various subareas of the quarry area. This analysis did not reveal any significant depth zonation of these features, i.e., there is no apparent segregation of shallow and deep solution cavities. Figure 21 shows the occurrence of voids, vugs, fractures, breccia zones, or zones of no drill cutting recovery with depth, expressed as the percentage of borings showing each of these features for any given depth. This analytical result is consistent with the ongoing dissolution of marble simultaneous with the gradual uplift of Ben Lomond Mountain.

Five boreholes drilled within or immediately adjacent to the expansion area encountered karst voids 10 to 40 ft tall (BD-41 and -42 and DDH-39, -49, and -53). The lateral and vertical interconnectivity of solution cavities within the marble is evaluated in Section 4.4.

4.1.4 **Santa Margarita Sandstone**

The Santa Margarita Sandstone is an important aquifer in several areas of Santa Cruz County, especially where it is exposed and well flushed with precipitation recharge such as in the Bonny Doon area. Typically, it is underlain by the Monterey Formation and Lompico Sandstone. In the

Bonny Doon area from the quarry northward, however, the sandstone lies directly over the granitic rock, schist, and marble.

Figure 22 shows the estimated elevation contours along the base of the Santa Margarita Sandstone. To the north of the quarry, the base of the sandstone dips gently to the southwest beneath the Bonny Doon area. South of the quarry, the dip of bedding to the southwest is steeper and the thickness of the Santa Cruz Mudstone overlying the Santa Margarita, increases substantially. The sandstone thickness exceeds 100 ft over much of the large outcrop area north of the quarry, attaining a thickness of 200 ft beneath the highest knolls, and is generally 50 to 100 ft thick in the immediate vicinity of the quarry. The saturated thickness is only roughly half as much, however. Well yields average about 25 gpm. The specific capacities reported by drillers for Bonny Doon wells completed in the Santa Margarita Sandstone suggests hydraulic conductivities generally ranging from 2 to 20 ft/day.

Above average rates of groundwater recharge typically occur over areas of exposed Santa Margarita Sandstone because of the high infiltration capacity and low moisture retention of its associated soils, which limit evapotranspiration and promote deep percolation.

As estimated in Figure 22, the western portion of the large sandstone exposure north of the quarry is underlain by granitic rock whereas the eastern side is underlain by schist and probably some marble. Additionally, the western side appears to be better drained by streams than the eastern side. This observation indicates that the sandstone on the eastern side may be partially drained by buried karst sinks. As shown in Figure 20, fracture zones connect this area to Reggiardo Creek and the quarry area.

4.1.5 Landslide Deposits

The approximately 1.5 acres of landslide deposits immediately east and northeast of Liddell Spring are permeable and transmit groundwater. Given their limited volume, these deposits have limited importance with respect to groundwater yield. However, a springflow turbidity response observed during construction of a landslide monitoring well (Farallon, August 2001) indicates a degree of hydraulic connection between the landslide and spring. Potential damage to the City's spring diversion from a reactivated landslide is discussed in Section 5.3.

4.2 Groundwater Occurrence

The conditions under which groundwater occurs within the marble and sandstone aquifers of the quarry area are indicated primarily by groundwater level and quality data from wells, and the flow and quality of springs. This section begins with a review of prior interpretations of groundwater occurrence, followed by part one of our hydrogeologic conceptual model, and concludes with an evaluation of the available water level data.

4.2.1 Previous Interpretations

Previous studies have commented on the highly variable and unpredictable groundwater levels of the quarry area. Lindsey (April 1967) described groundwater levels fluctuating >60 ft within 20 days. Kulakow (December 1988) discerned no defined groundwater elevation trends and no groundwater level relation to precipitation for a two year period. Watkins-Johnson Environmental

(November 1992) discussed abrupt water level changes for which there was no apparent explanation and little or no correlation with other wells, and recognized this behavior to be typical of karst aquifers. Farallon (August 2001) recognized that karst groundwater levels may change abruptly in response to storms, yet found that some hydrographs did not exhibit typical seasonal responses. In one case Farallon noted that an abrupt water level decline coincided with the drilling of an adjacent boring. In light of seemingly erratic water level records, Cloud (February 2000) questioned whether the water level records might be fraught with errors.

Previous investigators have also debated whether or not it is reasonable to construct groundwater-surface (i.e., potentiometric) contour maps. Todd (January 1963) stated that water-level observations supported the interpretation of an "extensive water table that is quite stable and has a well-defined shape" without any substantial groundwater flow through "underground tubes" (p. 8). Watkins-Johnson Environmental (November 1992) argued that constructing a potentiometric map was not justified given the complexity of the aquifer system. Because of aquifer anisotropy caused by interconnected solution cavities, such contours would be poorly related to the direction of groundwater flow. While acknowledging these limitations, Schipper and Reppert (February 1992) prepared a groundwater contour map that showed groundwater flowing to Liddell Spring from an area northeast of the quarry. SECOR (November 1997) cited aquifer anisotropy and insufficient data points (i.e., monitoring wells) as reasons for not producing a potentiometric surface map. EMKO (August 1999) said that it was unlikely that a uniform water table or potentiometric surface existed beneath the quarry area. Furthermore, there was too much uncertainty as to which wells represent the marble aquifer versus perched or isolated zones; this uncertainty could only be resolved by drilling shallow test holes as the quarry floor is lowered. Cloud (February 2000) noted the contradiction between interpreting an absence of significant karst conduits versus citing aquifer complexity as a reason for not constructing a potentiometric map; he also noted an insufficient distribution of monitoring wells.

Despite recognized aquifer complexities and water-level irregularities, several past studies have attempted to define rather distinct groundwater zones based on water-level data, as summarized below:

- With regard to the marble aquifer, Lindsey (April 1967) inferred the existence of (1) a deep zone of long-term groundwater storage that exhibits peak water levels during mid-summer but generally responds little to annual recharge and (2) shallower zones of relatively intermediate and short-term storage that respond more rapidly and dramatically to seasonal precipitation. He estimated that at least two consecutive years of below or above average precipitation were needed for the deeper zones to respond.
- Recognizing that the marble does not have a conventional saturated zone, SECOR (November 1997) performed slug tests on monitoring wells to characterize degrees of hydraulic interconnection among saturated zones. A rapid water level recovery indicated that the saturated zone encountered by a well is connected to the "marble aquifer," whereas a relatively slow water level recovery indicated that a zone is neither part of, connected to, nor representative of the marble aquifer. SECOR contended that unconnected zones transmit insignificant quantities of water and should not be subject to the 20-foot separation between

mining and maximum groundwater levels required by County ordinance. SECOR also based its aquifer definition on groundwater level hydrographs, whereby monitoring wells demonstrating limited water-level variability indicate zones not directly connected to the marble aquifer. Finally, SECOR asserted that borings that do not encounter saturation at the time of drilling indicate zones unconnected to the marble aquifer.

- EMKO (August 1999) stated that perched and/or isolated groundwater zones not connected to the marble aquifer are common in the quarry area, and such zones could be identified by water levels that fluctuate little in response to precipitation. EMKO also stated that groundwater within the marble aquifer typically occurs under confined conditions given that static water levels are often above the first encountered depths to water during drilling.
- Cloud (February 2000) wondered how perched zones could be isolated and yet gain and lose water as indicated by observed water level changes. He also noted that some initially dry borings later contained large depths of water.
- Based on its review of groundwater level data, Farallon (March 2000) said that it was not possible to determine whether any of the quarry area wells represented the same water-bearing zones.
- Brown and Caldwell (October 2000) stated that wells that could not be bailed dry indicated confined groundwater zones; wells with higher water levels than the depth of first encountered water indicated semi-confined zones; and wells not capable of producing significant amounts of water indicated unsaturated zones and/or isolated pockets of water.
- Pacific Geotechnical Engineering (February 2002) noted that the marble body contains both vadose zones (i.e., unsaturated or partially saturated) and phreatic zones (i.e., fully saturated). As such, water flows in the vadose zone under the influence of gravity through a subsurface network of partially full solution cavities, and in the phreatic zone through a fully saturated karst aquifer under the influence of a local water table and/or pressure gradient.
- PELA (May 2005) stated that the "karst terrane consists of two distinct zones—the deeper saturated zone and the unsaturated zone above it" (p. 74); it also referred to the shallow, "unsaturated" zone as isolated, perched, and/or unconnected. PELA classified nearly half of the quarry monitoring wells as "unsaturated zone" wells, including two wells capable of producing considerable amounts of water. PELA asserted that the hydraulic connection between the saturated and unsaturated zones is poor, and thus the quarry operation has little potential influence on Liddell Spring.

4.2.2 **Conceptual Model Summary, Part One**

An interpretation of the complex conditions under which groundwater occurs in the quarry and Bonny Doon area requires multiple lines of analysis, including the hydrogeologic units and their structure; groundwater levels and quality representative of particular depth zones and pathways; the location and water quality of springs; the results of tracer tests; and the response of groundwater and springs to recharge events. Having introduced the area's hydrogeologic framework in Section 4.1, we now present the first portion of our hydrogeologic conceptual model. Rather than subdivide the system into generalized zones (e.g., shallow versus deep), this interpretation identifies complete generic pathways between areas of groundwater recharge and points of groundwater discharge. This interpretation is supported by the analyses presented in the remainder of Section 4.

The groundwater flow system that encompasses the quarry and supplies the major karst springs consists of two or three principal types of pathways from their respective sources of recharge, and one or more relatively minor types of paths. One principal path and a possible second originate from groundwater recharge into exposures of Santa Margarita Sandstone across both the Bonny Doon plateau north of the quarry and the sandy knolls immediately east and northeast of the quarry. The other principal path is fed by stream capture along Laguna and Reggiardo creeks. Each type of path consists of a series of hydrogeologic segments and characteristic sequences of groundwater levels and quality. These paths are not mutually exclusive in that groundwater flowing along one may cross over into another.

The following discussion cites particular quarry monitoring wells as examples of the described conditions. Table 26 provides a summary of these wells and Figure 23 shows their location. The discussion also cites typical specific conductivities of area waters (expressed in microsiemens per centimeter [μS/cm]) as a proxy for the relative concentration of total dissolved minerals. The water temperatures cited below are from the February 2003 isotopic survey (PELA, May 2005). We present, reference, and analyze the data and other information supporting this conceptual model in the remainder of Section 4.

Figure 24 is a schematic illustration of the groundwater occurrence conceptual model. Table 27 summarizes the assignment of springs and monitoring wells to each flow-path segment.

- <u>Path *A* – Santa Margarita Sandstone to Quarry</u>

Path *A* originates from sandstone recharge upgradient of the quarry and consists of three segments that together reach and pass through the quarry marble.

<u>Segment *A*1:</u> The Bonny Doon area north of the quarry receives as much as 60 in/yr of average annual precipitation, much of which is recharged into more than 800 acres of exposed Santa Margarita Sandstone. Groundwater is mounded in the sandstone and generally occurs at shallow depths of 10 to 60 ft below ground surface except beneath the higher hills. These groundwater levels are indicated by driller reports for residential and agricultural water wells, in addition to the elevations of springs and gaining streams. Based on an estimated average saturated thickness of 40 ft and an assumed average specific yield of 16 percent, about 5,000 ac-ft of groundwater may be stored in the sandstone. The regional water table slopes away from the top of this mound to the south for about 1.5 miles, descending from about 1,700 ft msl near Ice Cream Grade to 1,100 ft msl just north of the quarry (Figure 25) under a relatively steady gradient of approximately 0.07 ft/ft. Groundwater also flows to the southwest and southeast toward the surrounding creeks, with some shallow groundwater discharging as small springs toward the edges of the sandstone outcrop (e.g., Whitesell, Strong, and Reggiardo springs). This groundwater has relatively cool temperatures (<12^{o}C) and a very low dissolved mineral content (<200 μS/cm) that is generally of a sodium-chloride type and potentially acidic.

Water tables also occur locally from groundwater recharged into the sandy knolls immediately east and northeast of the quarry, although probably at elevations near or below the base of the sandstone.

Included in this group is a seep (SP-5) that emerges from Santa Margarita Sandstone on a slope south of Plant Spring. Although this seep is essentially downgradient of the karst system, its water quality and ionic signature are similar to the sandstone groundwater upgradient of the quarry.

Segment *A*2: Immediately upgradient of the quarry, the flow of shallow groundwater encounters surficial and buried exposures of the highly permeable marble aquifer. This causes the groundwater level contours to wrap around the marble body where levels drop 300 ft over a relatively short distance of about 1,000 ft or less (Figure 25). Some of this vertical decent is achieved in a step-like manner, with groundwater extending laterally into karst voids at intermediate depths, as encountered by several monitoring wells with average groundwater elevations ranging from 770 to 1,010 ft msl (e.g., BD-40, -41, 42, and -44; M2A, M3B, and M6B). Wells with higher water surface elevations that can maintain some saturation tend to be in karst dead pools or pockets of perched and relatively isolated storage replenished by small but continual throughflow and/or seasonal and climatic fluctuations in the subsurface hydrology. Other wells encounter relatively shallow zones capable of transmitting considerable amounts of groundwater (e.g., BD-42). Karst voids form pathways into the marble aquifer preferentially along fracture zones, including the remnants of ancestral solution channels now elevated relative to the base level presented by discharge from Liddell Spring. Sinkholes aligned along these fractures facilitate the drainage of shallow groundwater, local runoff, and sediment into the karst aquifer. Groundwater also may flow into the marble along deeper flow paths from upgradient recharge areas.

The groundwater in this flowpath has a hydrogen and oxygen isotopic signature similar to that of the sandstone aquifer. However, this water is of a strongly calcium-carbonate type with moderately high mineral content (400 to 600 μS/cm), temperature (12-14°C), and pH. This considerable water quality departure from the sandstone aquifer reflects fairly long and direct contact with the marble. Temporary and seasonal springs and seeps have occurred as quarrying exposes these groundwater zones transitional between the upgradient regional and local water tables and the downgradient outlet to Liddell Spring. Groundwater drainage has occurred after quarry blasts (SECOR, November 1997) and we observed two springs discharging 10-15 gpm from the quarry walls at approximate elevations of 760 ft msl during April 2006 (the topography shown on Plate 2 dates to 2002 and therefore does not depict the correct elevation for these springs). The lack of any permanent springs as a result of quarrying is indicative of the karst aquifer's overall interconnectivity. Indeed, some of the wells that do not encounter groundwater at these intermediate depths indicate areas where vertical connectivity allows rapid, deep drainage.

Segment *A*3: Groundwater descending from the regional and local water tables upgradient of the quarry eventually reaches zones beneath the quarry floor that are directly tributary to Liddell Spring. As described below, another path of groundwater migration also flows into this general area. Because there is relatively little data characterizing groundwater conditions beneath the quarry floor, the amount and nature of mixing that occurs among these sources prior to spring discharge is uncertain. Among recently monitored wells, water levels are generally below 720 ft msl. Former wells now destroyed by quarrying had levels exceeding 750 ft msl. These may have represented perched zones; alternatively, groundwater levels may have lowered as a result of enhanced drainage from quarrying.

Percolation of incident precipitation and collected runoff within the quarry pit constitutes an important source of additional groundwater recharge along this segment of the flow path to Liddell Spring, contributing as much as 20 percent of Liddell Spring's average annual yield (Section 3.2). Averaging as much as 300 ac-ft/yr, this recharge pulse descends through fractures and dissolution features with sufficient energy to transport a considerable sediment load to groundwater. Surficial and subsurface sediment supplies are maintained by quarry blasting and ripping.

At least one well drilled through the quarry floor provided evidence of a high capacity groundwater zone (NZA). Furthermore, recent tracer tests showed this well to be hydraulically connected to upgradient sinkholes and Liddell Spring (PELA, May 20005). The travel time from this well to the spring was approximately 7 hours, indicating an average groundwater velocity of 2,600 ft/day. This was the fastest rate of travel observed during the recent tracer tests.

The remaining flow path to Liddell Spring is discussed under path *C* below.

- <u>Path *B* – Stream Capture to Quarry</u>

<u>Segment *B*1:</u> Path-*B* water originates as streamflow in the upper Laguna and Reggiardo creek watersheds. This water has a very low dissolved mineral content (<200 µS/cm) and cool temperatures (<12^{o}C) during the wet season. Lower in the watershed at the City's point of diversion streamflow maintains a fairly low mineral content (<400 µS/cm) of a consistent calcium-bicarbonate type. Samples collected near the Reggiardo Creek sinking-stream reach are also of this type, suggesting some influence by the watershed's marble prior to capture into the karst system.

PELA (May 2005) estimated sinking-stream capacities between 0.5 and 1 cfs for both Laguna and Reggiardo creeks, for a combined capacity of roughly 1,000 ac-ft/yr. The streamflow and diversion records presented in Section 3 suggest that flows of this magnitude are available for capture during most years. The actual capacity of these sinks fluctuates as a function of their sedimentation.

<u>Segment *B*2:</u> The second segment of flow path *B* begins with streamflow water (segment *B*1) entering both open and buried swallow holes along Reggiardo and Laguna creeks (Figure 24). The results of recent groundwater tracer tests indicate a strong hydraulic connection between three sinking-stream reaches and both Liddell and Plant springs (PELA, May 2005). Peak-concentration travel times from the Reggiardo Creek swallow hole to the springs were about one to two weeks, indicating an average flow velocity of about 300 to 500 ft/day (map distance). Average flow velocities to the springs from the other sinking-stream reaches were about 150 to 300 ft/day. Tracers originating from these sources were also detected in two quarry monitoring wells (M1B and M5A). Tracers introduced into the Laguna Creek swallow hole near Ice Cream Grade also were detected discharging from two springs (SP-21 & -30) located about halfway downstream to the City diversion.

Several quarry monitoring wells appear at least partially representative of the high permeability flow paths that must exist between the sinking-stream reaches and Liddell and Plant springs (M1B, M2B, M3A, M5A, and M6A). With a few exceptions, these wells generally have the following characteristics:

- Located along or near one of the four major southwest-trending fracture zones that connect Reggiardo and Laguna creeks to the immediate quarry area (see Figures 20 and 23).
- Well openings below 700 ft msl.
- Deep water levels relative to nearby, shallower wells.
- Moderate water temperatures (12.5-13.5°C).
- Fairly low dissolved mineral contents (200 to 400 μS/cm), similar to Reggiardo and Laguna creeks.
- Similar hydrogen and oxygen isotopic signatures as Reggiardo and Laguna creeks.
- Evidence of significantly productive groundwater zones.
- Positive tracer detections in at least two of these wells.

These attributes suggest that streamflow captured by the swallow holes flows to the springs through relatively deep and conductive dissolution conduits, which at times may be under confined pressure. The relatively low mineral content compared to flow path segment *A*2 suggests appreciably less contact with the marble due to both the nature and velocity of flow. The relatively deep zones of saturation are consistent with the tendency for karst conduits to cut down to near base level given the low hydraulic gradients needed to move water through such highly conductive zones. From the Reggiardo Creek swallow holes, the tracer travel times and velocities were faster to Liddell and Plant springs than to wells located mid-way (M1B and M5A), indicating that these wells are not representative of the most conductive pathways. Similarly, tracers may not have been detected in other wells thought to represent this pathway (M2B, M3A, M6A) because these wells did not directly intercept those conduits.

Monitoring well M5A is shallower with higher water levels than the other wells in this group. However, this is consistent with its location along the most upgradient fracture leading to the quarry marble body. Groundwater levels in this area are still transitional between the upgradient sandstone aquifer and the well-drained marble aquifer. In contrast, PELA (May 2005) included this well with their "perched", "isolated", and/or "unsaturated zone" wells, despite its positive tracer detection and evidence of high yield.

Groundwater from monitoring well M3A is more mineralized than the other path-*B*2 wells, but is also furthest from a major fracture zone. Similarly, monitoring wells PELA-3 and -4 have depths and water levels potentially representative of this group.

<u>Segment *B*3:</u> Similar to path segment *A*3, segment *B*3 represents the movement of groundwater beneath the existing quarry. Groundwater flowing through the karst conduits inferred as path *B*2 may or may not mix with other groundwater beneath the quarry floor before traveling the final distance to Liddell Spring. Relatively few available data characterize groundwater conditions beneath the quarry floor except to indicate that water levels have been generally below 720 ft msl

since the 1990's. Several now destroyed wells had maximum water levels ranging from 730 to 780 ft msl (DDH-32, -36, & -37, BD-43). Tracers from the Reggiardo and Laguna creek swallow holes were not detected in the one well (NZA) monitored within the existing quarry pit (PELA, May 2005), even though other tracers were detected and indicated a high-velocity pathway to Liddell Spring. This observation may indicate that flow paths *A*3 and *B*3 remain at least partially separate through the quarry area. However, NZA is not situated directly on a major fracture/fault line (Plate 2), indicating that it may be peripheral to the principal flow paths from the swallow holes. The water levels encountered during the drilling of boring NZA did not provide a strong indication of groundwater confinement beneath the quarry floor.

- Path *C* – Quarry to Liddell Spring

Several monitoring wells located between the active quarry and Liddell Spring (DDH-19, BD-45, & QM-2) or adjacent to the spring (QM-5 & DH-3) have water levels generally consistent with a gradient from the quarry to the spring. However, only some are roughly similar to the spring in terms of temperature (QM-2), total mineral concentrations (typically 400-500 µS/cm; QM-5 & DH-3), and/or ionic types (BD-45 & QM-2). None have similar isotopic signatures and none had positive tracer detections. These observations suggest that none of these wells represents a high capacity conduit, although the existence of such conduits may help to explain the spring's water quality, isotopic signature, and sediment transport. Thus, path *C* consists of both relatively slow groundwater flow and, potentially, as yet undiscovered conduit flow. The potential for confined pressures within such conduits decreases as Liddell Spring is approached and the separation from the ground surface diminishes. The convergence of most flow into one or more main conduits is consistent with karst aquifer development, as is the difficulty of locating such conduits. Liddell Spring's increased mineral concentration (>600 µS/cm) following storms and seasonal recharge is explained partially by an increased contribution from the typically slower, more mineralized component of path *C* flow (e.g., BD-45 & QM-2) in response to elevated groundwater pressures.

- Path *D* – Minor Flow Paths

Several other monitoring wells south of the quarry (DDH-10 & -13, QM-1, -3, & -4A) have elevated water levels relative to the gradient between quarry wells (e.g., NZA) and Liddell Spring. Compared to the spring, these tend to be of a different ionic type, higher mineral content, and different isotopic signature. These are also some of the warmest waters tested (>15^{o}C). Given that most groundwater flow is concentrated into the karst system, these wells represent relatively minor groundwater flow paths that may or may not contribute to Liddell Spring. However, some contribution from these sources may partially explain the spring's increased mineral concentration following storms and seasonal recharge.

A seep near Liddell Spring (SP-2) and two seeps near Plant Spring (SP-4 & -6) differ isotopically from the springs and are cooler (<12^{o}C), such that they also probably represent relatively minor flow paths. These flows probably are recharged by precipitation onto upgradient hillslopes, including the landslide deposits adjacent to Liddell Spring.

Finally, Pipe and Dump springs (SP-7 & -8) are highly mineralized calcium-sulfate waters that are isotopically dissimilar to either Liddell or Plant springs and may represent the influence of quarry waste piles.

- <u>Path *E* – Potential Fracture/Conduit Flow from Sandstone Recharge Areas</u>

As discussed in Section 4.1 above, areas of marble may occur beneath the roughly eastern half of the large Santa Margarita Sandstone outcrop north of the quarry. This area's relatively low drainage density and fairly minor spring discharge indicate that some of the sandstone's considerable recharge is captured by buried karst sinks. Roughly north-south fractures connect this area to the quarry marble. These conduits would be less developed than those conveying captured streamflow. As such, this water would be of a similar ionic and isotopic type as path-*A*2 groundwater, and possibly more mineralized. The existence of path *E* would help account for the fairly large flow needed to mix with paths *A* and *B* water to achieve the intermediate water quality character observed at Liddell Spring (Section 4.3). Fairly large combined flow from paths *A* and *E* is also consistent with an apparent high capacity flow path beneath the quarry (as evidenced by well NZA) that was devoid of any tracer from captured Reggiardo and Laguna creek streamflow.

- <u>Liddell Spring</u>

Liddell Spring accounts for more than 80 percent of the marble aquifer's total yield. Its average flow of 1,100 gpm appears to be primarily a mixture of flow paths *A* and *B* (and possibly *E*) based on their similar ionic type (calcium-bicarbonate) and the spring's intermediate isotopic signature and total dissolved mineral content. Path-*A* (and possibly -*E*) groundwater originates from sandstone recharge areas and acquires a moderately high dissolved mineral content as it percolates through the marble. Path-*B* groundwater originates from stream capture and maintains a lower dissolved mineral content because of relatively rapid travel through the karst system. A roughly 50:50 mixture of these waters gives the average mineral content of Liddell Spring (~480 µS/cm), although how and where this mixing occurs is uncertain. The contribution of relatively warm groundwater is also needed to achieve Liddell Spring's water temperature (14.4^{o}C). Minor contributions of more mineralized groundwater from path *D* and some flow components of path *C* may help explain the spring's seasonal and post-storm peak mineral concentrations.

When sampled in February 2003, the hydrogen isotope ratio for Liddell Spring (-34 δD) was midway between values for path *A* and *B* groundwaters. The oxygen isotope ratio for the spring (-5.9 δ^{18}O) was also midway between these sources assuming that the greatest volume of captured streamflow is skewed toward the lower oxygen isotope ratios.

- <u>Plant Spring</u>

Geologic mapping shows Plant Spring situated on a fracture lineament near a contact between schist and granitic rock, about 200 ft from the nearest marble outcrop (Plate 2). Nevertheless, its water quality and positive tracer detections indicate a strong link to the karst groundwater system. The source of Plant Spring's average flow of 180 gpm appears to be primarily from path-*B* type groundwater given its relatively low mineral content (typically 300-450 µS/cm) and cool temperature (12.8^{o}C). There is relatively little hydraulic gradient between groundwater in the quarry area and Plant Spring. Given that the quarry area appears to act as a drain for most path-*A* (and possibly *E*) groundwater, little water of that type emerges from Plant Spring.

- Williams Spring

Available maps suggest that Williams Spring emerges from an exposure of Lompico Sandstone more than 1,000 ft from the nearest marble outcrop. However, its calcium-bicarbonate water quality suggests a marble-aquifer source. Its small discharge appears to be derived primarily from type-*A*2 groundwater given its calcium-bicarbonate composition and relatively high dissolved mineral content (750 µS/cm). This flow probably derives from relatively local recharge into the marble aquifer.

- Groundwater Storage

As recognized by Todd (January 1963), the seasonal and year-to-year consistency of Liddell Spring discharge is evidence of the spring's connection to a large volume of groundwater storage. The fairly rapid groundwater velocities documented by tracers between stream swallow holes and Liddell Spring indicate that some amount of groundwater spends little time in the aquifer. At the same time, a large portion of captured streamflow is diverted into pore spaces and cavities marginal to the high conductivity pathways. When the inferred deep conduits (path *B*2) become fully saturated and pressurized during periods of high streamflow, groundwater is forced upward and outward into ancestral karst porosities that occur between the elevations of the Reggiardo Creek swallow hole at 1,000 ft msl and the quarry floor at 750 ft msl. This water would displace more mineralized path-*B*2 and -*B*3 groundwater, allowing its flow toward and discharge from Liddell Spring, helping explain the spring's seasonal and post-storm peak mineral concentrations. Residual storage of this nature probably accounts for some of the perched water encountered by wells.

Rough assumptions about the geometry and porosity of active storage in the marble block between Reggiardo Creek and the quarry suggest only a few thousand acre-feet of groundwater storage capacity (e.g., an area roughly 3,000 feet square with an average depth of 300 ft and 5 percent porosity [Section 4.1.3] ≅ 3,000 ac-ft), suggesting additional storage occurs elsewhere in order to account for sustained springflow during drought periods. Some of this storage may occur in other marble bodies connected by fractures and additional buried marble.

Water quality data also suggest that Liddell Spring is supplied by at least one other important source of groundwater storage. As discussed above, path *A* groundwater originates from some portion of the estimated 5,000 ac-ft of storage in the Santa Margarita Sandstone capping the Bonny Doon plateau north of the quarry. Additional storage probably occurs in the underlying rock, which may include marble and the inferred path *E* toward Liddell Spring.

4.2.3 **Monitoring Well Hydrographs**

Table 26 summarizes information for 40 quarry monitoring wells. Their locations are shown in Figure 23. Table 28 provides groundwater level data collected from these wells since 1992, and Figures 26 through 29 present the groundwater level hydrographs for 24 monitoring wells with recent data or past records that compliment one of the currently monitored wells. Watkins-Johnson

Environmental (November 1992) provided hydrographs for another 8 wells that have not been monitored since the 1970's.

The water level hydrographs are plotted in reference to sea level. However, the depths to water also are revealing (Table 28). Two wells have maximum depths to water greater than 400 ft below ground surface (bgs) (M1B, PELA-4), seven other wells have maximum water depths greater than 300 ft bgs (BD-41 & -42, M2A, M2B, M3A, M6A, & M6B), and five others >200 ft bgs (BD-44 & -45, M3B, M5A, PELA-3). Such great depths to water are rare in the region, and reflect extraordinary groundwater drainage into the karst groundwater system supplying Liddell Spring.

Long-term (1966-2006) hydrographs for wells BD-40, -41, -42, and -44 (Figures 26 and 27) depict groundwater elevations in transition between the regional sandstone aquifer to the north and east of the quarry and the marble aquifer beneath the quarry (i.e., path *A*2). These levels range widely between 820 and 1,140 ft msl, a range of more than 300 ft. As noted by previous investigators, these hydrographs are fairly erratic and only sometimes correlate to each other or the precipitation record. Sudden, large changes in water level may reflect the episodic draining or filling of karst voids due to marble dissolution and collapse. Similarly, the drilling of well M3B in early 1999 is believed to have breached a perched zone, causing the observed precipitous decline in BD-44 water levels (Farallon, February 2000). Levels in some of these wells appear to exhibit a slight downward trend (e.g., BD-40 & -41). Water levels have been relatively stable during the most recent period of monitoring (2003-06; PELA, May 2005).

Fairly recent (2000-06) hydrographs for well pairs M2A/M2B, M3B/M3A, and M6B/M6A (shallow/deep; Figures 26 and 27) exhibit water level differences of 50 to 200 ft between (a) shallow wells completed in zones transitional between the sandstone and marble aquifers (M2A, M3B, and M6B; path *A*2) and (b) the corresponding deep wells completed deeper in the marble (M2B, M3A, and M6A; path *B*2).

The combined 1959-2006 hydrograph for DDH-19 and BD-45 (Figure 28) represents the marble aquifer along path *C* between the quarry and Liddell Spring. Water levels often fluctuate 10 to 30 ft per year but also have changed abruptly by more than 100 ft. There is no apparent long-term trend.

Figure 29 presents 1999-2006 hydrographs for wells QM-1 through -4. QM-1 and -2 are screened below the elevation of Liddell Spring, QM-1 and -3 are screened in granite, and QM-1, -3, and -4 have water levels that are above the hydraulic gradient between the quarry and the spring (path *D*). These hydrographs are relatively flat.

There is no long-term record for groundwater levels beneath the active quarry. Wells monitored in this area until quarrying began (DDH-32 & -37; 1959-69) and slightly after (BD-43; 1966-76) had fairly flat water levels (±7 ft) except for a few anomalous spikes of up to 60 ft (Watkins-Johnson Environmental, 1992). We monitored water levels in well NZA following its completion with an in-situ pressure transducer and data logger. Unfortunately, this water level data was lost due to a data logger malfunction.

Farallon (August 2001) noted that groundwater levels in monitoring well QM-5, adjacent to Liddell Spring, rose following storms after a lag time similar to that of the spring's general response to storms.

4.2.4 **Upgradient Water Wells**

We reviewed 43 driller's reports for water wells constructed in the Bonny Doon area upgradient of the quarry during 1950-2002. These wells are on the sandy plateau between Mill Creek to the west and Reggiardo and Laguna creeks to the east and mostly within 1.5 miles of the quarry. Table 29 summarizes these wells by subsection. All but five of the wells are <180 ft deep. Among the 30 wells with reported water levels, all but three had levels <65 ft deep. These shallow water levels are representative of groundwater path *A*1. They contrast markedly with water levels as much as 400 ft deep in the quarry area, demonstrating the substantial groundwater drainage achieved by the marble aquifer discharging to Liddell Spring.

Estimated groundwater elevation contours for the area north of the quarry (Figure 25) are based on an extrapolation of these shallow water levels as well as the elevations of springs and gaining perennial streams.

When constructed, a well in subsection 10S/3W-25C off Smith Grade and another well somewhere along Martin Road reportedly had depths to water of 220 and 320 ft bgs, respectively. These anomalously deep levels may reflect one or more deeper zones drained by fractures and possibly karst conduits, as inferred for path *E*.

4.2.5 **Groundwater Surface Contours**

Figure 25 shows generalized contours for both an upper groundwater surface representative of surficial recharge into the Santa Margarita Sandstone and a lower surface representative of deep conduit flow from stream swallow holes. As stated above, the upper contours for the area north of the quarry are based on the shallow depths to water reported for numerous water wells (Table 29) and the elevations of springs and gaining streams. The contouring was done by hand and then digitized for reproduction by contouring software.

Figures 30 and 31 provide separate contour maps for each of the estimated groundwater surfaces in the quarry area with postings of their respective supporting data. Table 27 identifies the wells used for each map. The estimated contours are highly generalized given that each inferred surface is representative of multiple, although roughly equivalent, zones. In reality, these surfaces may be discontinuous with intermediate surfaces between them. Also, computed average water levels may be inconsistent given the monitoring wells' different periods of record. Lastly, there is some uncertainty associated with reported spring locations and/or elevations (e.g., discrepancies between available topographic maps and the reported elevations of several springs and seeps mapped by PELA (May 2005)).

As discussed previously, the shallow groundwater surface that descends gradually from the Bonny Doon area north of the quarry wraps around the quarry marble body in response to groundwater drainage into the karst aquifer, causing a water-level drop of several hundred feet over a relatively short distance (Figure 30). Contours of the upper groundwater surface along the immediate quarry boundary include discontinuous perched zones fed by this descending water.

The lower groundwater surface represents the top of the permanently saturated zone (Figure 31). These contours generalize what are actually at times separately pressurized karst conduits connecting stream swallow holes to the quarry area and Liddell Spring. The southwest sloping gradient of this surface represents the marble aquifer's apparent anisotropy relative to the generally southern regional gradient. The relatively deep groundwater levels indicated by two deep water wells north-northwest of the quarry (10S/3W-25C and 10S/3W-24 [located by section only]; Table 29) are consistent with the estimated lower groundwater surface. The estimated lower and upper groundwater surfaces intersect along Reggiardo Creek and merge in the granitic terrain northwest of the quarry and where the karst system terminates to the south of Liddell Spring.

Figure 32 posts the maximum groundwater elevations recorded for each monitoring well. On average these are about 15 ft higher than the estimated groundwater surfaces but range up to 60 ft higher.

4.3 **Water Quality**

Available water quality data for monitoring wells, springs, and streams include the following:

- Measurements of groundwater and spring temperature (Table 30).
- More than 40 general mineral analyses of samples from over 20 different sources (Table 31).
- Thirty or more general mineral analyses each for the City of Santa Cruz's diversions from Liddell Spring and Laguna (including Reggiardo) and Majors creeks (Tables 32, 33, & 34).
- Additional measurements of groundwater and surface-water specific conductance (Tables 35 & -36) and nitrate concentration (Table 37), including from data loggers installed in wells BD-45 and QM-2 and -4 during 1999-2000.
- A June 1982 water quality survey of surface water in East Liddell Creek and neighboring watersheds (Creegan & D'Angelo, 1984).
- Results of a February 2003 stable isotope survey (Table 37).
- Specific conductance and turbidity measurements for the City diversions (Figures 16 & 17).
- Specific conductance, turbidity, and temperature data from data loggers installed on Liddell Spring since 1997 (Figures 33 & 34) and Plant Spring from November 2002 through November 2004 (PELA, May 2005, Appendix C).

Farallon (March 2000) asserted that groundwater samples tested for turbidity, iron, and coliform were unrepresentative because of aspects of monitoring-well construction and groundwater sampling technique. We did not consider these data.

Figures 33 and 34 are plots of daily precipitation and Liddell Spring mean and maximum daily discharge, turbidity, specific conductance, and temperature recorded discontinuously by data loggers during 1997-2005. Changes in sampling equipment, method, and/or measuring technique are responsible for some of the variability and apparent shifts in the data values. Note that turbidity is plotted on a log scale. Also posted are the City's mean monthly rates of diversion (expressed in gpm) and typically bi-weekly measures of specific conductance and turbidity. The match between the mean daily flows and mean monthly diversions is reasonable. However, the bi-weekly specific conductance values for the City's spring diversion are typically up to 100 μS/cm higher than the data-logger values. Also, the City's measured turbidities tend to be one half to a full log cycle lower than the data-logger values. Nevertheless, the respective data sets consistently track each other.

The three plots in Figure 35 present Liddell Spring discharge, turbidity, and specific-conductance duration curves for various year and multi-year periods of the data-logger record. Liddell Spring discharge ranged between 850 and 1,100 gpm about 75 percent of the time, on average (Figure 35a). The scatter plots in Figure 36 demonstrate poor to moderate correlations among mean daily values of Liddell Spring discharge, turbidity, specific conductance, and temperature.

4.3.1 **Water Temperature**

Water temperature provides a useful indicator of groundwater movement. The temperature of groundwater residing long-term within the aquifer typically approaches that of the mean annual air temperature (i.e., about 17.6°C for Santa Cruz and 14.8°C for Ben Lomond). Groundwater recharged by winter rainfall and runoff will reflect relatively cool temperatures for some period of time. Conversely, slow migrating groundwater will mimic seasonal air temperatures when approaching the ground surface, such as groundwater emerging from a seep.

Table 30 summarizes available groundwater, spring, and streamflow temperature measurements. Groundwater moving relatively fast from recharge into the Santa Margarita Sandstone and marble aquifers toward points of spring discharge maintains fairly cool temperatures (e.g., Whitesell and Plant springs, less than 13°C). Groundwater moving slowly through less permeable zones is much warmer (e.g., QM-1, -3, & -4; 15-18°C). Whereas the relatively cool temperatures of Plant Spring indicate that it is derived mostly from stream capture, the more moderate temperatures of Liddell Spring suggest that it is a mixture of stream capture and long-term groundwater storage.

Figure 36d shows the correlation between Liddell Spring discharge and water temperature during 2004-05. Springflows below about 1,100 gpm had little correlation with temperature whereas higher flows were generally greater than 16°C, indicating that long-term groundwater storage contributes substantially to these flows. Conversely, the water temperature of Plant Spring varied little when monitored continuously during 2002-03 PELA (May 2005).

Figure 36e shows the correlation between Liddell Spring temperature and specific conductance. Flows with the lowest specific conductance (<400 μS/cm) are coldest (<15°C) whereas flows with the highest specific conductance (>450 μS/cm) are warmest (>16°C). Cold temperatures and relatively low mineral content reflect captured winter streamflow, whereas relatively warm water (approaching mean-annual air temperature) and higher mineral content reflect long-term groundwater storage. Liddell Spring's discharge of relatively warm, mineralized water during peak flow conditions indicates a direct and substantial contribution from groundwater storage.

4.3.2 **Ionic Water Types**

Table 31 summarizes general mineral analyses for about 20 different sources of water in the quarry area. The trilinear plot of these data in Figure 37 highlights two groups of samples that are representative of the marble and sandstone aquifers.

The majority of area waters are of a calcium-bicarbonate type, including most streamflow. However, water associated with the marble aquifer is of a strongly calcium-bicarbonate type, with calcium comprising typically 75 percent or more of the major cations and sulfate comprising <15 percent of the major anions (as milliequivalents per liter [meq/L]). The concentration of calcium in marble-aquifer groundwater is typically 6 to 13 times greater than the concentration of magnesium (as mg/L). However, the concentration of magnesium was proportionally higher in some wells near the end of the 1987-92 drought (BD-40, -41, & -44; Table 31).

Water associated with the Santa Margarita Sandstone tends to be of a sodium-chloride or mixed type (e.g., Whitesell and Reggiardo springs). Water that has been in contact with stockpiled quarry waste tends to be of a calcium-sulfate type (Pipe and Dump springs, possibly QM-2, and station 5 sampled by Creegan & D'Angelo). Wells completed in granitic rocks near the downgradient boundary of the marble aquifer have a mixed-sodium water quality (QM-1 & -3).

4.3.3 **Specific Conductance**

A water's specific conductance (i.e., electrical conductivity at 25°C, expressed in µS/cm) is proportional to its concentration of total dissolved minerals. Available measurements of specific conductance are summarized in Tables 35 and 36 and plotted on the map in Figure 38. The recommended drinking water standard for specific conductance is 900 µS/cm, with enforceable limits set at 1,600 and 2,200 µS/cm.

Groundwater and surface water upgradient and cross gradient from the quarry marble aquifer tends to be low in dissolved minerals (<200 µS/cm). Water in contact with the marble becomes more mineralized and generally ranges between 300 and 1,000 µS/cm. Along major fracture zones east of the quarry, the dissolved mineral content tends to be relatively low in deep wells compared to nearby shallower wells (e.g., M6A vs. M6B, M1B vs. BD-44, M2A vs. M3B). Because dissolved mineral content usually increases with depth, this observation indicates that these deep wells encounter zones influenced by relatively rapid groundwater flow through deep karst conduits that drain stream swallow holes (i.e., path *B*2 described in Section 4.2.2).

The average specific conductance of Liddell Spring (~480 µS/cm) is intermediate between groundwater derived from captured streamflow (generally 300-400 µS/cm) and more mineralized groundwater migrating relatively slowly from other sources of recharge (i.e., paths *A*, *D*, and *E*). If it is assumed that upgradient groundwater has an average specific conductance of 600 µS/cm, then a roughly 50:50 mix of captured streamflow and upgradient groundwater is needed to produce the average specific conductance of Liddell Spring. The relatively low average specific conductance of Plant Spring (~350 µS/cm) suggests that captured streamflow is its primary source of recharge.

Total mineral concentrations tend to be highest along the downgradient margin of the quarry operation. This may reflect the influence of quarry waste materials, including the dissolution of quarry dust. Also, groundwater flux is substantially reduced through much of this area due to the convergence of flow toward Liddell and Plant springs, resulting in less dilution of the remaining groundwater's mineral load, as indicated by water quality measurements from the QM-1, -2, and -3 (Table 35).

The specific conductance of Liddell Spring diversions (Figure 19) and discharge monitored by data logger (Figures 33 & 34) quickly rise to greater than 600 μS/cm during storm periods and gradually decline after each storm and throughout the dry season. This gradual recession is also apparent in the mean daily specific conductance duration curve (Figure 35b). The scatter plot in Figure 36a illustrates the direct, albeit rough, correlation between the spring's specific conductance and discharge. This trend is the opposite of that typically exhibited by streamflow, in which specific conductance gradually rises during the dry season as the groundwater contribution proportionally increases, and then quickly decreases as a result of dilution from precipitation and runoff during the wet season (Figure 16). The rapid pressurization of the karst aquifer by low-mineral winter recharge and captured streamflow causes the release of proportionally more high-mineral groundwater to Liddell Spring. The rise in springflow specific conductance usually peaks one-half to three days after a storm begins (see further discussion in Section 4.5.5). This observation demonstrates that a large volume of dynamic groundwater storage exists and contributes substantially during periods of both high and low discharge. The mechanics of how this storage operates are discussed further in Section 4.4.

When monitored during WY 2004, the specific conductance of the Liddell Creek East Branch tributary immediately downstream of Liddell Spring was 200 to 300 μS/cm greater than the spring. Also, the City's bi-weekly measurements of Liddell Spring specific conductance tended to be more erratic and 100 to 200 μS/cm higher than the spring data logger. The reasons for these differences are unexplained.

As discussed in Section 4.3.1, the mean daily specific conductance and water temperature of Liddell Spring are directly correlated (Figure 36e). Flows with the lowest specific conductance (<400 μS/cm) are coldest (<15^{o}C) whereas flows with the highest specific conductance (>450 μS/cm) are warmest (>16^{o}C). Cold temperatures and relatively low mineral content reflect captured winter streamflow, whereas relatively warm water (approaching mean-annual air temperature) and higher mineral content reflect long-term groundwater storage. Liddell Spring's discharge of relatively warm, mineralized water during peak flow conditions indicates a direct and substantial contribution from groundwater storage.

As shown in Figure 39, same-day values of specific conductance for the City's Laguna and Majors creek diversions are well correlated, whereas the specific conductance of Liddell Spring correlates poorly and slightly inversely to the stream diversions.

Three measurements of Plant Spring specific conductance from 1992 and 1997 ranged from 420 to 470 μS/cm (Table 36). PELA (May 2005, Appendix C) monitored the specific conductance of Plant Spring for two years beginning November 2002, documenting substantially less and characteristically different variably than Liddell Spring. Values trended gradually between about 320 and 340 µS/cm, with repeated dips of 30 to 40 µS/cm during some periods that were inconsistently correlated to precipitation and spring discharge.

4.3.4 **Stable Isotopes**

PELA (2005) conducted a stable isotope survey of 39 quarry-area wells, springs, seeps, and streams during February 21-25, 2003. Accumulated precipitation was 20 inches for the season to date, greater than 2 inches during the preceding 10 days, and about 1 inch during the sampling period. Precipitation was generally near or below average for WY 2003 (Table 7). Table 37 provides the survey results, including field measurements of water temperature, pH, and specific conductance for each sample.

Concentrations of the heavier isotopes of hydrogen and oxygen become depleted in water derived from evaporation. Thus, atmospheric moisture is depleted of the heavier isotopes relative to the ocean from which it evaporated. The isotopic composition of precipitation is further affected by the temperature and elevation of where it forms and falls. When precipitation accumulates on land, it becomes relatively enriched with the heavier isotopes as the lighter isotopes are disproportionately lost to evaporation. Once water percolates below ground it experiences no further evaporation and its isotopic ratios of hydrogen and oxygen remain fairly constant. Thus, groundwater at different locations, depths, and points of discharge can be grouped into similar origins and flow paths based on the similarity of these ratios, although various chemical processes can further alter the isotope ratios below ground.

Figure 40 is a plot of the ratios of oxygen-18 to oxygen-16 ($\delta^{18}O$) versus the ratios of deuterium to hydrogen (δD). The corresponding values of specific conductance are posted beside each point. The isotope-ratio pairs are grouped within five separate envelopes based on their ratio values, specific conductance, and contextual hydrogeology.

Group 1 consists of springs and seeps emerging from the Santa Margarita Sandstone (-5.4 to -5.8 $\delta^{18}O$, -32 to -34 δD). These have very low specific conductance values of less than 200 µS/cm. The envelope encompassing group 2 (-5.6 to -5.7 $\delta^{18}O$, -33 to -34 δD) nearly overlies group 1, however these samples are from monitoring wells completed in marble and have moderate to high values of specific conductance (350-900 µS/cm). The isotopic similarity of these groups, along with hydrogeologic interpretation, suggests that group 1 groundwater represents the source of group 2 groundwater; i.e., water recharged into the Santa Margarita Sandstone eventually migrates into the underlying marble aquifer. This interpretation is consistent with conceptual groundwater paths *A*1 and *A*2 presented in Section 4.2.2.

Group 3 consists of streamflow in the Laguna and Reggiardo creek watersheds (-5.7 to -6.2 $\delta^{18}O$, -34 to -37 δD). Given the time of year, very low specific conductance, and approximately 3 inches of precipitation immediately prior to and during the survey, these samples are probably more representative of seasonal runoff than baseflow. Stream samples taken at other times would probably have substantially different isotopic signatures. However, these samples do represent the seasonal flows most available for capture by the karst swallow holes.

Group 4 (-5.7 to -6.0 $\delta^{18}O$, -34 to -35 δD) consists of groundwater with moderately low specific conductance (~200-400 µS/cm) from relatively deep monitoring wells located along major fracture zones. This group overlies one end of the group-3 envelope, consistent with the assumption that this groundwater is recharged predominantly by stream swallow holes (i.e., conceptual groundwater path *B* presented in Section 4.2.2). This group probably receives some leakage from shallower zones, thus explaining its location toward groups 1 and 2 relative to the center of group 3. Also, the rapid arrival of tracers to Liddell Spring suggests that none of these monitoring wells directly encounter the highest permeability pathways.

Liddell Spring (-5.9 $\delta^{18}O$, -34 δD) plots midway between groups 1-2 and groups 3-4 in terms of δD, whereas in terms of $\delta^{18}O$ the spring plots approximately midway between groups 1-2 and the more depleted (i.e., more negative) portion of group 3. These data indicate that both sandstone recharge and swallow-hole stream capture contribute roughly equally to the spring. A similar conclusion is drawn from both the specific conductance and nitrate data discussed elsewhere. The fact that the spring's $\delta^{18}O$ is skewed toward the depleted end of group 3 is reasonable given that the greatest volume of swallow-hole recharge is from isotopically depleted stormflow.

Plant Spring (-5.8 $\delta^{18}O$, -35 δD) plots within group 4 in terms of both δD and $\delta^{18}O$. This and its moderately low specific conductance suggest that its source is mostly from captured streamflow.

Group 5 is isotopically enriched relative to the other groups (-5.1 to -5.5 $\delta^{18}O$, -31 to -34 δD, except for two outliers). This group includes all of the non-calcium-bicarbonate waters, including those that appear influenced by quarry waste and/or migrate along fairly minor flow paths separate from the karst groundwater system (i.e., conceptual path *D*). This group partially overlies group 1 but is distinguished by generally higher values of specific conductance. The Pipe Spring sample was isotopically depleted but highly mineralized, suggesting that it was derived from recent precipitation that had percolated quickly through quarry waste. A sample of highly enriched pond water (SS-9) suggests that the water had resided in the pond for an extended period of time and experienced considerable evaporation.

4.3.5 **Nitrate**

Nitrate concentrations are generally low (i.e., <1 mg/L) in naturally occurring surface water and groundwater. Potential sources of nitrate in the quarry area include wastewater disposal, fertilizers, agricultural wastes, and the explosives used in quarrying (ammonium nitrate and fuel oil [ANFO]). Nearly 400 septic systems occur within the potential source area for Liddell Spring that includes the Reggiardo and Laguna creek watersheds above the karst swallow holes and the Santa Margarita Sandstone recharge area (Johnson, December 2002). A turkey ranch was located immediately north of the quarry from about 1950 to the mid-1970's (CDM, July 1996). Orchards also occur north of the quarry, which may be fertilized. The drinking water standard for nitrate is 45 mg/L (as NO_3).

Table 37 provides a summary of available nitrate concentrations for quarry area monitoring wells, springs, and streams. Five monitoring wells were sampled for nitrate during 1992-98, four upgradient of the quarry (BD-40, -41, -42, & -44) and one between the quarry and Liddell Spring

(BD-45). Among all wells, concentrations averaged about 3 mg/L and ranged from below detection to 15 mg/L, with no clear spatial or temporal pattern.

Nitrate concentrations in Whitesell Spring upgradient of the quarry ranged from 28 to 56 mg/L when sampled in 1992 and 1997. This suggests a concentrated source, possibly residual waste from the former turkey ranch. Because the spring flows at 10 gpm or less, the actual nitrogen loading is relatively small.

Mill Creek, which drains a portion of the Santa Margarita Sandstone recharge area, had a nitrate concentration of 5 mg/L when sampled in September 1982 (Creegan & D'Angelo, 1984). Previous studies have found that nitrate loadings tend to be poorly attenuated in soils associated with the Santa Margarita Sandstone due to high percolation capacities (e.g., HEA, October 1982).

The nitrate concentrations of waters tested in the immediate quarry area include 2.3 mg/L in water ponded on the quarry floor, 4.2 mg/L in the discharge of Dump Spring, and 3.8 mg/L in the drainage channel leading to the quarry's detention basins (references provided in Table 37).

The nitrate concentrations of the City's diversions from Liddell Spring (Table 32) have averaged 1.8 mg/L and ranged up to 10 mg/L since 1967. Concentrations were <2 mg/L prior to 1977 and have since typically ranged from about 1 to 5 mg/L, with a few spikes occurring up to 5 to 10 mg/L, usually during December through February (Figure 19).

For the City's Laguna Creek diversion, the average nitrate concentration has been 0.4 mg/L with a peak of 2.6 mg/L. The nitrate concentrations of the City's Laguna and Majors creek diversions have not experienced noteworthy trends or spikes since 1972 (Figure 17).

When sampled in 1992 and 1997, Plant Spring had nitrate concentrations ranging from 0.7 to 2.1 mg/L. The few nitrate concentrations measured in Reggiardo Creek have been below 1 mg/L.

If it is assumed that groundwater upgradient of the quarry has an average nitrate concentration of about 3.5 mg/L and streamflow captured by swallow holes has an average concentration of about 0.4 mg/L, then roughly equal amounts of recharge from each source are needed to produce the average nitrate concentration of Liddell Spring. As discussed above, specific conductance data suggest a similar conclusion. The upgradient groundwater contribution could be less if quarry activities represent a relatively large nitrate load.

Liddell Spring's nitrate probably derives from a combination of sources, including ANFO, agriculture, and septic systems. Given the average daily flow rate of 900 gallons per minute, and an average nitrate concentration of 1.8 mg/l (as NO_3), the nitrogen loading of Liddell Spring is 4.5 pounds per day (as nitrogen). The typical nitrogen loading in the daily septic output of a three person household is about 0.1 pounds per day. Consequently, the daily nitrogen content of the output of Liddell Spring is comparable to the nitrogen content in the septic output of about 45 homes (Table 38). However, unlike Laguna and Majors creeks, the nitrate concentrations of Liddell Spring appear to have increased and become more variable since the early 1970's (Figures 17 and 19).

4.3.6 **Turbidity and Sediment**

Unlike other aquifers, karst groundwater systems have the capacity to transport significant amounts of both suspended and bedload sediment due to the relatively high velocity of groundwater flow through dissolution channels. Furthermore, sinkholes, stream capture, and marble dissolution and collapse provide replenishable sources of sediment.

The impact of sediment on water supply is commonly gaged in terms of turbidity. Turbidity is a measure of the scattering of light in water by suspended particulate matter and soluble colored compounds. Turbidity correlates approximately with the concentration of total suspended solids (TSS), although this correlation varies from stream to stream as well as seasonally and during storms (e.g., rising versus falling hydrograph). Turbidity itself is not a major health concern, but high turbidity can interfere with disinfection and provide a medium for microbial growth. As of January 2002, the Interim Enhanced Surface Water Treatment Rule requires that drinking water turbidity never exceed 1 NTU and not exceed 0.3 NTU in 95 percent of a month's daily samples.

Various accounts described the turbidity and sediment load of Liddell Spring prior to quarrying. Lindsey (July 1964) reported that the spring exceeded drinking water limits for turbidity and/or bacteria three times during 1963. Later, Lindsey (November 1968) noted the clarity of an autumn 1968 sample. Stewart (December 1971) acknowledged at least 2 high turbidity readings prior to the start of quarrying, one in 1965 and one in 1968. Stewart (March 1978) observed that Plant Spring had substantial flow without any silt. Watkins-Johnson Environmental (November 1992) noted records of elevated turbidity during several years prior to quarry operations. A data review by Earth Sciences Associates and Creegan & D'Angelo (May 1979) found that spring turbidity under natural, pre-quarry conditions sometimes exceeded standards later used to evaluate whether the quarry was having an impact.

Mineralogical analysis has been used to assess the source of Liddell Spring's sediment load. Creegan (March 1972) noted the presence of mica in springflow during times of high turbidity. Woodward-Clyde (1997) concluded that the source of Liddell Spring's sediment was neither marble nor Santa Margarita Sandstone, but some other sandstone. Kopania (December 2001) concluded that sand in the springbox did not originate from the marble bedrock and thus was not related to quarry activities. Balance Hydrologics (December 2002) performed x-ray diffraction on samples of suspended sediment collected from Liddell Spring in January 2002 and concluded that none of the local geologic formations could be ruled out as potential sources. The occurrence of mica could be traced to schist interbedded in marble or granitics, with a small probability that it was from the Santa Margarita Sandstone. Pacific Geotechnical Engineering (February 2002) concluded that the mineralogy of the springbox sediment does not point to a single source. Additional observations and interpretations of the sediment supply are provided below in Section 4.4.1.

To supplement these former studies, we performed x-ray diffraction (XRD) analyses on both water and loose material samples collected in February, March, and June 2004 and April 2006. For the loose material samples, only the finest fraction of sediment was analyzed by mixing the material in water and selecting only the particles that remained in suspension after set periods of time. Water samples were collected from Reggiardo, Whitesell, and West Liddell creeks;

Liddell and Plant springs; and quarry monitoring wells PELA-3 and NZA-1. Bulk samples were collected from two locations on the quarry benches and two locations on the quarry floor. Appendix A documents the sampling and analytical methodology and results.

We found that our finest grained prepared samples of loose material from the quarry had similar percentages of calcite as suspended sediment samples from Liddell Spring, about 10% (Appendix A). Based on visual inspection, the coarser grained sediment from the quarry is composed dominantly of calcite, derived from the working of the quarry. The coarser particles range in size from small pebbles to very fine sand and settle out of solution rapidly once the water is stilled. The finest grained sediment includes silt and clay. Much of this material is derived from the "terra rosa" coating of open fractures in the marble, and possibly from fine grained sediment washed in from surrounding terrain. This particle size remains suspended in water for some time after stilling and is more likely to contribute to turbidity downstream. The percentage of calcite decreased as the particle size decreased (Appendix A). The findings of our XRD study contradict PELA's (May 2005) assertion that the suspended sediment observed in Liddell Spring could not originate from quarry operations because only a relatively small portion consisted of calcite.

Figure 19 provides the long-term turbidity record for Liddell Creek diversions and Figures 33 and 34 give plots of mean and maximum daily turbidity recorded during 1999-2005. Changes in sampling method and/or measuring technique may be responsible for some of the variability and apparent shifts in data values. PELA (May 2005) monitored the turbidity of Plant Spring beginning in November 2002. Earlier studies monitored groundwater turbidities in monitoring wells, although several questions were raised regarding the sampling method, conditions, and data accuracy (Schipper and Reppert, February 1992; Watkins-Johnson Environmental, November 1992; Farallon, March 2000).

From about 1980 through the mid-1990's, the turbidity of Liddell Spring diversions mostly ranged between about 0.05 and 10 NTU (Figure 19). Prior to that, there were at least four years during the early 1970's when turbidities commonly ranged from 1 to 100 NTU, maintained a higher minimum of about 0.2 rather than 0.05 NTU, and peaked upwards to 500 NTU. As discussed in Section 4.6, observers at the time documented a strong correlation between the start of quarry operations and the ensuing years of increased spring sedimentation and turbidity. Since the mid-1990's, the overall turbidity trend has remained flat, however the incidence of turbidities between 10 and 100 NTU has increased and the minimum level is generally above 0.1 NTU. Given the similarity of the Laguna Creek turbidity record (Figure 18), this recent trend may reflect the City's ability to accept and handle more turbid water since 1994, as discussed in Section 3.5.1.

Figures 33 and 34 present the discontinuous Liddell Spring data-logger record for 1997-2005. This record includes spring flows that were too turbid for the City to divert, ranging up to 1,000 NTU. On average, mean daily turbidities exceeded 2 and 10 NTU about 15 and 4 percent of the time, respectively (about 8 and 2 weeks per year; Figure 35c). Mean daily turbidity correlates poorly with mean daily flow (Figure 36b). For example, turbidities >10 NTU have occurred on days with mean daily flows anywhere between 900 and 3,000 gpm (Figure 36b.). The lower limit of the turbidity-versus-flow envelope generally increases with increasing flow. However, the highest recorded turbidities have not occurred at the highest flows, but instead are most associated with flows between 900 and 2,000 gpm. In streams, turbidity is more highly correlated with flow, including maximum flows. Liddell Spring turbidities are slightly better correlated with specific conductance (Figure 36c). Together with the monitoring record (Figures 33 and 34), the poor correlation between Liddell Spring peak flows and peak turbidities indicates that peak turbidities tend to occur early during the spring's stormflow hydrograph.

Lewis (2003) documented the relation between turbidity and the concentration of suspended sediment for several northern coastal California streams. Without the consideration of additional information (e.g., rising versus falling hydrograph, antecedent conditions, sand fraction), these correlations tend to be rough. Nevertheless, this and other research demonstrate that suspended sediment (in mg/L) can be roughly approximated by multiplying turbidity (in NTU) by factors ranging between about 1.8 and 3.5 (Figure 41). Applying the high, low, and mid-range equations shown in Figure 41 to the WY 2005 mean daily turbidities and flows of Liddell Spring (Figure 34), and assuming different potential sediment densities, we calculate the following range of potential suspended sediment load:

Estimate Range	Annual Suspended Sediment Load (from equations in Figure 41) (lbs/yr)	Average Daily Suspended Sediment Load (lbs/day)	Assumed Sediment Density (lb/ft^3)	Average Volumetric Daily Sediment Load (ft^3/day)
Low	10,000	25	100	0.3
Mid-range	46,000	125	93	1.4
High	540,000	1,500	85	17

The assumed sediment densities (85 to 100 lb/ft^3) bracket those for loose sand, moist soil, pulverized limestone, and broken shale, sandstone, or marble. Thus, roughly a few cubic feet of sediment per day could account for the spring's observed turbidity during WY 2005.

4.4 Groundwater Movement and Sediment Transport

Having characterized general pathways through the groundwater system, this section evaluates the mechanics and interconnectivity of groundwater movement along and between these pathways, and their potential connection to sources of recharge and sediment. It includes a review of previous interpretations and analyses of tracer tests and continuous springflow monitoring.

4.4.1 Aquifer Connectivity to Water and Sediment Sources

Previous investigations commented extensively on the proximity, nature, and mechanisms of Liddell Spring's connection to water and sediment sources, especially in response to precipitation events:

- During heavy rain in January 1950, Kinzie (January 1950) observed that Liddell Spring discharge was muddy and carried some silt. The presence of moss in the flow was taken as an indication that there were openings to surface runoff relatively near the spring.
- Cox (January 1959) noted that for the first time in many years precipitation had increased the turbidity of Liddell Spring beyond the point that the City could divert from it. Gray sediment was believed to be coming from drilling operations.
- Having observed silt and debris in Liddell Spring shortly after the onset of precipitation, Wisser and Cox (June 1960) inferred that there was an entry point for surface runoff to enter the subsurface and impact water quality in the spring's immediate vicinity.
- Several observers documented considerable increases in turbidity and springbox sedimentation for several years following 1969 when the quarry overburden was first removed (e.g., Wyckoff, February 1970; Nordquist, August 1970; Stewart, December 1971; March 1978; Earth Sciences Associates and Creegan & D'Angelo, May 1979; see discussion in Section 4.6).
- Noting that there was little lag time between precipitation, high turbidity, and high coliform in Liddell Spring, Creegan (March 1972) concluded that the sediment and coliform were from the same source, and that either the source was close to the spring or the flow was relatively fast through a karst conduit.
- Engineering-Science (1991) noted that the structure built over the spring intake prevents contact with precipitation and runoff. Also, the fact that little or no decline in specific conductance occurred during storm events was atypical of a direct surface water contribution. However, the timing of the spring's turbidity response following precipitation was just a little slower than observed for coastal streams. This suggested that runoff and sediment were traveling to the spring from sinkholes via turbulent flow through subsurface conduits.
- Based on the concurrence of high coliform and high turbidity in Liddell Spring, and the lack of any channel in the ravine upgradient of the spring, Watkins-Johnson Environmental (November 1992) speculated that runoff could be entering the subsurface through a nearby solution feature. However, it noted that little sediment load was available in the ravine, and most of the runoff from the quarry area was rerouted to the sediment basins.
- SECOR (November 1997) stated that groundwater flow in the marble aquifer is predominantly "open hydraulic flow" through interconnected solution cavities.
- A fine- to medium-grained fill was placed and compacted over an area of exposed, fractured bedrock on the quarry floor in February 1998 following major storm events the preceding month. Observations and opinions differed as to whether this did or did not have a beneficial effect on the turbidity of Liddell Spring. SECOR (December 1998) claimed there was no moderation of turbidity levels during the remainder of WY 1998 that could be attributed to the cover, whereas EMKO (August 1999) said that low turbidity during a similar January 1999 storm indicated than an improvement had occurred.

- Also in February 1998, RMC filled a sinkhole (SH-11) that had captured runoff in the drainage tributary to the quarry, and rerouted its runoff to control sinkhole erosion exacerbated by the January storms (SECOR, March 1998).
- SECOR (December 1998) interpreted that the duration of elevated turbidity levels suggests that there are one or more locations within 6 hrs travel time from the spring where turbid runoff enters the aquifer. Neither the quarry nor Reggiardo Creek had been confirmed as a source location.
- Farallon (August 2001) observed an increase in the turbidity of Liddell Spring during the construction of monitoring well QM-5 when drilling advanced from 22 to 35 ft bgs. The spring cleared in about 90 seconds after drilling stopped.
- Noting a correlation between a pipe break on the quarry's upper access road and turbidity spikes in Liddell Spring, Pacific Geotechnical Engineering (February 2002) speculated that a point of surface water entry into the karst might exist on the hillslope above the spring and below the road. Based on Liddell Spring's response to precipitation, it inferred that multiple conduits supply the spring.
- Based on mineralogical analysis, both Pacific Geotechnical Engineering (February 2002) and Balance Hydrologics (December 2002) stated that particular sources of sediment could neither be identified nor ruled out with certainty.
- PELA (May 2005) acknowledged the potential existence of fully vertical conduits north of the quarry where the marble contacts schist and granitic rock, but asserted that such conduits did not occur within the immediate quarry area, which is instead characterized by a poor downward connection to the saturated zone.

The following summarizes SECOR's observations during the exceptionally wet winter of 1998 (SECOR, March 1998):

- A high-flow event in January 1998 caused the Liddell springbox to become completely filled with about 2 feet of sediment. The sediment was mostly very fine to medium-grained quartz and mica sand with organic debris. Some of the sand was reportedly similar to samples collected in Reggiardo Creek and one of its tributaries.
- Following the storm event, approximately 30 percent of the quarry floor was covered in standing water up to 10 inches deep. The water was slightly turbid and there was a thin layer of settled sediment on the quarry floor. When the water was deeper during and immediately after the storm, it appeared that water flowed toward and percolated into an area of exposed fractured bedrock. There was some scour along this flow path. Grab samples of sediment from the quarry floor consisted of poorly sorted fine- to coarse-grained sand with silt that appeared to be derived from angular marble fragments. Some iron-stained fine- to medium-grained subrounded quartz sand was present in the northeastern area of the quarry. Mica was a minor constituent of most of the samples. None of the samples appeared similar to the sediment that filled the Liddell Spring springbox.

- Also during this event, a sinkhole about 400 ft east of monitoring well BD-44 (probably SH-11) enlarged by 15 to 20 ft across and 8 to 10 ft deep.
- Earlier that season, the Reggiardo Creek swallow hole had been capturing all stormflow, but after this event it was completely filled in. As a result, no loss of streamflow was evident (~0.5 cfs). Sand bar samples taken from above and below the buried swallow hole consisted of very fine- to medium-grained quartz sand with relatively high mica content, similar to the sediment observed in the Liddell springbox.
- A small sinkhole north of the quarry was observed to capture runoff of about 5 gpm from Smith Grade. Sediment in the nearby tributary to Reggiardo Creek consisted of light brown very fine- to fine-grained subrounded quartz sand with mica and organic material. This material was reportedly very similar to the sand deposited in the springbox. Elsewhere north of the quarry, precipitation runoff occurred as sheetflow with little sediment transport or evidence of sinkholes.
- A ditch with very turbid water flowing from the crusher to the sediment basin did not appear to be leaking.
- Plant spring was clear with no sediment when observed during and after these storms.

4.4.2 **Tracer Tests**

Tracer tests have been recognized to provide a potentially critical means for evaluating Liddell Spring's connectivity to recharge and quarry operations. Four tests were performed between 1959 and 1968, with only one positive tracer detection at Liddell Spring. More recently, PELA (2005) introduced several sets of tracers and monitored their detection for nearly a year.

4.4.2.1 Pre-2004 Tracer Tests and Groundwater Velocity Estimates

Lindsey (March 1959) estimated that the transit time through the marble aquifer is roughly 3,000 ft in 8 hrs (9,000 ft/day) based on the time typically required for turbidity to reach Liddell Spring after heavy rains.

Wisser and Cox (April 1959) performed two 7-day tracer tests by introducing sugar into boreholes upgradient of Liddell Spring. No sugar was detected at either Liddell or Plant springs. This indicated to them the existence of a deep water table and only a few feet per day of groundwater movement. They concluded that it was highly improbable that Liddell Spring was connected to a network of karst conduits. As noted by Cloud (February 2000), the borings used to introduce the tracer may have had little or no connection to groundwater flow in the marble aquifer.

Todd (January 1963) estimated that the average groundwater velocity through the marble aquifer was about 22 ft/day. Thus, the time needed for groundwater to travel 1,100 ft from the nearest portion of the quarry to Liddell Spring was about 50 days, and from the furthest quarry area >140 days, not including the time for percolation through the unsaturated zone.

Lindsey (1968) performed a third tracer test by introducing sugar into the sinkhole that captures flow from Whitesell Spring. No positive detections were made. In a fourth test, sugar was introduced into boring DDH-19 located about 450 ft north and 200 ft higher in elevation than Liddell Spring. Sugar was detected in the spring after 6.5 days travel time, an average velocity of 70 ft/day. Arrival of the tracer's center of mass occurred in 10 to 20 days, suggesting an average velocity of 23 to 45 ft/day. The detection of sugar continued through day 36, which indicated to EMKO (August 1999) that the marble aquifer was characterized by a high degree of dispersion.

In a fifth test, SECOR (December 1998) introduced a sodium-bromide tracer into the Reggiardo Creek swallow hole in September 1998, approximately 5,000 ft from Liddell Spring. No tracer was detected in either Liddell or Plant springs after monitoring for 26 hrs. Detecting the tracer at Liddell Spring within this timeframe would have required an average flow velocity of about 4,600 ft/day. SECOR concluded that this swallow hole was not the source of turbidity that typically occurs in Liddell Spring within 4 to 6 hrs of a storm.

4.4.2.2 Recent Tracer Tests

PELA (May 2005) conducted tracer testing in three-phases during 2004-05. Various sets of tracers were released in March, August, and September 2004, and monitoring continued through February 2005. WY 2004 and the preceding three water years had below average to average precipitation (Table 7). Thus, the study did not coincide with conditions when turbidity is typically most elevated. As stated by PELA, "like in any other well-developed karst aquifer, the transport of sediments is episodic and is very sensitive to the flow regime" (p. 61).

The tracer test results need to be qualified in terms of (1) the hydrologic conditions at the time of the study, (2) the assumed criteria for positive detections, and (3) differences in adsorption tendency among the tracers used:

- Conclusions such as "sinkhole SH-11 is not actively connected to Liddell Spring" need to be qualified by adding "during conditions similar to that of the study period, which was relatively dry."
- A positive tracer detection was defined as two consecutive samples with 5 to 10 times background concentration (or quantification limit in the case of a non-detect background). Such criteria are somewhat arbitrary and their strict application may omit some detections of physical significance.
- Two different tracers were inserted into the Reggiardo Creek swallow hole (SS-1), one with a "very low" absorption tendency and one with a "moderate" adsorption tendency. At Liddell Spring, the former was detected within 13 days whereas the latter was never detected in three months. Given this discrepancy, there is some uncertainty regarding the results for tracers with "moderate" adsorption tendencies. Two different tracers, both with moderate adsorption tendencies, were inserted into SH-11 near the expansion area and neither tracer was detected at any of the sampling points using PELA's assumed detection criteria. These tracers had to travel a large vertical distance under relatively dry conditions to reach the

saturated zone. Under these circumstances, their moderate adsorption tendencies may have contributed to their lack of detection.

Figure 42 and the following discussion summarize the tracer test results. The tracer travel times and velocities cited below represent the arrival of peak concentrations. First-arrival velocities were up to three times faster (both velocities are provided in Figure 42). Velocities are based on map distance; actual velocities are generally faster to account for non-linear pathways through the fractured marble aquifer.

- The tracer introduced into monitoring well NZA located within the quarry reached Liddell Spring in about 7 hrs traveling 2,600 ft/day. This was the study's fastest observed tracer velocity. Tracers introduced into sinkholes northeast and northwest of the quarry (SS-4 and SH-6) reached well NZA traveling much slower, at average flow rates of 40 to 70 ft/day. Tracers introduced into the Reggiardo and Laguna creek swallow holes were not detected at NZA.
- The tracer introduced into sinkhole SH-6 reached Liddell Spring in 10 days traveling at greater than 400 ft/day. The tracer took longer to travel a shorter distance to well NZA. One explanation is that well NZA is branched slightly off a main conduit. The tracer introduced into SH-6 was also detected at monitoring well M5A.
- The tracer introduced into a Reggiardo Creek swallow hole (SS-1) reached Liddell Spring in 16 days traveling more than 300 ft/day. The tracer took longer to travel a shorter distance to monitoring well M1B, suggesting that M1B is on a slower, alternate path toward the springs. The same tracer reached Plant Spring in only 8 days traveling nearly 500 ft/day.
- The tracer introduced into the swallow hole of a Reggiardo Creek tributary (SS-2) reached Plant Spring in 13 days and monitoring well M1B in about 106 days. This tracer was first detected at Liddell Spring at 29 days, but detected concentrations were weak and no time of peak concentration was established. Tracers from SS-1 and SS-2 were detected at the same locations and thus may have followed common pathways. The longer times required for the SS-2 tracer to reach Liddell Spring and M1B may reflect fairly laminar flow whereby converging flow paths tend not to cross.
- The tracer introduced into a Laguna Creek swallow hole (SS-8) first reached Liddell and Plant Springs in about 67 days. Peak concentrations of dye were observed at 88 and 81 days for Liddell and Plant Springs, respectively, resulting in travel rates of 160 ft/day and 170 ft/day. This tracer also reached a spring downstream along Laguna Creek in 58 days, for an average flow rate of 100 ft/day. This tracer may have shared pathways with tracers from SS-1 and SS-2. PELA (May 2005) reported that the SS-8 tracer reached monitoring well M1B at peak concentration in 48 days, traveling 250 ft/day. This seems exceptionally fast when compared to the distance and time of travel from SS-1 and SS-2 to M1B. The same tracer was released from SS-2 during an earlier test phase and was still being positively detected at M1B one month prior to its release from SS-8. Thus, this detection may have been a residual of the first release of the tracer. While this tracer eventually may have reached M1B from SS-8, it probably took longer than inferred by PELA.

- Figure 43 presents one interpretation of the network of pathways followed by tracers during the 2004 tests. It builds on our interpretation of major fracture zones intersecting the marble aquifer. Although other fractures and pathways may exist, this interpretation is generally consistent with the data and our hydrogeologic conceptual model. Well NZA is assumed to be slightly off the main pathway through the quarry, so that upgradient flow from SS-4 and SH-6 took longer to reach it than expected, given the high rate of flow from NZA to Liddell Spring. Similarly, in order to explain why tracers were not detected in wells M2A and M6B, these wells are assumed to be slightly offset from the high permeability pathways following fracture zones.

Under the conditions tested, most of the streamflow captured by swallow holes along Laguna and Reggiardo creeks follows a series of fracture-zone segments along the eastern and southeastern margins of the flow system until reaching Liddell and Plant Springs. A relatively minor flow path branches off and intersects well M1B. Minor cross-gradient flow along another path connects SS-1 to M5A. Under the conditions tested, we infer that groundwater flow from north of the quarry (i.e., sandstone recharge) and released groundwater storage dominate groundwater flow in the northern portion of the fractured marble aquifer.

It should be noted that substantially different tracer test results might be achieved under wetter hydrologic conditions. During years of above average precipitation, groundwater recharge from captured streamflow exceeds the capacity of its dry-period pathways, causing flow through other portions of the fracture system. This change in flow regime is observed in the system response to individual storms, where the storm flow pressurizes more highly mineralized groundwater storage, causing its increased discharge to Liddell Spring and resulting in the observed increase in springflow specific conductance that lags after a storm event. The change in flow regime between wet and dry years could substantially alter flow paths and transit times.

4.4.3 **Springflow Response to Precipitation**

This section presents previous interpretations of Liddell Spring's response to storms as well as our independent analysis of storm responses during 2004-05.

4.4.3.1 Previous Observations and Interpretations

Many observers have commented on Liddell Spring's response to precipitation events. Since 1997 these observations have been based on the continuous monitoring of precipitation, springflow, spring turbidity, temperature, and specific conductance (Figures 33 and 34). These observations are discussed below and summarized in Table 39 in comparison to tracer results.

- Lindsey (July 1964) observed that Liddell Spring turbidity typically became elevated 48 hrs after a precipitation event.
- Watkins-Johnson Environmental (November 1992) observed that elevated turbidity began within 24 hrs of a storm having at least 2 in/day precipitation.
- When soils are nearly saturated, SECOR (March 1998) observed measurable water quality responses in Liddell Spring from precipitation of <0.2 in/hr. The increase in turbidity lags

the onset of precipitation by 3.5 to 5 hrs, as does a change in specific conductance. The duration of elevated turbidity is similar to the duration of precipitation and suggests one or more sources within 6 hrs travel time. Regarding specific conductance, SECOR (December 1998) noted that it could go up or down or both in response to a storm; for example, a sharp decline followed by a less rapid increase.

- EMKO Environmental (August 1999) described two different Liddell Spring responses to precipitation. First, after every storm minor increases in turbidity and specific conductance occur after a lag of 30 to 50 hrs and last much longer than the duration of the storm. Secondly, major and late-season storms result in an increase in turbidity and a decrease in specific conductance 3 to 6 hrs after precipitation begins, with durations longer than the storm. EMKO speculated that an initial decline in specific conductance resulted from the release of groundwater stored in the landslide deposits adjacent to the spring. The higher specific conductance observed in Liddell Spring 30 to 50 hrs after a precipitation event corresponds to (a) the timing of water-level rises in monitoring wells BD-45 and QM-2 and (b) the relatively high specific conductance of these wells.
- Farallon (March 2000) described the lag time between storm precipitation and the turbidity of Liddell Spring to be 3.5 to 6 hrs, indicating to Farallon that the source was >1,000 ft from the spring. The duration of both the storm and elevated turbidity were approximately the same, suggesting that one or more sources of turbidity are within 6 hrs travel time of the spring, and sources more distant than 6 hrs have little effect on the spring's turbidity. The magnitude of the spring's various responses to precipitation varies substantially in relation to antecedent moisture and precipitation intensity. Cloud (September 2000) pointed out that the travel times represented by the spring's lagged responses to rainfall consist of unknown vertical and horizontal components of travel through the aquifer.
- Farallon (August 2001) noted a correlation between the spring's lag times and antecedent moisture in the soil and unsaturated zone. The turbidity response lagged 10 to 14 hrs under low antecedent moisture and 2 to 5 hrs when wet, and was generally about equal in duration to the storm event. Farallon acknowledged that these interpretations were somewhat subjective, for example, due to the choice of a starting time. The landslide's close proximity suggested it could be a source, although other sources appear to exist with rapid recharge into marble. Farallon noted the similarity between the storm duration and the duration of the turbidity response. This similarity indicates a direct relationship between rainfall and turbidity, implying that one or more turbidity sources exist within 2 to 5 hrs travel time from the spring. No turbidity response occurred unless storm runoff exceeded a minimum threshold. The spring responded differently in WY 2000 compared to the preceding years by not exhibiting an initial drop in specific conductance.
- Kopania (December 2001) observed two types of turbidity events, a short-term turbidity increase within several hours of light to moderate precipitation, and a large scale sedimentation event, including transport of sand and organic material into the springbox, that resulted from large storms.

- Regarding Liddell Spring's WY 2005 record, Balance Hydrologics (May 2005) noted strong, peak turbidity responses 9-19 hrs after the onset of precipitation, and some secondary peaks. Inspection of their data plots for 16 precipitation events suggests that turbidity peaks occurred anywhere from 4.5 to 32 hrs after the onset of precipitation. The spring's discharge and specific conductance records for WY 2005 were not addressed.
- Based on 2002-03 monitoring data, PELA (May 2005) observed that Plant Spring's lagged response to precipitation varied as a function of precipitation intensity and antecedent conditions. However, the magnitude of the turbidity response did not correlate to precipitation intensity or the rate of springflow. Water temperature varied little and specific conductance was relatively constant except for relatively minor but repeated dips during some periods that were inconsistently correlated to precipitation and spring discharge. High turbidity was associated with low to moderate flows, such as those during the early portion of a storm hydrograph.

4.4.3.2 Interpretation of 2004-05 Storms

As is evident from the previous discussion and summary in Table 39, previous interpretations of Liddell Spring's response to precipitation vary greatly. This variability reflects several factors, including (a) changes in the hydrologic and hydrogeologic condition of the karst aquifer and (b) differences in the quantity and quality of data upon which the interpretations were based.

In this section we present an independent interpretation of Liddell Spring's response to 15 storm events from January 2004 through April 2005. This is the most complete period of continuous monitoring record available (Figure 44). WY 2004 was the fourth in a series of generally dry years whereas WY 2005 had above average precipitation (Table 7).

Figures 45 through 52 present storm-period plots of the available data-logger records for Liddell Spring, the precipitation gage at either the adjacent landslide or East Branch station, and the discharge or stage of Majors Creek. Majors Creek provides a non-karst, surface-runoff storm response for comparison. The periods plotted and 15 storm dates are as follows:

Figure	Period Plotted			No. Days	No. Events	Storm Events (start date)
45	1/15/04	-	2/14/04	30	2	1/26/04, 2/1/04
46	2/16/04	-	3/4/04	17	3	2/17/04, 2/24/04, 2/25/04
47	10/15/04	-	10/30/04	15	2	10/19/04, 10/26/04
48	12/1/04	-	12/15/04	14	2	12/7/04 (2)
49	12/26/04	-	1/9/05	14	3	12/26/04, 12/29/04, 1/2/05
50	2/14/05	-	2/24/05	10	1	2/15/05
51	3/17/05	-	3/31/05	14	1	3/21/05
52	4/1/05	-	4/16/05	15	1	4/8/05
			Total		15	

As summarized below and presented in detail in Table 40, we evaluated the following aspects of the data record for each of the 15 storm events [average value (range of values)]:

- Precipitation:
  - Season prior to storm [19 (2-40) inches]
  - Storm total [1.8 (0.5-3.4) inches]
  - Peak intensity [0.2 (0.1-0.6) inches/15-minute interval]
  - Storm duration [23 (5-64) hrs]
- Magnitude of peak response:
  - Liddell Spring discharge [1,800 (960-3,100) gpm]
  - Liddell Spring turbidity (first and secondary peaks) [125 (6-700) NTU]
  - Liddell Spring specific conductance [520 (435-600) μS/cm]
  - Majors Creek peak discharge or stage [46 (4-82) cfs; 4 (2-6) ft]
- Approximate response duration (listed in ascending order):
  - Majors Creek discharge or stage [23 (10-52) hrs]
  - Liddell Spring turbidity [45 (10-80) hrs]
  - Liddell Spring specific conductance [49 (15-84) hrs]
  - Liddell Spring discharge (data difficult to interpret; approx. similar to specific conductance)
- Time to peak response after start of precipitation (listed in ascending order):
  - Initial dip in specific conductance [18 (11-47) minutes]
  - Precipitation [10 (0.2-25) hrs]
  - Majors Creek discharge [14 (5-28) hrs]
  - Spring turbidity [15 (6-29) hrs]
  - Spring discharge [21 (6-38) hrs]
  - Spring specific conductance [34 (13-70) hrs]
- Time between peaks (listed in ascending order):
  - Majors Creek discharge and Liddell Spring turbidity [1 (1-3) hrs]

- Precipitation and Majors Creek discharge [3 (1-12) hrs]
- Precipitation and Liddell Spring turbidity [4 (2-14) hrs]
- Liddell Spring turbidity and discharge [6 (-1-15) hrs]
- Majors Creek and Liddell Spring discharge [7 (-0.3-15) hrs]
- Precipitation and Liddell Spring discharge [11 (1-18) hrs]
- Precipitation and Liddell Spring specific conductance [23 (7-45) hrs]
- Liddell Spring discharge and specific conductance [12 (-3-32) hrs]
- Liddell Spring first & secondary turbidity responses [48 (16-72) hrs]

The analyzed storms represent a wide range of antecedent moisture and precipitation conditions. Storm-total precipitation ranged from 0.5 to 3.4 inches and storm durations were 5 to 64 hrs. As with previous observations (Table 39), the various spring-response times ranged widely from less than 1 hr to nearly 3 days. For example, Liddell Spring peak discharge occurred anywhere from 6 to 38 hrs after the onset of precipitation.

Although the lag times vary, the order in which the turbidity, discharge, and specific conductance peaks occurred was very consistent between storms, as was the relative duration of each response. Figure 53 presents a schematic illustration of the average timing and duration of responses.

The initial storm response often was a small, brief dip in Liddell Spring's specific conductance within 1 hr after the start of precipitation. This suggests immediate but relatively minor runoff capture by a nearby sink, consistent with many of the observations cited in Section 4.4.1. Larger and longer initial declines in specific conductance were noted for prior years (SECOR, December 1998; EMKO, August 1999; Farallon, August 2001); these declines may have been related to an initial discharge of low-mineral water when the aquifer was exceptionally full of surface-water recharge following wet WY 1998.

Precipitation usually peaked before any of the other storm responses. On average, precipitation peaked 10 hrs after the storm began. Majors Creek discharge usually peaked next, exhibiting a relatively sharp, short-duration peak an average 13 hrs after peak precipitation. A rapid surface-water response relative to groundwater is reasonable and expected. Interestingly, Liddell Spring turbidity peaked nearly as quickly as Major Creek discharge, on average only 1 hr later. The turbidity peak occurred about 15 hrs after the start of precipitation, on average, and 6 hrs before peak spring discharge. Among all the responses evaluated, the timing of precipitation, peak streamflow, and spring turbidity were the most closely and consistently cross correlated. This is a strong indication that runoff-related processes contribute significantly to spring turbidity. Tracer tests indicate that several days or more are needed for water to travel to Liddell Spring from the Reggiardo and Laguna creek swallow holes. Therefore, the runoff-related processes responsible for initial peaks in spring turbidity must be occurring closer to the spring.

In terms of response duration, the Majors Creek hydrograph averaged 23-hrs long, the same as the average duration of storm precipitation. On average, elevated Liddell Spring turbidity lasted for 45 hrs and elevated specific conductance lasted for nearly 50 hrs. Durations of the spring discharge hydrograph are difficult to interpret because of apparent data anomalies (e.g., apparent instantaneous increases and decreases in discharge, probably due to equipment malfunction).

The Liddell Spring turbidity response and the Majors Creek discharge hydrograph had similar shapes—both had relatively steep rising and falling concave-shaped limbs. Conversely, the Liddell Spring discharge hydrograph and the specific conductance response had more gradual rising and falling convex-shaped limbs. This suggests that elevated turbidity is related relatively more to runoff processes whereas elevated specific conductance is related more to groundwater pressure and flow.

On average, the discharge of Liddell Spring peaked 21 hrs after a storm began. The springflow hydrograph is typically broader and more gradual than the stream hydrograph or the spring turbidity response. Within the saturated zone, the power to transport sediment should be greatest during peak springflow, however spring turbidity typically peaked about 6 hrs earlier. Relatively simultaneous discharge and turbidity peaks would be expected if turbidity were caused primarily by groundwater moving sediment through the saturated marble aquifer. Again, this observation indicates that runoff-related processes are substantially responsible for the occurrence of peak turbidity.

Liddell Spring's specific conductance peaked on average 34 hrs after storm precipitation began, exhibiting the longest and most gradual storm response. This suggests that as the aquifer becomes pressurized with captured streamflow and other recharge, a higher proportion of more mineralized groundwater is temporarily discharged from the aquifer. This inferred pressurization is consistent with the observed timing of increased groundwater levels (EMKO, August 1999).

The most delayed storm responses were secondary turbidity peaks in Liddell Spring. These occurred an average of 2 days after the storm began, and as long as 3 days afterward. These tend to be sharp, short-duration peaks similar to the initial turbidity response. These late turbidity responses may be related to stream capture, given roughly similar travel times for the fastest tracers to reach the springs from the nearest swallow holes during non-storm conditions.

As presented in Section 3.2, we also analyzed the response of Liddell Spring to the ponding of precipitation and runoff on the quarry floor. We recorded quarry-pond water levels continuously during a 16-day period in February-March 2004. Pond levels responded to precipitation events with a relatively rapid rise and fall, separated by a gentle water-level recession between events. Peak pond levels occurred about 4 to 9 hrs after the beginning of the precipitation event. The rate of water-level decline immediately following an event was about 4.5 to 5 in/day, whereas the slower rate of decline between events was about 1 in/day.

Considering the lack of external surface drainage and low seasonal evaporation, it is clear that most of the ponded water was lost to infiltration. The water level of the monitored quarry pond peaked within 0.6 to 3 hrs of Majors Creek peak discharge; furthermore, the pond and streamflow hydrographs were of generally similar shape, and were dissimilar to the springflow hydrograph (Figure 11). This observation indicates that pond levels were responding to runoff processes. The turbidity of Liddell Spring began to rise about 5 to 7 hours after the pond levels began to rise, consistent with the time needed for a groundwater tracer to reach the spring from monitoring well NZA. Peak spring turbidity occurred about 6 to 9 hrs after the beginning of the pond level rise, and about 2 to 5 hrs after the peak pond water level. As discussed further in Section 4.6, these results strongly suggest that runoff infiltration through the quarry floor has a direct effect on Liddell Spring turbidity.

4.4.4 **Conceptual Model Summary, Part Two**

Section 4.2.2 presented the first portion of our hydrogeologic conceptual model. It describes generic pathways between areas of groundwater recharge and points of groundwater discharge, each consisting of a series of hydrogeologic segments and characteristic sequences of groundwater levels and quality. This section builds on the conceptual model by discussing the dynamics of groundwater movement and sediment transport at various scales within the aquifer system. The subregional scale encompasses the entire pathways discussed previously. The site scale refers to the immediate area around and upgradient of Liddell Spring. The local scale refers to the area encompassing both the spring and the quarry.

- Sub-Regional Scale

Several lines of evidence support the interpretation that Liddell Spring has roughly two primary sources of water. From both hydrologic and hydrogeologic standpoints, the Santa Margarita Sandstone aquifer on the Bonny Doon plateau north of the quarry represents one major source of water, whereas captured Reggiardo and Laguna creek streamflow represents another. There is hydrogeologic connectivity between these sources and Liddell Spring, as discussed earlier in Section 4. In terms of water quality, Liddell Spring has values of water temperature, specific conductance, nitrate concentration, and stable isoptope ratios that are intermediate between these two sources. Conversely, Plant Spring is more similar to captured streamflow:

	Representative Approx. Averages				
	Temp. (^{o}C)	Spec. Cond. (µS/cm)	Nitrate (as NO_3) (mg/L)	Stable Isotopes (Feb. 2003) $\delta^{18}O$	δD
Areal recharge (Path *A*2, Fig. 24)	12-17	400-800	~3.5	-5.6	-33
Swallow-hole recharge (Path *B*2, Fig. 24)	12-14	300-500	<1	-6.0	-35
Liddell Spring	~15	400-500	~2	-5.9	-34
Plant Spring	~13	300-400	~1	-5.8	-35

The recent tracer tests were only successful at demonstrating the source from stream capture. However, an apparent pattern of tracer movement was consistent with the two-source model (Figure 43). Our interpretation of the tracer-test results suggest that groundwater originating from the stream swallow holes follows high permeability pathways through fracture zones along the eastern and southern margins of the marble aquifer toward the springs, whereas groundwater flowing into the marble aquifer from the north follows fractures toward and through the quarry area to Liddell Spring. During relatively wet periods we infer that the transmission of captured streamflow dominates more of the entire fracture system and pressures large amounts of groundwater into storage within voids higher in the marble (Figure 54).

A third important source of water to Liddell Spring is precipitation and runoff capture by the quarry and its contributing closed drainage, as discussed in Section 3.2.

Liddell Spring's unique and complex response to storm events probably results in part from its multiple sources of water. Furthermore, Liddell Spring has multiple potential sources of sediment, some of which may be relatively independent of the primary sources of water.

- Site Scale

As cited above, several previous investigators concluded that Liddell Spring has one or more nearby sources with some connection to the ground surface (e.g., Kinzie, January 1950; Wisser & Cox, June 1960; Creegan, March 1972; Watkins-Johnson, November 1992; Farallon, August 2001; Pacific Geotechnical, February 2002). Evidence includes the initial dip in spring specific conductance and the types of sediment and debris observed in the spring immediately after precipitation begins. Such sources probably account for only a small portion of the spring's discharge, and could not account for the total sediment load observed in response to a storm event.

- Local Scale

As documented above, the timing of Liddell Spring's various responses to storm events range from hours to days following the beginning of precipitation (Tables 40 & 41). Although variously defined, the earliest turbidity responses noted by this and previous studies generally range between 2 and 10 hrs, with frequent references to about 5 to 7 hrs (e.g., SECOR, March 1998 & December 1998; EMKO, August 1999; Farallon, March 2000 & August 2001). This timing is too slow for a source immediately nearby (e.g., a sinkhole or the landslide), and yet is too quick for travel from the Reggiardo and Laguna creek swallow holes. Tracers required at least several days to reach the springs from the swallow holes, which may be consistent with some of the slower turbidity responses (i.e., the late peak depicted in Figure 53). The tracer travel time to Liddell Spring from the quarry (well NZA) was 7 hrs, and this was during a several-year period of average to below average precipitation.

During 2004-05, the timing and character of Liddell Spring's turbidity responses were very similar to the discharge hydrographs for nearby Majors Creek (Figure 53). During all the events analyzed, the gap between stream discharge and spring turbidity peaks was never more than 4 hrs. Similarly, the timing and character of Liddell Spring's turbidity response was very similar to the recorded level of a quarry-floor pond (see Section 3.2). Conversely, the spring's turbidity response was poorly correlated to the timing of peak spring discharge, occurring an average of 6 hrs and as many as 15 hrs earlier.

Sediment that might contribute to turbidity at Liddell Spring is stored in the karst system. However, several lines of evidence show that the source of sediment that is being introduced into the system and/or entrained into the flow is a result of runoff-related processes independent of the spring's primary sources of recharge. First, the occurrence of distinct turbidity peaks that do not correlate with peak spring discharge indicates that the turbidity is not principally a result of karst sediments being entrained by increased conduit flow (Figure 36b). Second, the timing of the turbidity peaks is too early to be a result of turbid stream water reaching Liddell Spring from the Reggiardo or Laguna Creek swallow holes. Third, the turbidity peak is nearly coincident with peak local runoff, both within the quarry, as indicated by the water level data from the quarry, and within a nearby, non-karst drainage (Majors Creek). If the turbidity observed at Liddell Spring were simply a result of increased flow velocities picking up sediment from within the karst system, we would see more continuous, pulsed, and/or random transport, up to the point of peak spring discharge. Potential sources and mechanisms of sediment transport are discussed more below.

- Sediment Sources

Liddell Spring's potential sources of sediment include eroded material and channel sediment washed into sinkholes, stream sediment intercepted by swallow holes, sediment stored or in-transport within the subsurface, erosion and collapse of rocks within the subsurface, broken rock and rock dust from quarry blasting, and material fallen and washed into open fractures. Clastic sediment that accumulates in the springbox and suspended sediment responsible for turbidity may have distinctly different sources. Sediment pulses may be released when sediment-filled karst voids become breached and exposed to conduit flow.

Bedrock underlying both the watersheds and groundwater recharge areas tributary to Liddell Spring is essentially limited to four types: schist, marble, granitic rocks, and Santa Margarita Sandstone. Because each of these is well distributed throughout the tributary area, there is limited opportunity to identify particular sediment source areas based on mineralogy.

- Connectivity

The high groundwater velocities demonstrated by tracer tests clearly indicate the occurrence of high permeability pathways through the marble aquifer. These pathways occur preferentially along near-vertical fracture zones and consist of interconnected voids formed by dissolution of the marble bedrock. It is reasonable to infer that such conduits form continuously while the area undergoes tectonic uplift, leaving a network of interconnected, older voids above those currently forming. This network of voids lying above the permanent saturated zone provides the flow system with a large surplus capacity. This high capacity is evidenced by the system's ability to absorb recharge throughout the wettest years without the emergence of additional springs or substantial lengthening of the springs' storm-response hydrograph. This three-dimensional network of voids provides for both pressurized flow in fully saturated conduits at depth and turbulent, cascading flow above.

Evidence of the aquifer's interconnectivity includes the existence of active sinkholes and swallow holes and the emergence of drill cuttings or drilling mud in Liddell Spring during exploratory drilling for the quarry (e.g., Cox, January 1959). The occurrence of perched zones is highlighted by the completion of shallow monitoring wells encountering pockets of residual drainage and/or recharge. However, many other borings encounter dry voids, indicating good vertical drainage through the typically unsaturated portions of the marble aquifer. Good vertical drainage is also demonstrated by the occurrence of perched zones capable of yielding significant water, but which disappear into quarried areas over relatively short distances (e.g., wells BD-42 and M5A near the northern boundary of the proposed amendment area). Also, we observed open, near-vertical fractures extending several hundred feet down through the quarry walls and through the quarry floor. Finally, our analysis of more than 200 boring logs did not reveal any significant vertical zonation of the marble aquifer's macroporosity (Figure 21).

- Subsurface Dynamics

Water and sediment movement through void spaces lying above the permanently saturated zone may occur under the following conditions:

- The entire vertical column of voids may be fully exposed to major sources of recharge such that water entering the top of the column is unconfined and potentially turbulent. The shallow flow has the capacity to entrain sediment accumulated above the usual top of saturation. However, the potential for continuous turbulent flow to Liddell Spring from either the major stream swallow holes or cascading groundwater from the Bonny Doon sandstone aquifer seems unlikely.
- We infer from tracer tests and water-level and quality data that preferential flow paths of high permeability occur through low-angle dissolution channels oriented deep along major fracture zones. Less dynamic zones of saturation surrounding the major fracture flow paths contain more mineralized groundwater. When flow through the most permeable pathways approaches some upper capacity during major recharge events, the system becomes pressurized, increasing pressurized groundwater flow and/or discharge from the more mineralized zones (Figure 55). This process is demonstrated by the substantial rise in specific conductance observed as a relatively late response to storm events. This pressurization is also coincident with observed rises in groundwater levels. During and following exceptionally wet years when increased groundwater storage occurs (e.g., WY 1998), the initial response to this pressurization may be the release of relatively fresh groundwater storage, consistent with a larger initial dip in specific conductance observed at such times. Interconnected karst voids lying above the permanent zone of saturation probably facilitate the flow of more mineralized groundwater to Liddell Spring in response to storms. Because Liddell Spring's turbidity peaks well before specific-conductance and discharge, it is unlikely that this additional groundwater discharge contributes substantially to sediment transport and turbidity.
- The pressurization of the groundwater system described above plays an important role in replenishing groundwater storage. As the system is pressurized from the bottom up by flow through deep dissolution channels, groundwater is forced into undersaturated low and moderately permeable zones. As pressures subside, water remains temporarily stored. The water to first drain back into the deep permeable pathways is most similar to the original recharge in terms of quality and temperature, allowing the spring to maintain relatively uniform properties during the dry season. Water that remains stored for relatively long periods becomes warmer and more mineralized.

- Interconnected voids above the permanent zone of saturation are also available for the capture and transport of runoff from locations other than the major stream swallow holes. As discussed in Section 3.2, we estimate that a considerable amount of precipitation and runoff is captured by the quarry, possibly as much as one fifth of Liddell Spring's average annual flow. The quarry represents a substantially greater sink than the naturally occurring sinkholes in the area. Flow across the quarry floor sufficient to cause scour has disappeared down open fractures (SECOR, March 1998), the witnessing of which once prompted the quarry operators to place a compacted cover over a portion of the quarry floor. Because the quarry and its contributing drainage area have little moisture loss or retention and no surface outlet, considerable percolation must occur. Percolation of this drainage entrains sediment at the surface and in the subsurface created through blasting, ripping, and the disturbance of overburden, as well as naturally occurring sediment deposited in subsurface voids. Highly permeable interconnected voids have the potential to transport this water and sediment in a turbulent and cascading flow down to the zone of saturation and laterally toward Liddell Spring (Figure 55). The average timing between peak precipitation and peak spring turbidity (~5 hrs) is generally consistent with the observed time for tracers to reach the spring from the quarry (~ 7 hrs). A turbidity source related to captured runoff is consistent with the similarity between the spring's turbidity response and the storm hydrographs for Majors Creek and a monitored quarry-floor pond (see Section 3.2).

A reasonably good correlation between spring turbidity and spring discharge would be expected if spring turbidity were simply a function of the spring's hydraulic power. However, the correlation between Liddell Spring's turbidity and rate of discharge is poor (Figure 36b). Also, the timing of spring-turbidity and -discharge peaks is distinctly different, with the turbidity peak typically occurring considerably earlier. Indeed, the turbidity peak seems to occur before the system becomes fully pressurized, as indicated by subsequent peak levels of specific conductance.

Explanations for the lag between peak spring turbidity and discharge could include the following:

- Sediment supplies within the aquifer zone or zones responsible for turbidity may become depleted before peak spring discharge occurs. It seems unlikely for such sediment depletion to occur consistently throughout the succession of winter storms given that the entire system must contain large amounts of sediment in various stages of transport and storage. Rather, we would expect to see more continuous or multiple pulses of transport, especially up to the point of peak spring discharge.

- Even at peak rates, the hydraulic power of the spring's discharge may be insufficient to entrain sufficient sediment to explain the observed turbidity. Instead, turbidity pulses may be created at points in the system where turbid water enters the system or turbulent flow entrains sediment in the subsurface and delivers it to groundwater flowing to the spring. Relatively late turbidity responses that occur days after a storm reflect such pulses arriving from where water cascades into swallow holes along Reggiardo and Laguna creeks and entrains sediment that can be held in suspension all the way to Liddell Spring. The spring's primary and more immediate turbidity response, however, must be explained by sources of turbid water and/or sediment closer to the spring. Reasonably good and consistent correlations between the Majors Creek hydrograph, the quarry-floor pond hydrograph, and the spring turbidity response (all occurring well before peak spring discharge) suggest that one or more primary sources of turbidity are related to runoff capture locally upgradient of the spring. As discussed further in Section 4.6, it is reasonable to conclude that a primary source is related to the quarry, its operation, and its interception of rainfall, runoff, and sediment. .

4.5 Water Balance

This section evaluates the water balance of the spring and stream drainages near Bonny Doon Quarry.

4.5.1 Previous Interpretations

- Areal Recharge

Wisser and Cox (June 1960) estimated that the quarry area provided one-fiftieth of the groundwater storage available to Liddell Spring and one-eighteenth of its average annual recharge.

Todd (January 1963) estimated that average annual precipitation in the quarry area was distributed as follows (in/yr):

Precipitation		Evapotranspiration & Interception		Runoff		Deep Groundwater Flow
39	=	27	+	10	+	2

He assumed that all runoff is effectively captured by the karst aquifer within Liddell Spring's recharge area. Thus, based on an effective recharge rate of 12 in/yr, he estimated that the spring's recharge area encompassed 1,440 acres, or 2.25 mi^2.

Assuming average annual precipitation of 37 in/yr, Creegan & D'Angelo (1984) estimated the local water budget as follows:

Precipitation		Evapotranspiration & Interception		Runoff
37	=	26	+	11

Both Watkins-Johnson Environmental (November 1992) and SECOR (November 1997) recognized that approximately 4 mi^2 of exposed Santa Margarita Sandstone around and north of the quarry comprise an important recharge area for Liddell Spring.

Assuming Todd's effective areal groundwater recharge rate of 12 in/yr, EMKO (August 1999) estimated that Liddell Spring requires a recharge area of 2,825 ac (4.4 mi^2); thus, assuming a total area of 175 ac, the quarry and amendment area comprised approximately 6 percent of the hypothetical recharge area. EMKO delineated a "groundwater-shed" but did not indicate whether this matched the estimate of the needed acreage for recharge. EMKO dismissed the significance of recharge into the Reggiardo Creek swallow holes because of SECOR's failure to detect a tracer in Liddell Spring within 26 hrs of its release (SECOR, December 1998). EMKO also suggested that recharge into the Santa Margarita Sandstone was inconsequential in areas where the water table lay below the bottom of the sandstone. Finally, EMKO held that quarry operations enhanced aquifer recharge, and thus mining to within less than 20 ft of the water table would provide a water-supply benefit. Cloud (February 2000) took issue with several of these interpretations.

PELA (May 2005) did not explicitly consider groundwater recharge processes for Liddell Spring other than swallow holes along Reggiardo and Laguna creeks and various sinkholes with relatively minor drainage areas.

- Sinkholes and Swallow Holes

SECOR (December 1998) estimated that a Reggiardo Creek swallow hole captured about 100 gpm at the time of a September 1998 tracer test.

Farallon (August 2001) observed about 25 gpm flowing across the quarry floor and disappearing into a new, deep hole.

PELA (May 2005) estimated sinking-stream capacities from 0.5 to 1 cfs for both Laguna and Reggiardo creeks. This represents a combined stream-capture capacity of roughly 1,000 ac-ft/yr. Some of this water may discharge to downstream springs as opposed to Liddell or Plant springs. PELA's 2003-04 tracer tests provided a definitive demonstration of the interconnection between Liddell Spring, four stream swallow holes (including "Whitesell Creek"), and one sinkhole.

4.5.2 **Estimated Groundwater Balance**

Table 41 presents an estimated average annual water balance for the spring and stream drainages near Bonny Doon Quarry. Supporting information includes gaging and diversion records, and reasonable estimates of drainage areas and average watershed precipitation.

A previous study provides guidance for estimating the proportion of precipitation that becomes total streamflow (i.e., both seasonal runoff and baseflow from groundwater discharge) versus evapotranspiration (Geomatrix, March 1999). Our estimates reflect enhanced recharge from stream capture by swallow holes and relatively low evapotranspiration in sandy-soil and quarried areas.

Estimation of the remaining water balance is constrained by recorded diversions from Liddell and Plant springs and Laguna and Reggiardo creeks, and flow-gage records for Laguna Creek and Liddell Spring. We estimate that a transfer of approximately 1,300 ac-ft/yr from the Laguna and Reggiardo watersheds is needed to supply the estimated annual yields of Liddell and Plant springs. Some of the transferred water originates from areal groundwater recharge (i.e., path *A*) and some from stream capture (i.e., path *B*). Constrained by known yields, this simple yet reasonable conceptual water balance helps to confirm our understanding of the overall hydrologic system.

4.6 Groundwater Response to Quarrying

Bonny Doon Quarry is a major, potentially influential activity within the groundwater system contributing to Liddell Spring. Some quarry operations occur as near as 500 ft to the spring; the actively mined quarry is about 1,500 to 2,500 ft upgradient and occupies roughly 80 acres. Since 1970, the quarry has mined an estimated 34 million cubic yards of marble (see Section 1.5) from the same body of rock that forms the Liddell Spring aquifer. Assuming a porosity of 5 percent (Section 4.1.3), the volume mined to date represents nearly 1,200 ac-ft of pore space. The quarry has lowered the marble surface several hundred feet to within as little as 50 ft of the underlying groundwater. Mining and removal of overburden have left the fractured rock exposed, and blasting disturbs the rock in the subsurface. The quarry pit and the hillslope drainage into it have no external drainage. Tracer tests indicate that groundwater flowing beneath the quarry floor reaches Liddell Spring in 7 hours.

This section addresses the potential connectivity between quarry operations and the marble aquifer; Liddell Spring conditions following the initial removal of overburden in 1969-70; the potential effect of the quarry on springflow quantity and nitrate concentration; and the potential effects of quarry blasting and runoff capture on spring turbidity. The following discussion on each of these topics summarizes past work and then presents an independent assessment based on our data analysis and hydrogeologic conceptual model.

4.6.1 Quarry-Aquifer Connectivity

As summarized below, previous studies have evaluated and interpreted the degree of connectivity between quarry activities and the marble aquifer supplying Liddell Spring:

- Springbox sediment suspected to originate from exploratory drilling prior to quarrying (Cox, January 1959) demonstrated the potential connection between the quarry-area subsurface and the spring.
- Todd (January 1963) recognized that rock dust and sediment mobilized by vibrations could increase turbidity, but concluded that slow groundwater movement between the quarry and Liddell Spring would allow sediment to settle before reaching the spring. Also, he expected the sediment load to dilute substantially before reaching the spring.
- Observations of spring sedimentation as a result of initial quarry activities during the late 1960's and early 1970's demonstrated a strong, apparent connection between quarry operations and the spring (see Section 4.6.2).
- Watkins-Johnson (November 1992) recognized that solution cavities exposed by quarrying provided a pathway for turbidity originating from the quarry floor. Similarly, open boreholes without surface seals were potential conduits for sediment transport to groundwater. Open fractures and solution cavities might also intercept turbid runoff in conveyance to sediment basins.
- SECOR (November 1997) recognized that reduced filtering from overburden removal and exposure of fractures and conduits could potentially affect springflow.

- SECOR (March 1998) observed sediment and scour along the quarry floor indicating the drainage of substantial runoff into the subsurface during a major storm.
- Observations and opinions differed as to whether fill placed and compacted over an area of exposed, fractured bedrock on the quarry floor had any beneficial effect on spring turbidity (SECOR, December 1998; EMKO, August 1999).
- PELA (May 2005) recognized that sediments on the quarry floor could contribute to spring turbidity if open fractures allowed water carrying sediment to drain into the subsurface. However, because of postulated poor hydraulic connectivity between the unsaturated and saturated zones, PELA deemed that the quarry's potential sediment contribution to groundwater was limited.
- Nevertheless, PELA (May 2005) acknowledged there was sufficient connectivity between the ground surface and groundwater for the turbidity of Liddell Spring to be potentially "affected by…logging, construction, and clearing" (p. 73).

Our analysis does not indicate any substantial vertical zonation of the marble's macroporosity. The quarry is surrounded by many sinkholes, while several former sinkholes and caverns have been excavated by mining. Major fracture zones are interpreted to have a controlling influence on the distribution of high-permeability pathways through the marble, and several such fracture zones intersect the quarry and link it to Liddell Spring. Considerable volumes of runoff percolate into the quarry pit without evidence of discharge other than to Liddell and possibly other springs. Whatever hydraulic separation may have existed between the ground and groundwater surfaces, little remains now that mining has proceeded to within 50 ft of underlying groundwater. Tracers indicate that groundwater flowing beneath the quarry pit reaches Liddell Spring in 7 hrs. Although subject to interpretation, observations of Liddell Spring's response to overburden removal, blasting, and heavy precipitation are generally consistent with significant quarry-aquifer connectivity.

4.6.2 **Removal of Overburden**

The removal of overburden from the quarry area began in 1969. The actual mining of marble began in August 1970. Among these and following years, precipitation was substantially above average during WYs 1969, 1973, and 1974 (Table 12). Months of significantly above average precipitation included January, November, and December 1970; November 1972; and February and November 1973. Observations and interpretations of Liddell Spring conditions during the initial years of quarry activity are summarized below:

- Wyckoff (February 1970) attributed excess Liddell Spring turbidity and coliform to bulldozer work clearing the quarry site. Observations and opinions differed as to whether the springbox was effectively preventing contamination from surface runoff.
- Nordquist (August 1970) noted extremely high occurrences of Liddell Spring turbidity during 1969-70.
- As cited by Watkins-Johnson (November 1992), an attorney for the City of Santa Cruz stated in November 1970 that the quarry operation appeared to be a direct cause of Liddell Spring water quality problems.
- According to Stewart (December 1971), the Liddell Spring box completely filled with sediment as a result of storm events in 1969 and 1970 and had to be cleaned out. Problems subsided in 1971 after road building and major grading ended, and exposed openings into the aquifer were covered with compacted soil.
- Also according to Stewart (March 1978), the springbox built in 1959 had never needed cleaning before quarry activities began. The City began having problems with spring turbidity after excavation of a sinkhole that received runoff from the original quarry face.
- In their data review, Earth Sciences Associates and Creegan & D'Angelo (May 1979) documented decreased springflow quality between December 1969 and March 1974. The coinciding startup of quarry activities was deemed the probable cause of the increased turbidity.
- In another data review, Watkins-Johnson (November 1992) noted that several instances of very high Liddell Spring turbidity were recorded from 1970 through 1974. The highest values (1,400 to 5,000 ppm) occurred during a storm event in late February and early March 1970. Several instances of turbidity >100 ppm were recorded as a result of above-average precipitation in November and December 1970. Clearing and earthwork activities in 1969 and the commencement of quarrying in August 1970 were interpreted to be responsible for the excess turbidity levels, in particular the removal of vegetation and overburden and the exposure of solution cavities to runoff.
- TRA (April 1996) concluded that temporary increases in turbidity occurred during the time when the overburden was removed and the initial phase of quarry operations.
- SECOR (November 1997) noted that overburden was stripped from the quarry area during each of 7 preceding years, however there was no documented reduction in Liddell Spring water production.
- EMKO (February 2000) acknowledged a temporary decrease in Liddell Spring water quality coinciding with the first years of quarry activity in 1969-74. During 1974-79, however, spring water quality was substantially the same as before quarrying.
- Tomkins (October 2002) stated that considerable increases in Liddell Spring turbidity occurred following the initial stripping of overburden at the quarry in the late 1960's and early 1970's.

These accounts link documented instances of Liddell Spring sedimentation and elevated turbidity with overburden removal, initial quarrying, and above-average precipitation during 1969-74. Although these early quarry activities were separated from underlying groundwater by generally several hundred feet of as-yet unquarried marble, there was good connectivity between quarry operations and the spring. The connection can be no less now that several hundred feet of marble have been removed from above a groundwater zone demonstrated through tracer testing to contribute to Liddell Spring. More recent overburden removal is assumed to have been relatively minor compared to the initial clearing of the quarry site.

4.6.3 **Groundwater Yield**

Previous interpretations of whether or not quarrying impacted groundwater yield include the following:

- Todd (January 1963) recognized that some aspects of quarrying could increase spring yield (e.g., by lowering evapotranspiration), while others aspects might decrease spring yield (e.g., sealing fractures). However, he concluded that the effects of quarrying would be minor because of the small size of the quarry area relative to Liddell Spring's overall recharge area.
- Lindsey (1968) predicted that the quarry would not affect the volume of spring flow, although there was some potential for a slight increase in spring turbidity.
- Earth Sciences Associates and Creegan & D'Angelo (May 1979) concluded that reduced water production from Liddell Spring was due to turbidity and not a reduction in springflow quantity.
- Engineering-Science (April 1991) said there were no reports of reduced springflow quantity. Instead, it was possible that recharge to the spring could be enhanced by quarrying.
- Schipper and Reppert (1992) asserted that the City had been able to increase water production from Liddell Spring compared to pre-quarry historical records.
- SECOR (November 1997) noted that new springs had not occurred as a result of quarrying, although limited quantities of water sometimes drained from the rock after blasting. SECOR also concluded that the potential for the quarry to adversely impact nearby water wells was minimal because such wells were upgradient and generally completed in the Santa Margarita Sandstone.
- EMKO (August 1999) found no evidence that quarrying had affected the quantity of Liddell Spring discharge.
- Cloud (February 2000) believed there was insufficient information as to whether quarrying had impacted the flow rates of Liddell Spring. Potential benefits from increased recharge were probably offset by the potential for increased spring turbidity.
- EMKO (February 2000) cited data from the 1920's, 1930's, 1950's, and 1960's as evidence that the quarry had not reduced springflows (as discussed in Section 3.4.1, 1917-36 was a prolonged drought).

- Kopania (December 2001) noted that mining from above the saturated zone could not disrupt lateral groundwater pathways to the spring. If mining did disturb vertical infiltration pathways, the remaining network of cracks, faults, fractures, caves, and solution cavities could compensate for any lost capacity.
- The Initial Study for the proposed amendment area (SCCPD, November 2001) concluded that the volume of perched groundwater encountered by quarrying had been small and contributed apparently little to Liddell Spring.

Because the total discharge of Liddell Spring was not regularly gaged prior to 1997, the available data do not allow a definitive assessment of whether or not quarrying has affected spring yield.

As presented in Section 3.5.1, a precipitation-diversion double mass curve for Liddell Spring (Figure 13b) does not show historical shifts in production other than what can be explained by climatic cycles. Since 1994 the City has been able to divert slightly more turbid water, potentially offsetting or overshadowing changes in spring conditions. Also, the last 10 years began with a considerably wet six-year period, with near-average to wet conditions since then.

Our April 2006 observation of two springs discharging from the quarry walls suggests that quarrying may have exposed several springs over the years that did not become permanent or substantially affect Liddell Spring. Such springs may infiltrate back into the marble aquifer, as has been observed. However, such groundwater exposure exacerbates sanitary concerns typically associated with karst groundwater.

The unsaturated void space of unquarried marble may have provided temporary storage for recharging groundwater. Thus, the capacity of the subsurface to absorb large recharge events may have diminished, such that potential recharge is now rejected. Rejected recharge may appear as increased runoff as well as discharge from minor springs. To the extent that rejected recharge collects in the quarry pit, most of this water may eventually percolate into the marble aquifer. In any event, the diversion record does not reflect a decline in production.

4.6.4 **Groundwater Quality**

This section addresses the potential influence of quarrying on the concentrations of nitrate and total dissolved minerals (i.e., specific conductance) in groundwater. Springflow turbidity is addressed in the two subsequent sections.

Water quality data are available for Liddell Spring diversions since the 1960's; quarry monitoring wells since 1992; and spring monitoring since 1997. The available long-term record represents only the flows actually diverted by the City and may have been influenced by various changes in sampling and analysis procedure.

4.6.4.1 Nitrate

Observations and interpretation regarding groundwater nitrate and quarrying include the following (all values as NO_3):

- The quarry operation stopped using an on-site septic tank leachfield in December 1970 (Wyckoff, April 1971).
- In order to minimize the chances of groundwater nitrate contamination, Lindsey (April 1968) recommended “strict planning of shooting and loading” so as to avoid large accumulations of shot rock on the quarry floor.
- Engineering-Science (April 1991) noted that Liddell Spring nitrate concentrations had been about 1 mg/L, then increased slightly during the early years of quarrying (1970-77), followed by a moderate but sharp increase as quarry production increased and the quarry pit deepened during 1986-90. Peaks up to 4.6 mg/L were associated with winter and spring precipitation recharge. Nitrate concentrations seemed to plateau after blasting methods were tailored to minimize the potential for nitrate contamination.
- Creegan & D'Angelo (March 1984) attributed elevated nitrate concentrations in Mill Creek upgradient of the quarry to Bonny Doon residential on-site wastewater disposal.
- Schipper and Reppert (February 1992) stated that loadings of residual nitrogen from quarry explosions were insufficient to effect springflows of 1 mgd (700 gpm). They noted elevated but erratic nitrate concentrations in groundwater sampled from monitoring wells both up and down gradient of the quarry. They identified potential sources upgradient of the quarry, including orchard fertilization and a former turkey ranch.
- Watkins-Johnson (November 1992) documented substantially elevated nitrate (>50 mg/L) and coliform in the discharge of Whitesell Spring emerging from the Santa Margarita Sandstone upgradient (north) of the quarry.
- Farallon (March 2000) measured a nitrate concentration of about 2 mg/L in water ponded on the quarry floor and noted that this was higher than typical for precipitation (about 0.2 mg/L) but similar to concentrations in Liddell Spring.
- Tompkins (October 2002) described apparent increases in Liddell Spring nitrate concentration and expressed ongoing concerns that the quarry as a potentially causal factor.

As discussed in Section 3.5, the nitrate concentration of diversions from Laguna and Majors creeks has been relatively stable, whereas the nitrate concentration of Liddell Spring diversions has been more erratic with a roughly upward trend (Figure 17). Base concentrations increased from about 1 mg/L prior to the mid-1970’s to about 2 mg/L since then. Also, peak concentrations >5 mg/L have occurred several times in the past decade.

Liddell Spring derives a major portion of its yield by capturing streamflow from Laguna and Reggiardo creeks. Because the nitrate concentration of direct diversions from these streams has been relatively low and stable, the spring’s other sources of recharge must be responsible for its elevated nitrate concentration. Blasting with ANFO likely represents one source of nitrate, considering that water ponded in the quarry had about 2 mg/L nitrate. Other sources appear to be at least as significant, however, given the occurrence of elevated nitrate concentrations in monitoring wells both up and down gradient of the quarry. The repeated detection of >30 mg/L in Whitesell Spring indicates a considerable and concentrated upgradient source, possibly the former turkey farm. Also, as estimated in Table 37, septic tank leachate from about 45 homes could account for the average nitrate concentration of Liddell Spring. Assuming there has been no major increase among these potential sources, groundwater flow to Liddell Spring may be roughly in equilibrium with respect to the concentration of nitrate.

4.6.4.2 Specific Conductance

The specific conductance of diversions from Liddell Spring appears to have undergone a roughly 50 µS/cm increase between the 1960's and 1980's, and then another roughly 50 µS/cm increase between the 1980's and 1990's (Figure 19). Levels became somewhat lower and more erratic beginning in 2001, perhaps as a result of six years of above-average precipitation. It is conceivable that quarrying has contributed to the otherwise slight upward trend in dissolved mineral concentrations.

4.6.5 **Liddell Spring Turbidity and Blasting**

The timing, magnitude, and location of quarry blasting have been documented since 1997. The explosions are conducted when it is not raining using 30- to 50-ft deep holes drilled into the marble. Several previous studies have evaluated the potential increase in Liddell Spring turbidity in response to blasting, as summarized below and in Table 42:

- Stewart (December 1971) reported elevated Liddell Spring turbidity coincident with quarry blasting in July 1971.
- SECOR (December 1998) evaluated monitoring data for 12 blast events and found that 7 were accompanied by measurable increases in Liddell Spring turbidity, each lasting 1 to 3 hrs with increases of 0.5 to 12 NTU. SECOR concluded that the effect of blasting was very limited in magnitude and duration.
- EMKO (August 1999) evaluated the spring monitoring record coinciding with 125 blasting events and found that only 5 were followed by turbidity increases >10 NTU. These 5 events occurred several hours after the blast and lasted several hours. EMKO remained uncertain whether or not there was a causal relation between blasting and these 5 events.
- Cloud (January 2000) considered the possibility that the spring landslide contributed turbidity in response to blasting.
- Farallon (March 2000) evaluated 34 blasting events that occurred during relatively dry weather conditions and concluded that a turbidity response was possible to probable for 18 of them. The largest turbidity responses were from blasts on the quarry floor (90-110 NTU). The turbidity responses occurred 0.5 to 5 hrs after the blasts and lasted 0.5 to 6 hrs.
- Cloud (September 2000) analyzed the Liddell Spring monitoring record and identified numerous small turbidity peaks (1.5-3 NTU) associated with blasting that had not been considered by others. These peaks tended to decline gradually over 7 hrs and were not associated with precipitation.

- Brown & Caldwell (October 2000) analyzed the same data and found no definitive correlation between blasting events and long-term increases in spring turbidity.
- Cloud (May 2001) identified 13 probable and 17 possible spring-turbidity responses to blasting. He also acknowledged some anomalous turbidity peaks with no apparent cause.
- Farallon (August 2001) concluded that only 9 percent of blast events had definite turbidity responses. These turbidity responses occurred 0.2 to 4.5 hrs after the blast, caused turbidity increases from 2.8 to 44 NTU, and lasted 1.5 to 18 hrs. Blasts conducted on the lowermost benches were most likely to be followed by a turbidity response. The turbidity response lag times and durations had no correlation to the blast location. Only 3 out of 80 blasts resulted in turbidities exceeding 10 NTU.
- Kopania (December 2001) compared the effect of blasting to naturally occurring earthquakes.
- PELA (May 2005) found that the impact of blasting on Liddell Spring turbidity was likely to be <2 NTU, occur within 6 hrs, and last approximately 22 hrs. PELA's conclusions were essentially unchanged after additional analysis (PELA, January 2006).
- Balance Hydrologics (May 2005) evaluated the spring-turbidity response to 6 blast events. Peak responses occurred 2 to 8.5 hrs after the blast, with the faster responses occurring during mid- to late-winter when saturated conditions had established. The turbidity responses ranged from about 2 to 25 NTU and lasted about 5 to 11 hrs.

In summary, most previous investigators have acknowledged that some increase in turbidity occurs as a result of some blast events. These responses are highly varied, however, similar to Liddell Spring's range of responses to storm events.

We performed an independent assessment of 22 blast events during 2004-05 (Table 43). Figure 56 is a plot of the spring monitoring record during two of these events. Plots of the gaging record during the other events are included in Figures 45 through 52. No turbidity peak was apparent following three of these events. Among the other 19 events, peak turbidity levels ranged from 2 to 78 NTU and occurred 2 to 7 hrs after the blast, with an average lag of 4.4 hours (Table 43). Periods of increased turbidity after blasting lasted about 1 to 21 hours. Weather conditions varied considerably among these events. Our close inspection of the gaging record suggests that these turbidity peaks were blast related. Nevertheless, there is considerable variability and uncertainty associated with Liddell Spring's turbidity record.

Although the inferred turbidity responses to blasting are relatively small compared to storm-related turbidity, any increase in turbidity is undesirable from a water-supply standpoint. Perhaps more importantly, however, is the indication that blast events contribute to the generation and/or mobility of sediment responsible for turbidity. Blasting may effectively increase the supply of sediment available to percolating water and groundwater flow during and following storm events.

4.6.6 **Liddell Spring Turbidity and Precipitation**

Previous observations and conclusions regarding the quarry and Liddell Spring's turbidity response to precipitation include the following:

- Earth Sciences Associates and Creegan & D'Angelo (May 1979) reviewed the affect that increased turbidity during 1969-74 had on the City's ability to divert from Liddell Spring. They found that pre-December 1969 data were inadequate for establishing pre-quarry turbidity conditions. Also, there had been changes in sampling methods and measuring techniques. Nevertheless, they were able to estimate annual losses in City water production during the years following the start of quarry operations.
- Tompkins (Santa Cruz Water Department, as cited by Engineering-Science, April 1991) said that instances when Liddell Spring flows had to be turned-out of the diversion pipeline due to high turbidity had become noticeably more frequent since quarry operations began. He said that the turbidity response occurs more quickly following precipitation events and requires less intense storms to reach levels of concern.
- Engineering-Science (April 1991) concluded that Liddell Spring turbidity had increased following heavy rains since quarrying began. Prior to quarry operations, high turbidities were observed infrequently and only after very intense storms. Because turbidity increases had coincided with quarry operations and little other disturbance had occurred in contributing upgradient areas, the quarry was suspected as a probable cause. Turbidity increases were expected to continue as mining operations continued to lower and expand the quarry floor, and cease following reclamation and revegetation of disturbed areas.
- Watkins-Johnson (November 1992) developed various explanations for increased spring turbidity and identified runoff from the quarry floor as a primary source.
- Farallon (March 2000) recognized the generally erratic nature of Liddell Spring's turbidity response to storms. However, because the cover placed over a portion of the quarry floor in February 1998 was seen to have no dramatic effect on spring turbidity, Farallon ruled out the quarry floor as a source of turbidity.
- Weber, Hayes and Associates (May 2001; April 2002) reviewed turbidity data for the Liddell Spring diversion and concluded that quarry operations have the potential to cause elevated spring turbidity.
- Tompkins (October 2002) stated that Liddell Spring turbidity and sedimentation events increased in both frequency and severity immediately following the start of quarry activities, then stabilized, and then increased again starting in the late 1980's. Sedimentation events filling the springbox and pipeline had occurred almost annually since 1996, requiring repeated cleaning of the spring and purging of the pipeline. Impacts also include increased reliance on water stored for drought use in the City's Loch Lomond reservoir when spring turbidity caused diversion reductions (T. Tompkins, City of Santa Cruz Water Department, personal communication, February 27, 2006). He also identified potential downstream impacts to protected species from increased sedimentation.

As discussed and analyzed in Section 4.4.3, Liddell Spring's turbidity response to precipitation occurs within hours to days. The turbidity response is complex, highly variable from storm to storm and year to year, and may include multiple turbidity peaks stretching out over several days. Because (a) the City only measures the turbidity of springflows it actually diverts (on a roughly bi-weekly schedule) and (b) continuous turbidity measurements did not begin until 1997, the data record cannot be used to demonstrate a definitive causal, before-and-after relation between quarrying and springflow turbidity. Furthermore, sampling and measurement methods have changed, as has the City's ability to divert slightly more turbid water.

Thus, an assessment of whether or not quarrying is having an effect on springflow turbidity must rely on an interpretation of the local groundwater system. A connection between quarry activities and groundwater has been demonstrated by the extreme sedimentation and turbidity events that coincided with overburden removal and the start of quarry operations. Additionally, aquifer connectivity and a subsurface source of sediment are demonstrated by the spring's turbidity response to blasting.

Under current conditions, we infer that interconnected voids above the permanent zone of saturation capture and transmit substantial volumes of incident precipitation and runoff that percolate from the quarry area into the marble. This water is generally turbid and may entrain additional sediment from the quarry surface and within the subsurface, such as that created through blasting, ripping, and the disturbance of overburden, as well as naturally occurring sediment deposited in subsurface voids. As discussed in Section 4.3.6, an average of only a few cubic feet of sediment per day could account for Liddell Spring's turbidity. Highly permeable interconnected voids have the potential to transport this water and sediment in a turbulent and cascading flow down to the zone of saturation and laterally toward Liddell Spring.

The average timing of Liddell Spring's primary (and usually initial) turbidity peak following peak storm precipitation (~5 hrs) is generally consistent with the observed time for tracers to reach the spring from groundwater beneath the quarry (~7 hrs) and the typical turbidity response to quarry blasting (~4 hrs). Actual travel times could be faster or slower given that the tracer test was performed under non-storm conditions and did not include transport through the unsaturated zone (i.e., because the tracer was injected into well NZA). The timing of the main turbidity peaks appear too slow for sources immediately adjacent to the spring (e.g., the landslide or nearby inferred sinkholes) and too fast for transport from the Reggiardo and Laguna creek swallow holes (based on tracer times of at least several days). This interpretation is consistent with the City's claim that turbidity peaks are larger and occur more quickly in response to precipitation since quarrying began (Tompkins, April 1991).

The consistent rise and decline of spring turbidity, quarry-floor pond depth, and stream discharge (Majors Creek) prior to peak spring discharge indicates that sediment is introduced, or at least entrained, by runoff-related processes affecting groundwater in the quarry area. As estimated in Section 4.3.6, a sediment volume averaging only a few cubic feet per day can account for the spring's overall turbidity.

While other turbidity sources and delivery mechanisms likely exist, the available data and our understanding of the local groundwater system indicate that the quarry operation has a significant contributing influence on spring turbidity.

4.6.7 **Clastic Sedimentation**

The record of Liddell springbox sedimentation events is mostly anecdotal. Several observers documented substantial increases in turbidity and springbox sedimentation for several years following 1969 when the quarry overburden was first removed (e.g., Wyckoff, February 1970; Nordquist, August 1970; Stewart, December 1971; March 1978; Earth Sciences Associates and Creegan & D'Angelo, May 1979; see discussion in Section 4.6). A cause-and-effect relationship between quarrying and subsequent sedimentation events is less certain. SECOR (March 1998) documented one such event in response to a major storm in January 1998. Tompkins (October 2002) stated that Liddell Spring sedimentation events had increased in both frequency and severity immediately following the start of quarry activities, then again starting in the late 1980's, and occurring almost annually since 1996. Water-year precipitation was above average throughout 1996-2000. Such events required cleaning the springbox, purging the diversion pipeline, and temporarily relying on other City water-supply sources. Sedimentation of the channel downstream of the spring presents a potential impact to wildlife habitat.

Clastic sediment that accumulates in the springbox and suspended sediment responsible for turbidity may have distinctly different sources. While springbox sedimentation appears to have resulted directly from the quarry's initial removal of overburden, direct evidence attributing subsequent sedimentation with quarry activities is generally incomplete or lacking.

4.6.8 **Conclusions**

We conclude the following regarding the response of groundwater and springflow to quarry operations:

- Considerable interconnectivity exists between runoff collected in the quarry, groundwater flow, and Liddell Spring discharge.
- There has been no apparent decline in the quantity of Liddell Spring discharge as a result of quarrying.
- Quarry activities probably contribute to groundwater nitrate. However, other sources appear to be as or more important. Concentrations of nitrate and other dissolved minerals in Liddell Spring discharge are not exhibiting definite and/or noteworthy upward trends.
- Quarry blasting is correlative with episodes of elevated spring turbidity.
- The bulk volume of sediment needed to account for Liddell Spring's turbidity (roughly several cubic feet per day, on average) could be generated by quarry operations.
- Observed quarry ponding and estimates of overall quarry recharge indicate that the quarry represents a substantial input to the groundwater system and Liddell Spring discharge during storm events.

- The timing and nature of Liddell Spring's turbidity response to precipitation, relative to the timing of runoff collected in the bottom of the quarry and groundwater travel times from the quarry to the spring, indicate that runoff captured by--and percolated into--the quarry pit, along with sediment generated by quarrying, are an important component of turbidity at the spring.
- Springbox sedimentation likely resulted from the quarry's initial overburden removal. While it may be reasonable to suspect that quarry operations have been partially responsible for subsequent sedimentation events, direct evidence of this is generally lacking.