EXECUTIVE SUMMARY

Geologic, Hydrologic, and Hydrogeologic Technical Appendix for Bonny Doon Quarry Proposed Expansion EIR

INTRODUCTION

Purpose

CEMEX operates the Bonny Doon Limestone Quarry near Davenport in Santa Cruz County, California (Figure 1). In an application originally filed by RMC Pacific Materials (RMC), the previous quarry operator, CEMEX seeks to amend its use permit by expanding the working area of the quarry into an adjacent area of approximately 17.1 acres (Figure 2). The processing of this application by the Santa Cruz County Planning Department (SCCPD) requires preparation of an environmental impact report (EIR). In support of the EIR, this technical appendix provides an analysis of geologic, hydrologic, and hydrogeologic factors relevant to potentially significant impacts identified in the project's Initial Study (SCCPD, November 2001), and an assessment of potentially applicable mitigation measures.

Previous Work

Studies of the quarry-area hydrogeology were conducted prior to surface mining during the late 1950's through the 1960's (e.g., Wisser and Cox, April 1959; Todd, January 1963; Lindsey, July 1968). The conditions of Liddell Spring discharge were documented following site preparation and initial quarrying in the late 1960's and early 1970's (e.g., Wyckoff, February 1970; Nordquist, August 1970; Stewart, December 1971).

An EIR for the quarry operation in 1991 (Engineering-Science, April 1991) prompted two follow-up hydrogeologic assessments (Schipper and Reppert, February 1992; Watkins-Johnson Environmental, November 1992). A subsequent EIR (Thomas Reid Associates, October 1996) was followed by a series of hydrogeologic studies that included continuous springflow monitoring (e.g., SECOR, December 1998; EMKO Environmental, August 1999; Farallon Consulting, August 2001; Balance Hydrologics, December 2002). Concurrent studies addressed the landslide near Liddell Spring (Woodward-Clyde Consultants, 1997; Pacific Geotechnical Engineering and Balance Hydrologics, February 2002).

Most recently, the area hydrogeology has been investigated by P.E. LaMoreaux & Associates (PELA, May and October, 2005), for RMC, with ongoing monitoring of Liddell Spring and nearby springs by Balance Hydrologics (e.g., April 2005), for the City of Santa Cruz.

Available Data

The available database relevant to this analysis includes the following information:

- Lithologic logs for approximately 225 borings associated with the quarry.
- Water level and water quality data for approximately 40 quarry monitoring wells, 25 of which are still active.

- Information summarized from driller's reports of 43 water wells on surrounding and upgradient properties.
- The quantities and quality of water diverted by the City of Santa Cruz from Liddell Spring and Laguna and Majors creeks.
- Monitoring of intermittently continuous discharge and water quality for Liddell Spring (since 1997), Plant Spring (since late 2002), the East Branch of Liddell Creek (since 2000), and Laguna and Majors creeks (most recently since 2003).
- Monitoring of quarry-pond water levels and x-ray diffraction analyses of suspended sediment samples, conducted by Nolan Associates.
- Various precipitation records.

Study Objectives

The purpose of this study was to provide an evaluation of potential geologic, hydrologic, and hydrogeologic environmental impacts and constraints relevant to the proposed project. The proposed quarry expansion has the potential to cause several significant environmental impacts with respect to geologic and hydrogeologic conditions. The quarry is located in an isolated body of marble surrounded by granitic, metamorphic, and sedimentary rocks. Dissolution of the marble rocks along fractures by percolating groundwater has created a localized karst aquifer system of interconnected subterranean channels and caverns that are fed by groundwater inflow from adjacent rock bodies and by percolating surface water and streamflow from above. Surface outflow from the karst aquifer system occurs at springs located in the Liddell Creek drainage on the southerly (downslope) side of the marble body. The principal spring in Liddell Creek is an important water supply for the City of Santa Cruz. Environmental concerns associated with the proposed quarry expansion include:

- Turbidity in Liddell Spring has the potential to impact the water supply for the City of Santa Cruz. Expansion of the quarry could cause additional turbidity in the spring water.
- The expanded quarry activity could potentially alter flow paths in the karst aquifer and reduce flows to Liddell Spring and Liddell Creek. Such an occurrence would impact the city water supply and the fisheries downstream of the spring.
- The renewed quarrying (including blasting), in conjunction with changes in surface or subsurface water flow, could affect the stability of a landslide adjacent to the spring facility, potentially impacting the spring diversion facilities and turbidity at the spring. These activities could also induce new landsliding within or adjacent to the quarry, potentially impacting the environment or persons working in the quarry.
- Extensive grading to remove overburden from the marble deposit in the expansion area and placement of the overburden soils as fill in the existing quarry will expose a considerable area to accelerated erosion, potentially leading to increased sedimentation downstream.

Our study approach has been to organize and interpret the existing geologic, hydrologic, and hydrogeologic data for the quarry area and Liddell Spring, supplemented by specific, additional data collection. Because of the large volume of previous work that has been done in the Quarry area, we have been careful to acknowledge previous work and build on it, or refute it, as appropriate.

Quarry History and Proposed Expansion

Mining of the 80-acre marble quarry began in August 1970 (SECOR, November 1997). Roughly 37 million cubic yards of marble have been removed during the past 36 years. Averaged over the existing 80-acre quarry, this represents an average depth of mining of nearly 300 feet (excluding the depth of overburden).

CEMEX proposes to amend Use Permit 3236-U, as modified under COC 89-0492, to expand the working area of the marble quarry into an adjacent area of approximately 17.1 acres. This area is outside the currently approved mining plan but within the maximum mining limit defined in the original use permit. Overburden material will be placed within approximately 17.1 acres of the existing quarry pit.

Mining will consist of working the benches outward toward the permit limits and dropping the pit floor from its current elevation to the permitted maximum depth of 750 feet above mean sea level (ft msl). The working benches will maintain current dimensions—approximately 40 ft high by a minimum 16 ft wide.

Because of the difficulty in pre-determining peak groundwater elevations due to the complex hydrogeology, CEMEX (following RMC's August 1999 application) proposes drilling shallow borings as the pit is lowered to test for groundwater. If groundwater is encountered in any borehole, CEMEX proposes to pump groundwater from the hole for 12 to 24 hrs. A sustained yield of 50 gpm or more would suggest that this zone is part of the "marble aquifer" (see RMC Lonestar, August 1999).

The County has concluded that the existing sediment control basins will adequately serve future quarry operations including the expansion area (SCCPD, November 2001). The quarry pit is currently acting as the terminus of a closed basin, allowing captured drainage to percolate to groundwater. The final drainage plan for the quarry (Bowman and Williams, 2001) shows the quarry draining to sediment control basin #3. No increase in water use is expected.

GEOLOGY

Introduction

The Bonny Doon Limestone Quarry site is situated on the gently sloping southwestern flank of Ben Lomond Mountain, a large, eroded plutonic massif that has been up-faulted along its steep northeast-facing slope. The quarry presently occupies about 80 acres between native (pre-quarry) elevations of about 800 and 1100 feet above mean sea level (ft msl). Due to quarrying, the original topography has been modified into a large open pit with a floor between 750 and 760 ft msl. The proposed 17.1 acre amendment area will extend northeasterly from the present quarry into an area with native elevations between 1100 and 1235 ft msl.

The existing geologic mapping for the quarry and surrounding area consists of a few regional-scale geologic maps (Leo, 1967; Clark, 1970; Clark, 1981; Brabb, 1997) and numerous larger scale geologic maps by various consultants who have worked on the quarry (e.g., Wisser and Cox, 1958; Watkins-Johnson, October and November, 1992; Jo Crosby and Associates, July, 1997; Farallon Consulting, March, 2000). There is a wealth of exploratory boring data available for the current project. Exploratory drilling for the quarry began in 1958.

We performed approximately nine days of field mapping for the project. Our field mapping served to refine previous geologic mapping, but we did not attempt to resolve every detail of the local geology. In preparing the geologic map, we made use of the exploratory boring data to the greatest extent possible. The boring data proved accurate in identifying igneous or metamorphic rock types but was unreliable for characterizing the nature and thickness of the overlying sedimentary rocks. Consequently, it was used only sparingly in defining the distribution and thickness of sedimentary rocks.

Physiographic Setting

The study area is located on the southwestern flank of Ben Lomond Mountain, overlooking the Pacific Ocean. This side of Ben Lomond Mountain is a relatively broad, gently sloping surface displaying a series of ascending, stairstep-like topographic benches that are the remains of old marine terraces preserved by gradual uplift of the mountain. Visible marine terrace deposits are identified up to about 800 feet in elevation, and the effects of marine erosion probably extend farther up the mountain.

The broad surface forming the flank of Ben Lomond Mountain is cut by a series of southwest flowing streams occupying narrow, V-shaped stream valleys separated by wide, flat-topped ridges. This drainage pattern is locally interrupted where large bodies of marble bedrock crop out. In these areas, dissolution of the marble by percolating groundwater leads to the formation of sinkholes (or swallow holes) connecting to underground caverns.

The topography of Ben Lomond Mountain in areas underlain by marble can be highly irregular, appearing as knobs or short ridges separated by short, intersecting valleys, with sinkholes often formed at the valley intersections. This topographic pattern is due to dissolution taking place preferentially along older fractures in the marble and is readily apparent in the study area on aerial photographs taken prior to development of the quarry. The solution fractures affect the flow of ground water, as will be discussed in more detail in a later section of this executive summary.

Regional Geologic Setting

The quarry property is situated on the western slope of the central Santa Cruz Mountains, part of the Coast Ranges physiographic province. The northwest-southeast structural grain of the Coast Ranges is controlled by a complex of Pleistocene- and Holocene-active faults within the San Andreas fault system. Southwest of the San Andreas fault, the Coast Ranges, including the Santa Cruz Mountains, are underlain by a large, northwest-trending, fault-bounded, elongate prism of granitic and metamorphic basement rocks. The marble being mined in the quarry is part of a metamorphic rock unit that also includes schist and quartzite. The granitic and metamorphic rock basement is overlain by a sequence of dominantly marine sedimentary rocks of Paleocene to Pliocene age and non-marine sediments of late Pliocene to Pleistocene age.

The study area is tectonically active. The Santa Cruz Mountains are cut by several active faults, of which the San Andreas is the most important. Along the coast, the ongoing tectonic activity is most evident in the formation of the series of uplifted marine terraces that sculpt the southwest slope of Ben Lomond Mountain. The Loma Prieta earthquake of 1989 and its aftershocks are recent reminders of the geologic unrest in the region.

Regional Seismicity

California's broad system of strike-slip faulting has a long and complex history. Locally, the San Andreas, Zayante-Vergeles and San Gregorio faults and the Monterey Bay-Tularcitos fault zone present a seismic hazard to the subject project. These faults are associated with Holocene activity (movement in the last 11,000 years) and are therefore considered to be active. The most severe historical earthquakes to affect the project site are the 1906 San Francisco earthquake and the 1989 Loma Prieta earthquake, with Richter magnitudes of about 8.3 and 7.1, respectively.

Local Geologic Setting

The geology of the study area is complex, a result of over 100 million years of geologic history, including collisions of crustal plates and multiple cycles of tectonic upheaval and erosion of the land surface. These episodes of tectonic deformation are recorded as metamorphism of older sedimentary rocks, intrusion of plutonic igneous rocks, folding and faulting of sedimentary layers, and by erosional remnants of once extensive geologic formations.

Rock units in the study area are separable into three major groups: granitic intrusive rocks, of Late Cretaceous age, pre-Cretaceous metasedimentary rocks, and sedimentary rocks of Tertiary and Quaternary age. The granitic intrusive rocks form the core of Ben Lomond Mountain and the pre-Tertiary basement for most of the Santa Cruz Mountains. The granitic rocks intruded and metamorphosed older sedimentary rocks, forming schist, quartzite, and marble, with some hornfels and calc-silicate rocks. Foliation in the schist, and relict bedding in the marble are parallel, and both are parallel to non-faulted contacts between the two rock types, indicating that these metamorphic textures express relict sedimentary bedding.

Sedimentary rocks of Tertiary age and thin, surficial deposits of Quaternary age occur in isolated bodies on and around the quarry property. The Tertiary rock units include the Monterey Formation, Santa Margarita Sandstone, and Santa Cruz Mudstone, while Quaternary deposits include marine terrace deposits, doline fill, alluvium, colluvium, landslide deposits and soil (residuum).

Geologic Structure

Geologic structure in the study area is a result of intrusion of granitic plutonic rocks at depth into metasedimentary country rock in Cretaceous time, followed by uplift and unroofing of the plutons and repeated cycles of sedimentary deposition and tectonic deformation throughout the Tertiary Period. Metamorphic rocks in the study area appear as a regularly bedded, but faulted, sequence of moderately to strongly metamorphosed sedimentary rock. The metamorphic rocks show a regular, approximate east-west strike with moderate northerly and southerly dips. However, bedded sections are discontinuous due to nearly ubiquitous faulting.

In areas with substantial marble, the metamorphic rocks are cut by orthogonal or near-orthogonal fractures, which are visible in the landscape as aligned valleys, swales, or notches in ridges. The fracture lineaments are often short and intersecting. In areas of karst, the fracture intersections are frequently marked by sinkholes. In some cases, these fractures are clearly faults with major displacement. In other cases, the fractures appear to have little displacement but have been etched into the landscape by preferential dissolution of the marble bedrock.

In the quarry exposure, we mapped a significant structural discontinuity trending west-southwest. The layering of the marble within the quarry dips south to south-southwest on the southeast side of the discontinuity and west to northwest on the northwest side. This discontinuity is coincident with several parallel or sub-parallel, curvilinear faults mapped in the quarry and may represent a faulted antiform. The schist-marble contacts on either side of the zone are consistent with the relict bedding attitudes. This fault zone forms a major structural boundary in the quarry.

Another fault zone trending northwest through the northwest portion of the quarry forms a second, though less pronounced, structural boundary. The relict bedding attitudes in the marble on the northeast side of the fault are dipping northwesterly to north-northwesterly, while those to the southwest of the fault dip westerly.

We noted many lesser faults throughout the quarry, but these features were not associated with distinct changes in the orientation of relict bedding. These faults included both low-angle thrusts and high-angle faults, with the amount of total offset usually indeterminate. The rocks exposed in the quarry are universally jointed. Many of the joints in the quarry show evidence of solution, including raspy “meringue” weathering patterns and thick linings of terra rosa sediment (derived from mineral impurities left behind after dissolution of the marble). In visual inspection, concentrations of solution fractures in the walls of the quarry stand out as dark, steeply dipping zones separated by relatively lighter colored marble. The darker color of these zones derives from the concentration of terra rosa on the fracture surfaces.

Geologic structure within the Tertiary sedimentary section is relatively simple. Formations below the mid-Miocene unconformity, the Monterey Formation and Lompico Sandstone, show local folding and faulting; these units crop out east of the quarry. The younger formations in the quarry area, the Santa Margarita Sandstone and Santa Cruz Mudstone, unconformably overlie the Monterey Formation and all older rocks. These formations are relatively undeformed, with shallow dips to the southwest.

Surface Processes

Surficial geologic processes in the study area include weathering, erosion, and mass wasting (landsliding). Weathering of surficial materials and erosion by wind and water are the principal processes active in developing natural landscapes. When erosion leads to the development of steep slopes, landsliding may occur. In turn, landsliding breaks up the rock formations on the slope, leading to additional weathering and erosion.

Erosion related to quarrying occurs in two modes. During our site investigation, we observed turbid runoff from the quarry area, some of which is captured by the quarry drainage system and carried to the sediment (settlement) ponds. However, most of the runoff from the quarry is retained within the topographic sink of the quarry floor, where it percolates into the marble bedrock. A small percentage of this ponded runoff evaporates.

The sediment carried by the runoff is derived from erosion of exposed slopes cut in the sedimentary units overlying the marble, from weathered schist or diorite exposed in and around the quarry, from residuum left behind after dissolution of the marble (terra rosa), from doline fill, and from spoils deposited following removal of overburden from the marble.

The most extensive erosion associated with proposed quarry expansion will likely occur during stripping of vegetation and overburden removal, when large amounts of loose sediment will be generated by excavating and transporting the Santa Margarita Sandstone and Santa Cruz Mudstone. The excavation should be carefully staged to prevent erosion.

Landsliding

Landsliding is a natural process that accompanies erosional downcutting and oversteepening of slopes. Like erosion, it can also be exacerbated by cultural activities. Road building or earth moving results in steep cut slopes and loose fill soils, both of which can be prone to landsliding. Roads can also collect naturally dispersed runoff and concentrate it into a rapidly flowing stream that can trigger erosion or landsliding.

We observed two landslides of significance in the area of the quarry. One of the landslides has been studied extensively by Pacific Geotechnical Engineering (2001), because of its potential impact on Liddell Spring. The second one occurred in the winter of 2006 in the southeastern quadrant of the quarry. This landslide was about 150 feet wide and 320 feet long. It moved as a rock and debris slide in weathered marble, along with a substantial soil component. The detachment surface exposed in the headscarp was an older shear zone of undetermined thickness, striking about N55°W and dipping steeply to the southwest (roughly parallel to prominent joints in this wall of the quarry).

Karst Processes: Geologic Influence on Groundwater Flow

The study area has experienced episodes of subaerial erosion and submarine deposition throughout its geologic history, as indicated by the middle to upper Tertiary sedimentary sequence overlying the granitic and metamorphic basement. In the early to mid Pleistocene, the study area was subject to sea level fluctuations of 300 to 400 feet every 100,000 years on average, caused by worldwide climatic variations and episodic glaciation in the higher latitudes. More recently, it has been elevated hundreds of feet above sea level and exposed to subaerial erosion for at least the last 500,000 years (mid Pleistocene to Holocene), based on estimated uplift rates for this section of the coastline (Bradley and Griggs, 1976). In other words, over the last 25 million years, the marble body in the study area has had an extraordinarily complex hydrogeologic history, characterized by dramatic fluctuations in climate and base level.

Groundwater flow in areas underlain by soluble rock, such as marble or limestone, is substantially different than groundwater flow in most other types of rock. In marble, the initial permeability may be quite low, but even slight downward flow over time will gradually dissolve the rock, forming solution channels through which water can flow more readily. In some cases, the solution channels enlarge to form caverns with underground ponds and streams. These solution cavities usually begin forming along bedding planes, fractures, or faults. In the quarry area, solution of the marble is strongly controlled by the fracture patterns. The influence of the fracture system on dissolution of marble bedrock and groundwater circulation is well documented by the alignment of sinkholes along major fractures (or faults) -- and particularly by the preferential location of prominent sinkholes (open or buried) at the intersection of two fractures.

The exposure afforded by the quarry walls provides a remarkable view of the hydrogeologic character of the marble over a vertical distance of 350 feet. Solution-widened fractures in the quarry walls are steeply dipping to vertical and commonly form continuous zones of solution channeling from the original ground surface through the quarry floor.

Although there is interbedded schist throughout the marble section (as well as igneous sills and dikes), SECOR (1997) concluded that these interbeds do not have a substantial effect on flow paths through the marble. We concur with this conclusion, because the formation of solution channels has been guided by fractures and faults that cut across the rock layering.

Prominent topographic lineaments in the Bonny Doon Ecological Preserve, an area largely underlain by the Santa Cruz Mudstone, are consistent with the pattern of fractures mapped in the marble terrane. These lineaments strike northeast to east-northeast from the quarry area across the Ecological Preserve, with the two southernmost lineaments trending toward marble outcrops mapped in Laguna Creek. These lineaments imply the presence of solution-widened fractures in marble underlying the Santa Margarita Sandstone in the Ecological Preserve. Mapping in Laguna Creek indicates that marble layers within the schist are relatively common throughout this area. These observations, in conjunction with the dye tracer test results, indicate the existence of karst solution channels beneath Laguna Creek and the Ecological Preserve.

Geologic Hazards

Seismic Hazards

Seismic shaking at the subject site may be intense during the next major earthquake along one of the local fault systems. It is important that seismic shaking be considered in the evaluating project design. Our seismic shaking evaluation for the quarry site included an estimate of expected seismic shaking intensities based on both deterministic and probabilistic methods. For the purpose of evaluating seismic shaking at the site, we have considered the San Andreas, Zayante-Vergeles, San Gregorio, and Monterey Bay-Tularcitos fault systems. These faults are considered active seismic sources by the State of California.

The San Gregorio fault zone, passing within 7.5 km of the site, is expected to generate the largest earthquake ground motion at the site. The characteristic earthquake on this fault ($M_{W(MAX)} = 7.2$) is expected to generate estimated ground motions of up to 0.67g (67% of the “force” of gravity). The duration of strong seismic shaking from this event will be about 19 seconds. The recurrence interval for this earthquake is about 400 years.

The U.S. Geological Survey and the California Geological Survey together produced a probabilistic seismic hazards assessment for the state of California. The probabilistic ground motions are expressed as the potential for a certain intensity of ground motion to be exceeded during the design life of a project. The joint U. S. Geologic Survey and California Geological Survey study found ground motion intensities of 0.43g and 0.7g, corresponding to a 10% and a 2% chance of being exceeded in 50 years, respectively. The "10% in 50 year" ground motion is considered appropriate for residential and non-critical structures. The ground motion with a 2% probability of being exceeded is considered appropriate for critical structures, such as hospitals or fire stations.

The ground motion values discussed above are only expected values based on uniform site conditions in firm bedrock. Ground motions at the crest of very steep slopes can be several times as intense as in adjacent valleys. Topographic amplification is therefore considered to be important for steep, high slopes such as quarry faces.

Seismic shaking could damage buildings and other structures associated with the quarry operation, and could induce landsliding or other types of ground failure, as will be discussed below. The expansion of quarrying to the amendment area does not, to our knowledge, include development of new structures and therefore will not increase risks associated with structural collapse of buildings.

Seismically Induced Ground Deformation

The principal seismically induced ground failure hazards that are likely to affect the quarry area are co-seismic ground cracking along crests of quarry slopes, probably accompanied by seismically induced landsliding, rock falls and rock topples along the quarry faces. Ground cracks, by themselves do not pose a hazard, except as a potential contribution to landsliding. The potential impacts of seismically induced landsliding are similar to those of non-seismically triggered landsliding, described below. Soil liquefaction and differential settlement are not considered hazards in the quarry. However, it is possible that liquefaction or differential settlement during an earthquake could impact the embankment dams that retain the sediment ponds.

Golder Associates (1991) evaluated the stability of the earth embankments (levees) used to form sediment basins at the limestone quarry. The evaluation did not include a formal liquefaction hazard evaluation. They did, however, give a qualitative assessment of liquefaction hazard, noting that "Liquefaction could result in localized levee instability or complete failure…" (p. 13). In their analysis, they considered Sediment Basin 2 to be marginally susceptible to liquefaction and Sediment Basin 4 to be susceptible to liquefaction. The levee for Sediment Basin 3 was considered susceptible to permanent deformations of up to 9" if it is saturated during a major seismic event. The impact of levee failure could be to release sediment laden water into local stream drainages and flood downstream areas, a significant impact. Increased runoff from the amendment area could increase the impacts associated with the existing quarry.

Ground Surface Rupture Hazard

Active faults have the potential to rupture the ground surface during earthquakes. Ground surface rupture will damage structures placed across the zone of rupture. The faults mapped in the area of the quarry are related to deformation that took place during metamorphism, igneous intrusion, and uplift of the basement rock, most of which took place in late Cretaceous and early Tertiary time. These faults are not genetically related to the current tectonic environment that includes a transform plate boundary in Central California. In our opinion, the potential for ground surface rupture to impact the proposed quarry expansion is low.

Landsliding and Slope Instability Hazard

We observed two types of landslide in the quarry area. The landslide complex adjacent to Liddell Spring was classified by Pacific Geotechnical Engineering (2001) as a combination of an earth flow and debris flows. The debris flow portion of the landslide is considered to have been caused in part by stockpiled spoils from the quarry. PGE concluded that this landslide posed some hazard to the springbox at Liddell Spring and to water quality at the spring.

A second landslide was observed in the quarry itself. This landslide failed on a quarry face as a combined rock- and debris-type landslide. It appears to have been facilitated by an existing fracture surface projecting out of the quarry wall.

Both of these landslides illustrate the potential impact of quarry operations on slope stability. Additional landsliding around Liddell Spring could impact operation of the Santa Cruz City diversion and water quality at the spring. Landsliding within the quarry could threaten quarry workers during the quarry operation or damage land adjacent to the quarry after the end of active quarrying, increasing the risk of erosion. A large slope failure on north slope of quarry could impact the transition zone from shallow groundwater to deep groundwater in the karst aquifer, potentially affecting water quantity and quality and Liddell Spring.

An evaluation of the stability of the planned quarry slopes was performed for the proposed finished quarry configuration by Jo Crosby and Associates (JCA, 1997; 1998; 1999). Our peer review of the stability analysis and the recent landslide in the quarry indicate that finished quarry slopes may be susceptible to landsliding. The proposed quarry expansion will create approximately 12% more steep slopes, which would marginally increase the potential for landsliding. However, the overburden from amendment area will be placed within the existing quarry and will help buttress existing steep slopes against landsliding. Consequently, we are of the opinion that the proposed amendment will result in no net increase in landslide impacts, and may serve to lower overall landslide hazard within the quarry.

Based on the findings of PGE (2001), the proposed quarry expansion is unlikely to increase the risk posed to Liddell Spring by landsliding, provided that no spoil is dumped on slopes adjacent to the spring and that adequate site drainage is maintained.

Erosion Hazard

The proposed quarry expansion has the potential to cause erosion that may result in sedimentation of downstream water and turbidity at Liddell Spring. The removal of overburden from the original quarry area in 1969-70 is closely linked to instances of sedimentation and turbidity in Liddell Spring. The amendment area is partially overlain by as much as 150 ft of Santa Margarita Sandstone, a poorly consolidated and weakly cemented sandstone. The mechanical removal of this material will create loose sand and silt that will likely be washed into buried karst sinks and open fractures. The expansion of mining to the amendment area may therefore increase erosion potential due to removal of vegetation, mechanical reduction of sedimentary rocks overlying the marble, and increased runoff quantities due to increased exposure of bare rock.

The mining plan amendment and drainage plan prepared for the quarry (Bowman and Williams, 2000; Bowman and Williams, 2001) shows all runoff being captured and retained within the quarry until the expansion area quarrying is partially complete. Runoff retained within the quarry largely percolates into the quarry bottom. The retention of sediment laden runoff on the quarry floor may result in turbid water entering the karst aquifer via open fractures or conduits, which may then contribute to turbidity and sedimentation at Liddell Spring. As long at runoff from the amendment area is retained within the quarry, the potential for sedimentation of downstream areas is low.

The Bowman and Williams (2001) plan shows drainage from the quarry floor to sediment pond #3 being established between 2007 and 2012 by lowering of the ingress/egress ramp and crusher area to elevation 750, from the current elevation of about 800 feet (or slightly more) . Once drainage of the quarry to the sediment basin is established, the potential for sedimentation of downstream areas is increased should the sediment basin levees be breached due to strong seismic shaking.

There does not appear to be any interim drainage or erosion control plan to help mitigate runoff and erosion during the removal of overburden in the amendment area. The removal of overburden will have significant impacts on erosion and sedimentation, unless mitigated.

HYDROLOGY

Introduction

The quarry-area hydrology is characterized by the spatial and temporal distribution of precipitation, quarry-area drainage, nearby stream and spring flow, and water diversions by the City of Santa Cruz and CEMEX. Based on various available records, mean annual precipitation at the quarry is estimated to range between about 34 and 40 inches per year (in/yr). Upgradient of the quarry, precipitation increases with elevation to as much as 60 in/yr. The period during recent field studies for the quarry, water years (WYs) 2001-04, was generally dry with about 90 percent of average precipitation.

Quarry Drainage

The quarry is encompassed by a 125-acre drainage area and an additional 70 acres that drain to sinkholes adjacent to the quarry. Because the quarry pit has no drainage outlet, most of the runoff that reaches the quarry floor is assumed to percolate. An 8-acre swale downgradient of the quarry leads to Liddell Spring. The County senior civil engineer concluded that the capacities of the existing sediment basins are adequately sized for the quarry operation, including the proposed amendment area (SCCPD, November 2001).

We observed open fractures along the quarry benches and piping through areas of fill on the quarry floor intercepting precipitation and runoff. We also installed a pressure transducer and data logger in one of several ponds on the quarry floor, all of which contained turbid water during periods of rain. We inferred that most of the ponded water percolated into the subsurface. The timing and shape of the quarry pond hydrograph were similar to the flow hydrographs for nearby gaged streams. 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 a quarry monitoring well. Peak spring turbidity occurred within about 6 to 9 hrs of the beginning of the pond level rise, about 2 to 5 hrs after the peak pond water level, and consistently prior to peak spring discharge. These results strongly suggest that runoff infiltration through the quarry floor has a direct effect on Liddell Spring turbidity.

Using a simple water budget, the total volume of mean annual recharge into the drainage area encompassing the quarry and adjacent sinkhole drainages is estimated to average nearly 300 ac-ft/yr. During the wettest years, this amount may be two or more times greater.

Springs

Liddell Spring is located immediately south of the Bonny Doon marble quarry. It is the largest spring in the region. The City of Santa Cruz monitors its monthly diversions from the spring and total instantaneous springflow has been recorded intermittently since 1999.

During WYs 1999-2005, monthly average flow rates ranged between 760 and 1,720 gpm and averaged about 1,100 gpm. Instantaneous gaged flows have ranged from about 600 to 3,100 gpm. Based on the available gaging data, including the City of Santa Cruz's recorded diversions, the total mean annual flow of Liddell Spring is estimated to be approximately 1,500 ac-ft/yr.

Plant Spring is about 1,400 ft east of Liddell Spring. From November 2002 to November 2004, flows averaged 184 gpm (about 300 ac-ft/yr) and ranged from 66 to 338 gpm.

Many relatively minor springs occur elsewhere in the area.

Water Production

Liddell Spring has been a source of water for the City of Santa Cruz since 1913. Historically, Liddell Spring has provided a reliable water supply in terms of both quantity and quality. About 30 percent of the City of Santa Cruz's water supply is derived from its North Coast pipeline, which conveys water diverted from Liddell Spring and Laguna, Reggiardo, and Majors creeks. The City's pre-1914 appropriative water rights for these sources allow unlimited diversions up to the pipeline's capacity. Of the 3,300 ac-ft/yr total average diversion, Liddell Spring has supplied 1,250 ac-ft/yr since WY 1972, or 39 percent. Prior to June 1994 the City's North Coast pipeline directly served some customers. This limited the allowable turbidity of diverted flows to about 2 nephelometric turbidity units (NTU). Since then, the turbidity threshold of divertible flows has risen to about 10 to 25 NTU. However, this does not appear to have resulted in a substantial shift in the overall rate of diversion.

The specific conductance of Liddell Creek diversions follows a seasonal trend that is the inverse of the stream diversions, peaking during the wet season and gradually falling during the dry season. This suggests that high hydraulic heads resulting from wet-season recharge cause the discharge of more mineralized groundwater than during other times of year.

The specific conductance and nitrate concentrations of Liddell Spring diversions were lower during a relatively intensive 1967-70 monitoring period when compared to data collected after 1980. Nitrate concentrations since 1977 have typically ranged from about 1 to 5 mg/L, with a few values in the range of 5 to 10 mg/L. The nitrate concentrations of the stream diversions have been relatively stable at generally <2 mg/L.

Liddell Spring diversions showed several years of substantially elevated seasonal turbidity beginning in 1970, coinciding with the start of quarry operations. Minimum turbidity levels were elevated through the remainder of the 1970's. From the mid-1970's through the mid-1990's, the turbidities of Liddell Spring diversions generally ranged between about 0.1 and 10 NTU. Although the overall turbidity trend has remained flat, the incidence of turbidities between 10 and 100 NTU increased beginning in the mid-1990's. This increase may be due to changes in the diversion strategy after construction of a new supply line for north coast customers, rather than an actual increase in high turbidity levels.

Others have noted the role of antecedent moisture in the behavior of Liddell Spring, stating that flow conditions were heavily influenced by the preceding years' precipitation. A multiple regression analysis of the correlation between annual diversions and current-year and prior-year precipitation confirms this observation, indicating that Liddell Spring diversions are more highly correlated to the three prior years' precipitation than to the current year's precipitation.

Based on monitoring data for 1997-2005, the turbidity of Liddell Spring increases to as much as 1,000 NTU in response to storms. Remote monitoring allows the springflow to be turned-out by remote control to prevent excessive turbidity from entering the North Coast pipeline. The diversion must be restarted manually, however, causing an interruption typically longer than the period of elevated turbidity. According to anecdotal accounts, elevated turbidity currently persists for days following storm events, whereas sometime in the past these periods of elevated turbidity lasted only hours. This assertion cannot be tested given that hourly turbidity data have only been collected since 1997.

CEMEX diverts up to 21 gpm (927,000 gal/month) from Plant Spring, mostly for dust control at the quarry.

HYDROGEOLOGY

Introduction

The primary components and boundaries of the groundwater system underlying the quarry, proposed expansion area, and overall Liddell Spring recharge area 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.
- 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.
- A southern, downgradient boundary consisting of various geologic units that abut the apparent termination of the karst system.

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.

The 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. Exposures of granitic rock surround nearly the entire karst groundwater system, which helps to focus groundwater flow toward Liddell Spring.

Schist generally has low permeability and generally is not an important 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. A large portion of the Santa Margarita Sandstone outcrop appears to be underlain by schist and probably some marble. 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.

The Santa Margarita Sandstone is an important aquifer in the Bonny Doon area where it is exposed and well flushed with precipitation recharge. It lies directly over the granitic rock, schist, and marble.

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 indicates a degree of hydraulic connection between the landslide and spring.

Bonny Doon Quarry is located within a block of faulted marble roughly 4,000-ft square. 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. 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 summary suggests 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.

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. 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.

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. Each fracture zone consists of multiple fractures, and this grid of major fractures is bisected by numerous other fractures. Liddell Spring is located at the southern, downgradient tip of this grid.

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. 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. 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. Fractures and conduits do become blocked for periods of time when bridged with sediment or collapsed marble.

We reviewed 225 borings with known locations and elevations drilled for the quarry. Karst voids and porous zones comprised nearly 10 percent of all the logs, more than half of which were filled with sediment. Five boreholes drilled within or immediately adjacent to the expansion area encountered karst voids 10 to 40 ft tall. Based on these results, the marble's overall porosity may be as much as 5 percent. There is no apparent segregation of shallow and deep solution cavities, consistent with the ongoing dissolution of marble simultaneous with the gradual uplift of Ben Lomond Mountain.

Groundwater Occurrence

Conceptual Flow Paths

The groundwater flow system that encompasses the quarry and supplies the major karst springs consists of two principal types of pathways from their respective sources of recharge. One path originates 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 path consists of a series of hydrogeologic segments and characteristic sequences of groundwater levels and quality.

Path *A* originates from precipitation recharge into about 800 acres of exposed Santa Margarita Sandstone in the Bonny Doon area north of the quarry. Groundwater is mounded in the sandstone and generally occurs at shallow depths of 10 to 60 ft below ground surface. An estimated 5,000 ac-ft of groundwater may be stored in this area of sandstone. The regional water table slopes gently southward through Bonny Doon, descending from about 1,700 ft msl near Ice Cream Grade to 1,100 ft msl just north of the quarry. Groundwater also flows to the southwest and southeast toward the surrounding creeks, with some shallow groundwater discharging as small springs. This groundwater is relatively cool and has very low dissolved mineral concentrations of a sodium-chloride type. Water tables also occur locally from groundwater recharged into the sandy knolls immediately east and northeast of the quarry.

Path *A* shallow groundwater encounters the marble aquifer immediately upgradient of the quarry. The aquifer's highly permeable karst features cause the groundwater level contours to wrap around the marble body and drop 300 ft in elevation over a relatively short distance. Some of this vertical decent is achieved in a step-like manner, with groundwater extending laterally into karst voids at intermediate depths, forming what appear to be perched zones encountered by several monitoring wells. Some of these perched zones are capable of transmitting considerable amounts of groundwater. This groundwater has a hydrogen and oxygen isotopic signature similar to that of the sandstone aquifer, but has a strongly calcium-carbonate type and a moderately high mineral content as a result of 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. 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. Groundwater also may flow into the marble along deeper flow paths from upgradient recharge areas.

Path *B* originates as streamflow in the upper Laguna and Reggiardo creek watersheds. This water has a very low dissolved mineral content and cool temperatures during the wet season. Lower in the watershed, streamflow increases in mineral content and has a calcium-bicarbonate type, indicating some influence by the marble. Sinking-stream capacities for Laguna and Reggiardo creeks have been estimated at roughly 1,000 ac-ft/yr. Flows of this magnitude are available for capture during most years.

Path *B* continues where streamflow is captured by swallow holes along Reggiardo and Laguna creeks. Recent groundwater tracer tests indicate a strong hydraulic connection between three sinking-stream reaches and Liddell and Plant springs. 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). Groundwater encountered in several monitoring wells suggest that captured streamflow from swallow holes flows to the springs through relatively deep and conductive dissolution conduits, which at times may be under confined pressure. These wells are located along major fracture zones, are perforated below 700 ft msl, have deep water levels relative to nearby shallower wells, have fairly low dissolved mineral concentrations, have similar hydrogen and oxygen isotopic signatures as Reggiardo and Laguna creek streamflow, and encounter productive groundwater zones. 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.

With uncertain locations and amounts of mixing, groundwater along paths *A* and *B* flows through the marble aquifer beneath the quarry floor and nearby areas toward Liddell Spring. Percolation of incident precipitation and collected runoff within the quarry pit and surrounding drainage area constitutes a substantial source of additional groundwater recharge along this segment. 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. Tracer tests have showed that a monitoring well located on the quarry floor is hydraulically connected to upgradient sinkholes and Liddell Spring downgradient. The travel time from this well to Liddell Spring was approximately 7 hours, indicating an average groundwater velocity of 2,600 ft/day, the fastest rate of travel observed during the recent tracer tests. Plant Spring appears to be fed by path *B* groundwater uninfluenced by percolation from the quarry.

As groundwater flow is further concentrated within the karst system as Liddell Spring is approached, relatively minor groundwater flow paths occur away from the major karst conduits.

Liddell Spring accounts for more than 80 percent of the marble aquifer's total yield and appears to be a mixture of flow paths *A* and *B* based on similar ionic type and an intermediate isotopic signature and dissolved mineral content. 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. Although the fairly rapid groundwater velocities documented by tracers between stream swallow holes and Liddell and Plant springs indicate that some groundwater spends little time in the aquifer, a large portion of captured streamflow is diverted into pore spaces and cavities marginal to the high conductivity pathways. When the inferred deep conduits between the swallow holes and the springs become fully saturated and pressurized during periods of high streamflow, groundwater is forced upward and outward into the unsaturated karst porosity. This water displaces more mineralized groundwater, helping explain Liddell Spring's seasonal and post-storm peak mineral concentrations.

Groundwater Levels

Nine quarry monitoring wells have groundwater depths greater than 300 ft and five others have depths greater than 200 ft. Such large depths are rare in the region, and reflect the extraordinary drainage of groundwater into the karst system supplying Liddell Spring. Water supply wells in the Bonny Doon area upgradient of the quarry have water levels typically less than 60 ft deep.

Several monitoring wells have groundwater levels representative of the transition between the regional sandstone aquifer to the north and east of the quarry and the marble aquifer beneath the quarry. These levels vary over a 300-ft range, are fairly erratic, and only sometimes correlate to each other and the precipitation record.

Generalized upper and lower groundwater surfaces may be conceptualized. The upper surface reflects surficial recharge into the Santa Margarita Sandstone and the lower surface reflects deep conduit flow from stream swallow holes. Each surface represents multiple although roughly equivalent zones. In reality, these surfaces may be discontinuous with intermediate surfaces between them.

The shallow groundwater surface descends gradually from the Bonny Doon area north of the quarry, then 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. 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 and generalizes separate karst conduits connecting stream swallow holes to the quarry area and Liddell and Plant springs. This surface has a southwest sloping gradient indicative of the marble aquifer's anisotropy relative to the southward regional gradient.

Water Quality

Nitrate

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. A turkey ranch operated immediately north of the quarry from about 1950 to the mid-1970's. Orchards that may be fertilized also occur north of the quarry.

Nitrate concentrations in quarry monitoring wells have 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. 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. 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.

Nitrate concentrations in the City's diversions from Liddell Spring were less than 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. The nitrate concentrations of the City's Laguna and Majors creek diversions have not experienced major trends or spikes since 1972.

The spring's nitrate concentration probably derives from a combination of sources, including ANFO, agriculture, and septic systems.

Turbidity and Sediment

Unlike other aquifers, karst groundwater systems have the capacity to transport considerable 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.

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.

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.

Various accounts described the incidence of elevated turbidity and sediment in Liddell Spring prior to quarrying. Mineralogical analysis of suspended sediment samples collected from Liddell Spring does not point to a single source and suggests that none of the local geologic formations can be ruled out as potential sources.

During the early 1970's the turbidity of Liddell Spring diversions commonly ranged from 1 to 100 NTU and peaked upwards to 500 NTU. Observers documented a strong correlation between the start of quarry operations and the ensuing years of increased spring sedimentation and turbidity. From about 1980 through the mid-1990's, the turbidity of Liddell Spring diversions mostly ranged between about 0.05 and 10 NTU. 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, this recent trend may reflect the City's ability to accept and handle more turbid water since 1994.

The relatively continuous Liddell Spring turbidity record since 1997 includes spring flows 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. Mean daily turbidity correlates poorly with mean daily flow. Turbidities greater than 10 NTU have occurred on days with mean daily flows anywhere between 900 and 3,000 gpm. The highest recorded turbidities have not occurred at the highest flows, but instead are most associated with flows between 900 and 2,000 gpm. The poor correlation between Liddell Spring peak flows and peak turbidities suggests that peak turbidities tend to occur early during the spring's stormflow hydrograph.

Applying correlations between turbidity and suspended sediment for coastal California streams and assuming reasonable sediment densities, we demonstrate that roughly a few cubic feet of sediment per day can account for the spring's observed turbidity.

Groundwater Movement and Sediment Transport

Springflow Response to Precipitation

We analyzed 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. WY 2004 was the fourth in a series of generally dry years whereas WY 2005 had above average precipitation. The analyzed storms represent a wide range of antecedent moisture and precipitation conditions. As with previous observations, the various spring-response times ranged widely. However, 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

Following peak precipitation, Liddell Spring turbidity peaked nearly as quickly as Major Creek discharge. Among all the responses evaluated, the timing of precipitation, peak stream discharge, 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.

Whereas plots of Liddell Spring turbidity and Majors Creek discharge had similar relatively steep rising and falling limbs, Liddell Spring discharge and specific conductance had more gradual rising and falling limbs. This suggests that elevated turbidity is most related to runoff processes whereas elevated specific conductance is related more to groundwater pressure and flow.

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 spring discharge and turbidity peaks would be expected if turbidity were caused primarily by groundwater moving sediment through the saturated marble aquifer. Instead, runoff-related processes appear significantly 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.

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.

Water levels in the monitored quarry pond peaked similarly to Majors Creek discharge, indicating 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 the quarry area. 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. These results strongly suggest that runoff infiltration through the quarry floor has a direct effect on Liddell Spring turbidity.

Conceptual Groundwater Model

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. 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. A third major source of water to Liddell Spring is precipitation and runoff capture by the quarry and its contributing closed drainage.

The recent tracer tests were only successful at demonstrating the stream capture sources. However, the apparent pattern of tracer movement was consistent with the two-source model. 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.

Several previous investigators concluded that Liddell Spring has one or more nearby sources with some connection to the ground surface. 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.

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.

The timing of Liddell Spring's various responses to storm events range from hours to days following the beginning of precipitation. The earliest turbidity responses noted by this and previous studies generally range between 2 and 10 hrs, and average about 5 to 7 hrs. 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. The tracer travel time to Liddell Spring from the quarry was 7 hrs, and this was during a several-year period of average to below average precipitation. The timing and character of Liddell Spring's turbidity response is similar to quarry-floor pond levels and Majors Creek discharge, and dissimilar to peak spring discharge.

Several lines of evidence show that sediment is being introduced into the groundwater system and/or entrained into the groundwater flow as a result of runoff-related processes independent of the spring's primary sources of groundwater recharge: turbidity peaks do not correlate with peak spring discharge; the timing of turbidity peaks is too early to be a result of turbid stream water reaching Liddell Spring from the Reggiardo or Laguna Creek swallow holes; turbidity peaks are nearly coincident with peak local runoff. If the turbidity observed at Liddell Spring was simply a result of increased flow velocities entraining sediment within the karst system, more continuous, pulsed, and/or random transport would occur up to the point of peak spring discharge.

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 fracture zones and consist of interconnected voids formed by dissolution of the marble bedrock. It is reasonable to infer that such conduits formed continuously while the area has undergone 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.

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. 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. 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.

Interconnected voids above the permanent zone of saturation are available for the capture and transport of runoff from locations other than the major stream swallow holes. 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. 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. 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, the storm hydrographs for Majors Creek, and a monitored quarry-floor pond.

A reasonably good correlation between turbidity and the rate of springflow would be expected if turbidity were simply a function of the spring's hydraulic power. However, the correlation between turbidity and Liddell Spring's rate of discharge is poor. Also, the timing of turbidity and springflow peaks are distinctly different, with the turbidity peak typically occurring considerably earlier.

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 cascaded into swallow holes along Reggiardo and Laguna creeks and entrained sediment that could then 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 springflow) suggest that one or more primary sources of turbidity are related to runoff capture locally upgradient of the spring. The quarry is clearly a candidate for one of these sources.

Groundwater Response to Quarrying

Bonny Doon Quarry is a major activity within the groundwater system contributing to Liddell Spring. Some quarry operations occur as near as 500 ft from 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 from the same body of rock that forms the Liddell Spring aquifer. Assuming a porosity of 5 percent, 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.

Our analysis does not indicate any significant 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 inferred 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. Substantial volumes of runoff percolate into the quarry pit without evidence of discharge other than to Liddell and possibly Plant 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.

The removal of overburden from the quarry area began in 1969 and actual mining began in August 1970. Accounts from 1969-74 link documented instances of Liddell Spring sedimentation and elevated turbidity with the removal of overburden, the initiation of quarrying, and above-average precipitation. For the most part, these early quarry activities were separated from the underlying groundwater by several hundred feet of as-yet unquarried marble. Thus, it must be concluded that there was good hydrogeologic connectivity between quarry operations and Liddell Spring at that time. 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 instances of overburden removal have been relatively minor compared to the initial clearing of the quarry site.

Because the total springflow of Liddell Spring was not gaged regularly prior to 1997, the available data do not allow a definitive assessment of whether or not quarrying has affected spring yield. Our analysis does not show historical shifts in production other than what can be explained by climatic cycles. Quarrying may have exposed several springs over the years that did not become permanent or substantially affect Liddell Spring. The unsaturated void space of marble now quarried 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.

Nitrate concentrations in diversions from Laguna and Majors creeks have been relatively stable, whereas the nitrate concentrations of Liddell Spring diversions have been more erratic with some upward trend. Liddell Spring derives a substantial portion of its yield by capturing streamflow from these creeks. Therefore, the spring's other sources of recharge must be responsible for its elevated nitrate concentrations. Blasting with ANFO represents one likely source. Other sources appear to be at least as important, however, given the occurrence of elevated nitrate concentrations in monitoring wells both up and down gradient of the quarry.

Most previous investigators have acknowledged that some increase in turbidity occurs as a result of blast events. These responses are highly varied, however, similar to Liddell Spring's range of responses to storm events. We evaluated 22 blast events during 2004-05. 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. Although weather conditions varied considerably among these events, we infer that most of these turbidity peaks were blast related. 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. More importantly, 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.

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 was demonstrated by the 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. 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 initial and primary turbidity peak following peak storm precipitation is generally consistent with the observed time for tracers to reach the spring from groundwater beneath the quarry and the turbidity response to blasting in the quarry. The timing of the main turbidity peaks appear too slow for sources immediately adjacent to the spring (e.g., the landslide or nearby sinkholes) and too fast for transport from the Reggiardo and Laguna creek swallow holes. 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.

The consistent rise and decline of spring turbidity, quarry-floor pond depth, and nearby stream discharge prior to peak Liddell Spring discharge indicates that sediment is introduced, or at least entrained, by runoff-related processes affecting groundwater in the quarry area. 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 strongly indicate that the quarry operation has an important contributing influence on spring turbidity.

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. A cause-and-effect relationship between quarrying and subsequent sedimentation events is less certain. 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 overburden removal, direct evidence attributing subsequent sedimentation with quarry activities is generally incomplete or lacking.

CONCLUSIONS

We draw the following conclusions regarding potential geologic impacts of the proposed expansion of the mining area:

- Very strong seismic shaking may occur during the project lifetime. Seismic shaking could damage buildings and other structures associated with the quarry operation, and could induce landsliding or other types of ground failure. The existing level of hazard due to seismic shaking is not expected to increase due to the quarry expansion.
- The principal seismically induced ground failure hazards that are likely to affect the quarry area are co-seismic ground cracking along crests of quarry slopes, seismically induced landsliding, rock falls and rock topples along the quarry faces. It is possible that liquefaction or differential settlement during an earthquake could impact the embankment dams that retain the settlement ponds, releasing sediment laden water into local stream drainages, a potentially significant impact.

- Landsliding within the quarry, whether due to ground saturation or seismic shaking, is possible and could threaten quarry workers during the quarry operation or damage land adjacent to the quarry after the end of active quarrying, increasing the risk of erosion. There is a small possibility that a large slope failure on north slope of the quarry could impact the transition zone from shallow groundwater to deep groundwater in the karst aquifer, potentially affecting water quantity and quality and Liddell Spring. The incremental increase in landslide potential resulting from enlargement of the quarry is balanced by the proposed placement of spoils within the quarry, which will help buttress portions of the quarry against landsliding.
- The proposed quarry expansion has the potential to cause erosion, resulting in turbidity at Liddell Spring and sedimentation of downstream waters. Unless mitigated, the proposed quarry expansion may result in significant impacts.

Conclusions regarding potential hydrologic impacts include:

- Existing runoff and sediment retention basins have been deemed adequate to handle the proposed quarry expansion. The proposed drainage plan for the amendment area initially routes runoff to the quarry pit, but runoff will be re-directed to sediment retention basin #3 at some point during the mining of the amendment area. Until the runoff is redirected to the retention basin, runoff and sediment collected in the quarry pit will mostly migrate to groundwater and contribute to Liddell Spring flow and turbidity. When runoff is redirected to retention basin #3, groundwater recharge quantities flowing to Liddell Spring may decrease, but the quarry's potential contribution to turbidity at Liddell Spring will also decrease. The impacts on Liddell Spring turbidity and flow quantities are considered potentially significant.
- Runoff and sediment collected in the quarry pit migrates to groundwater and contributes to Liddell Spring flow and turbidity. We estimate that roughly half of Liddell Spring's turbidity is directly or indirectly attributable to quarry operations. This contribution will continue as a result of mining in the amendment area, a potentially significant impact.

We draw the following conclusions regarding the response of groundwater and springflow to quarry operations and potential impacts of the proposed quarry expansion:

- Substantial interconnectivity exists between precipitation, runoff, and sediment collected in the quarry, groundwater flow, and Liddell Spring discharge and turbidity, based on the following observations:
  - Overburden removal prior to the inception of mining at the quarry resulted in elevated turbidity at Liddell Spring
  - The removal of overburden and mining reduces recharge filtering and exposes fractures and dissolution channels that interconnect with groundwater. These have the potential to transport water and sediment from the quarry in a turbulent and cascading flow down to the zone of saturation and laterally toward Liddell Spring, resulting in spring turbidity.

- Observed quarry ponding and estimates of overall quarry recharge indicate that the quarry represents a considerable contribution to the groundwater system and Liddell Spring discharge during storm events relative to other sources.
- The timing and nature of Liddell Spring's turbidity response to precipitation, relative to (a) the timing of runoff collected in the bottom of the quarry and (b) 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, contribute substantially to turbidity at the spring. Springbox sedimentation likely resulted from the quarry's initial overburden removal.
- 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.
- Quarry blasting appears to mobilize and possibly generate subsurface sources of sediment that contribute to spring turbidity, both as an immediate response to blasting and potentially during subsequent storm events.

Based on these observations, we conclude that the proposed quarry expansion could have a significant impact on turbidity at Liddell Spring. This impact, in turn, has the potential to impact the City of Santa Cruz's water supply. These impacts include: reduced production and increased operational costs as a result of halting diversions during periods of elevated turbidity and springbox sedimentation; increased reliance on other sources of water at such times, including the use of water intended for drought use; operational costs and lost production from purging pipelines and treating more highly turbid water at the Graham Hill treatment plant; and increased exposure to surface contamination in the event that groundwater temporarily surfaces in mined areas. The City has not provided estimates of potential production or cost impacts associated with elevated turbidity.

- 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 substantial upward trends. The potential impact of the mining amendment on nitrate concentrations at Liddell Spring is considered to be less than significant.
- There has been no apparent decline in the quantity of Liddell Spring discharge as a result of quarrying.
- Historic groundwater levels are at or above the proposed depth of mining along the northern side of the amendment area. There is some potential for mining to intercept groundwater flowing to Liddell Spring. Intercepted groundwater will percolate back into the Karst aquifer under the present drainage conditions and will therefore have little impact on flow quantities at Liddell Spring. When drainage of the quarry to Sediment Basin 3 is established, surfacing groundwater may be conducted out of the recharge area for Liddell Spring, potentially reducing flow at the spring, a potentially significant impact. Surfacing of groundwater flow

in the quarry could result in an increased potential for contamination of water flowing to Liddell Spring.

- The final drainage plan for the quarry requires lowering of the ingress/egress ramp on the south side of the quarry by about 50 feet. This lowering will require blasting of rock immediately upstream from Liddell Spring, which will likely result in an increase in turbidity at the spring. This impact is potentially significant.