# Groundwater Assessment of Alternative Conjunctive Use Scenarios

# Technical Memorandum 2: Hydrogeologic Conceptual Model

**Prepared for**

**Soquel Creek Water District**
**Soquel, California**

**Prepared by**


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September 22, 2004

Ms. Laura Brown, General Manager
Soquel Creek Water District
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Subject: *Hydrogeologic Conceptual Model, Technical Memorandum 2, Groundwater Assessment of Alternative Conjunctive Use Scenarios*

Dear Ms. Brown:

We are pleased to present to you and the Soquel Creek Water District Board of Directors our completed Hydrogeologic Conceptual Model report for use in the District's Groundwater Assessment of Alternative Conjunctive Use Scenarios. This report is the culmination of a nearly year-long effort to compile and interpret several decades of studies and data on the Soquel-Aptos groundwater basin.

With this report, we have developed and thoroughly documented a comprehensive interpretation of the groundwater system. Our key findings address the risk of saltwater intrusion, the potential effects of groundwater pumping on stream baseflow, and the sustainable yield of the District's groundwater supply. Based on these key findings, we provide initial responses to seven sets of questions posed by the Board in May 2004 regarding conjunctive use, restoration of the groundwater basin, and fulfilling CEQA requirements.

This report provides a sound foundation for the District's ongoing and subsequent phases of implementing conjunctive use, including preparing a programmatic EIR; developing a groundwater management model (e.g., modification of its IGSM); establishing and achieving target groundwater levels; refining estimates of groundwater yield and the need for supplemental water; and logistical planning related to selected alternative(s).

We look forward to presenting the report at the October 19, 2004 Board of Directors meeting, responding to the Board's questions and comments, and providing our recommendations for advancing the conjunctive use program in its subsequent phases of implementation.

Once again, we would like to thank the District for our involvement in this challenging and rewarding project. We look forward to the opportunity to contribute further toward the management and conjunctive use of the District's groundwater resources, building on the significant investment in understanding represented by the Hydrogeologic Conceptual Model.

Sincerely,

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## Abbreviations, Symbols, and Acronyms

| | |
|---|---|
| AA to F | stratigraphic units of Purisima Formation |
| ac-ft/yr | acre-feet per year |
| *b* and *b'* | aquifer and aquitard thickness (ft) |
| *B* | leakage factor (Hantush-Jacob solution, 1/ft) |
| β | leakage factor (Hantush method, ft) and delayed drainage coefficient (Neuman method, dimensionless) |
| bgs | below ground surface (ft) |
| BMP | Basin Management Plan |
| cfs | cubic feet per second ($ft^3$/sec) |
| CIMIS | California Irrigation Management Information System |
| CWD | Central Water District |
| CY | calendar year (Jan-Dec) |
| *dz*/*d*l | vertical hydraulic gradient |
| DWSAP | Drinking Water Source Assessment and Protection program |
| EIR | environmental impact report |
| ET | evapotranspiration |
| ETo | reference evapotranspiration |
| FCWCD | Flood Control and Water Conservation District |
| ft msl | elevation in feet relative to mean sea level |
| gpm | gallons per minute |
| GSE | ground surface elevation (ft msl) |
| GW | groundwater |
| *i* | horizontal hydraulic gradient (also, *d*h/*d*/l) |
| IGSM | Integrated Ground and Surface Water Model |
| in/yr | inches per year |
| *K* and *K'* | aquifer and aquitard hydraulic conductivity (horizontal unless otherwise specified) (ft/day) |

## Abbreviations, Symbols, and Acronyms (continued)

| | |
|---|---|
| $K_H$ and $K_V$ | horizontal and vertical hydraulic conductivity (ft/day) |
| LKA | Linsley, Kraeger & Associates |
| LSCE | Luhdorff & Scalmanini Consulting Engineers |
| mgd | million gallons per day |
| M-W | Montgomery Watson (consultants) |
| PVWMA | Pajaro Valley Water Management Agency |
| Qa | geologic map symbol for the Aromas Sands formation |
| Qa-$_{U}$, Qa-$_{L}$ | Aromas Sands upper and lower units |
| $Q_b$ | baseflow |
| $Q_p$ | pumping rate of well (gpm) |
| $Q_s$ | stormflow |
| $Q_t$ | total streamflow |
| $r$ | distance from pumping well (ft) |
| $r_p$ | distance from pumping well beyond which partial penetration effect is negligible (ft) |
| RFP | request for proposals |
| $\Delta S$ | change in storage |
| $S$ and $S'$ | aquifer and aquitard storativity (dimensionless) |
| $s$ | drawdown (or "displacement") (ft) |
| $S_c$ | specific capacity (gpm/ft) |
| $S_s$ | specific storage (1/ft) |
| $S_y$ | aquifer specific yield (dimensionless) |
| SC-# | prefix to SCWD monitoring well number |
| SCWD | Soquel Creek Water District |
| SSPA | S.S. Papadopulos & Associates |
| $T$ | aquifer transmissivity (ft$^2$/day) |
| $t$ | time since pumping began (min) |
| $t'$ | time since pumping stopped (min) |
| $t^*$ | time since pumping began after which a semilogarithmic solution is valid ($u$<0.05) (min) |
| $t_d$ | time since pumping began after which effect of delayed gravity drainage is negligible (min) |
| Tp | geologic map symbol for Purisima Formation |
| Tp? | possible interval of Purisima Formation below unit AA |
| Tu | geologic symbol for undifferentiated Tertiary sandstone older than Purisima Formation |
| $u$ | argument of well function $W(u)$; $u = (r^2 \times S \times 1{,}440)/(4 \times T \times t)$ |
| USGS | United States Geological Survey |
| WY | water year (e.g., WY 2004 extends from October 1, 2003 to September 30, 2004) |

## Conversion Factors

1 cfs = 449 gpm = 724 ac-ft/yr
1 gpm = 1.61 ac-ft/yr
1 gpd/ft = 7.48 ft$^2$/day (units of transmissivity)

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# Groundwater Assessment of Alternative Conjunctive Use Scenarios
# Soquel Creek Water District

## Technical Memorandum 2
## Hydrogeologic Conceptual Model

## Executive Summary

This report presents a hydrogeologic conceptual model of the Soquel-Aptos groundwater basin. The conceptual model is a comprehensive synthesis of available information and knowledge relevant to understanding the groundwater flow system; evaluating the potential for saltwater intrusion and diminished stream baseflow; supporting the decisions needed to implement conjunctive use; and providing a foundation for subsequent analysis.

There has been considerable uncertainty regarding the fundamental nature of the Soquel-Aptos groundwater system and related groundwater issues. This report's comprehensive hydrogeologic assessment serves as the basis for defining these issues and supporting the analyses needed to address them. As such, this effort has evolved into a primary goal of this current phase the Soquel-Aptos groundwater basin assessment.

The conceptual model includes the following elements:

- Hydrogeologic framework of aquifer and aquitard units (Section 2)
- Aquifer and aquitard properties (Section 3)
- Groundwater occurrence, movement, and storage as interpreted from water level, water quality, and pumping data (Section 4)
- Groundwater budget (Section 5)
- Potential for saltwater intrusion (Section 6)
- Stream-aquifer interactions (Section 7)
- Recommendations regarding conjunctive use, data needs, and additional analysis (Section 8)

The report supports Soquel Creek Water District's (SCWD) proposed development of a supplemental water supply to be used conjunctively with its existing groundwater resource. Ongoing saltwater intrusion currently threatens several of its Aromas-area wells, and a significant potential exists for eventual intrusion near its Purisima wells. A supplemental water supply is needed to allow reductions in pumping and reestablish the hydraulic gradients needed to prevent additional intrusion. This executive summary concludes with a direct response to seven sets of questions posed at the May 4, 2004 SCWD Board meeting.

***Saltwater Intrusion*** – In SCWD's Aromas area, the saltwater interface has been moving onshore since monitoring began in the mid-1980s. The hydraulic gradient between SCWD's southern-most production wells and the coast is not sufficient to halt further inland movement. This is consistent with an apparent deficit in the local groundwater budget. The responses of water levels and chloride concentrations to changes in pumping indicate that intrusion can be impeded by local reductions in groundwater production. Although implementation of PVWMA's Basin Management Plan (BMP) was expected to provide a regional solution to overdraft and saltwater intrusion, it appears that SCWD faces a threat of lost groundwater production before such measures become effective. Furthermore, a local component of overdraft likely exists that the Pajaro Valley BMP may not resolve. For these reasons, SCWD must reduce production from its Aromas-area wells, especially to the southeast.

Monitoring near SCWD's Purisima wells does not show definitive signs of active saltwater intrusion. However, earlier intrusion into shallow zones is well documented and subtle indications exist of possible saltwater leakage to deeper zones. The persistence of deep-aquifer groundwater levels at or below sea level along the coast represents a significant potential for eventual saltwater intrusion. Once saltwater is detected, efforts to remediate the aquifer will be slow. A supplemental water supply is needed to reduce pumping and restore the hydraulic gradients necessary to prevent saltwater intrusion into the Purisima aquifer.

***Stream-Aquifer Interactions*** – Aquifer tests and monitored hydraulic gradients show that downward leakage occurs from shallow aquifers and streams to deep aquifers pumped by SCWD. Thus, pumping from deep wells decreases groundwater contributions to the baseflow of Soquel Creek and other area streams. However, the hydraulic connection between these streams and deep Purisima aquifers is sufficiently slow and diffuse that pumping has a small and attenuated effect on baseflow. Moreover, this effect is masked by a number of other factors that collectively have a greater impact on baseflow. As such, this and previous studies have not established a direct depletion of baseflow by groundwater pumping. We estimate that chronic baseflow depletions as small as 0.5 cubic feet per second (cfs) could be detected, and that historical baseflow depletions at the Main Street gage have been below this threshold. If groundwater production from inland wells (either existing or new) near Soquel Creek and/or other streams were to increase, such thresholds could be exceeded.

***Beltz Wells*** – During critical drought years occurring on average once every 25 years, the City of Santa Cruz plans to produce as much as 2 million gallons per day (mgd) for as many as 200 days per year from it Beltz wells. This amounts to about 1,200 acre-feet per year (ac-ft/yr), about equal to historical maximum annual production from the Beltz wells.

Saltwater entering the aquifer as a result of Beltz pumping could eventually migrate toward SCWD production wells. The Beltz wells would probably be impacted first, in which case curtailed Beltz production would probably prevent the further saltwater movement into the Purisima aquifer near Pleasure Point. The recent installation of additional monitoring wells by the City of Santa Cruz allows for improved management of coastal groundwater levels and early detection of saltwater intrusion.

SCWD and the City of Santa Cruz operate municipal wells in the same subarea of the Soquel-Aptos groundwater basin. As such, they together impact the overall water budget and could collectively exceed the local sustainable yield. Some collaborative institutional mechanism is needed to operate the basin for optimal yield and minimal impact.

***Groundwater Yield*** **–** Using a simple mass balance approach, our estimates of groundwater recharge and consumptive use for the Purisima area leave an estimated 400 ac-ft/yr of net groundwater discharge to the ocean, which probably occurs at shallow depths. However, the persistence of deep-aquifer groundwater levels at or below sea level along the coast represents a significant potential for saltwater intrusion. Thus, our representative estimate of total groundwater production (6,700 ac-ft/yr) probably exceeds the sustainable yield of the Purisima area. It follows that SCWD's share of this production (up to nearly 3,800 ac-ft/yr) is not fully sustainable.

In the Aromas area, we estimate that total groundwater production (about 3,600 ac-ft/yr) exceeds the sustainable yield given that saltwater intrusion is actively occurring and apparently necessary to balance the groundwater budget. It follows that SCWD's share of this production (up to 2,200 ac-ft/yr) is not fully sustainable.

Based on a simple mass balance approach and rough estimates of the pumping reductions needed to restore hydraulic gradients, reasonable estimates of SCWD's sustainable production do not exceed 3,000 ac-ft/yr for the Purisima area or 1,800 ac-ft/yr for the Aromas area, and maybe somewhat less. Because SCWD lacks the authority to control groundwater pumping by others, its portion of the estimated sustainable yield could be negatively impacted by the increased production of others. Additional analysis based on the technical foundation provided by this report is needed to improve these estimates. The experience gained from restoring groundwater levels and monitoring intrusion will provide the ultimate indication of sustainable yield.

***Need for Supplemental Water*** – Assuming a current total SCWD demand of 5,500 ac-ft/yr, our preliminary rough estimate of the pumping reductions needed to prevent saltwater intrusion is about half of the planned 2,000 ac-ft/yr supplemental supply, split almost evenly between the Purisima and Aromas areas. We also support the redistribution of some Aromas pumping as currently being considered by SCWD, such as to the presently inactive Aptos Jr. High School well. If coastal groundwater levels do not rise to satisfactory levels, or if other pumpers increase their production, larger pumping reductions and greater amounts of supplemental water may be required. Before demands increase significantly in the future, a margin of safety is provided by the remaining supplemental supply and the anticipated water savings from planned conservation measures.

***Groundwater-Level Objectives*** – Preliminary groundwater-level objectives are needed for all coastal monitoring wells. These can then be modified over time based on additional analysis and experience. Establishing such targets may be relatively straightforward in the Aromas area given documented relations between water levels, pumping, and evidence of intrusion. This also may be the case for shallow portions of the Purisima Formation with evidence of past intrusion. Establishing groundwater-level objectives for deeper portions of the Purisima Formation is more difficult because of the strong anisotropy of the layered aquifers, uncertain and/or weak evidence of past or ongoing intrusion, and the unknown configuration of the freshwater-saltwater interface. Modeling may be needed to refine these goals, including estimating the length of time that groundwater levels may fluctuate below target levels without causing significant risk of water-quality degradation at pumping wells due to saltwater intrusion (e.g., during interruptions in the supplemental supply).

***Restoring the Groundwater Resource*** – Initial pumping reductions could be increased to more quickly restore the hydraulic gradients needed to prevent saltwater intrusion. Approximately half of the planned 2,000 ac-ft/yr supplemental supply may be available for this purpose. Because the supplemental supply will have a significantly greater cost than the groundwater production it replaces, decisions regarding initial pumping reductions will require careful and considered analysis. This management approach will undoubtedly involve an element of trial-and-error.

To push the interface offshore as quickly as it migrated onshore requires an equal but opposite hydraulic gradient. However, there are limits on how high water levels can be raised. Also, offshore storage will increase more slowly than the rate of supplemental water use because of increased groundwater discharge to the ocean. Furthermore, pushing back the interface is affected by the slow reversal of cation-exchange processes. Thus, agressively pushing the interface offshore may be infeasible or require prohibitive amounts of supplemental water. This further justifies the need to arrest further onshore movement soon.

Saltwater intrusion in SCWD's southern Aromas area is part of an ongoing regional problem that extends into Pajaro Valley. Degradation of SCWD's southeastern-most wells may not be prevented by the eventual implementation of PVWMA's BMP and SCWD's plans for conjunctive use. SCWD may need to consider additional, more immediate measures, whether on its own or in cooperation with PVWMA, such as facilitating the reduction of other pumping in the Aromas area and adjacent portions of Pajaro Valley.

***In-Lieu Recharge and Groundwater Storage*** – Reduced pumping may not translate directly into groundwater saved for later use because of increased discharge to the ocean and reductions in induced leakage into confined and semi-confined zones. Shallow groundwater may instead migrate toward other points of discharge such as streams and the ocean. Onshore groundwater storage may be a more important factor for conjunctive use in the Aromas area, where unconfined zones are thicker and more widespread. Additional inland monitoring wells and groundwater modeling could help evaluate this potential.

Over the long term, use of supplemental water at the rate needed to achieve groundwater-level objectives will gradually push the freshwater-saltwater interface further offshore and increase the offshore storage available for drought use. Because the current position of the interface is unknown except in the southern Aromas area, reliance on offshore storage may be risky in the near term.

***Interruptible Supplemental Supplies*** – Both regional options being considered are subject to interruptions in the supply of supplemental water available for conjunctive use. Because the developed aquifers respond little to climatic fluctuations, the effect of such interruptions may not be much worse during droughts. Nevertheless, the developed aquifers exhibit limited onshore storage capacities and the storage remaining offshore is unknown. SCWD could increase its use of supplemental water prior to potential interruptions (e.g., the early phase of a drought) so that groundwater levels begin relatively high if and when more intensive pumping becomes necessary. However, only a portion of the unpumped groundwater may be effectively stored. As increased future demands claim larger portions of the supplemental supply, SCWD will lose some of its flexibility to reduce pumping in such instances.

***Enhanced Recharge*** – Enhanced groundwater recharge does not constitute conjunctive use because it would not provide SCWD with the flexibility to adjust pumping when and where needed to achieve groundwater-level objectives. Nevertheless, the protection and enhancement of groundwater recharge may be useful elements of responsible groundwater basin management.

Efforts to enhance recharge may successfully augment shallow groundwater supplies, but may have a limited effect on deep water levels, which are mainly controlled by pumping. As such, it is an unlikely means of preventing saltwater intrusion in the Purisima area, but may have greater merit in the less confined shallow zones of the Aromas area. Additional studies and modeling are needed to evaluate the relative benefits of targeting recharge over particular outcrop areas.

***Groundwater Injection*** – Groundwater injection has the advantage of introducing water directly into aquifer zones where it is most needed to restore groundwater levels. Water-level responses from injection are quick and predictable. As currently proposed, the direct use of a supplemental water supply and the associated reductions in groundwater production will probably provide sufficient means for attaining water-level objectives. However, at some time in the future the ability to selectively inject supplemental water may provide a valuable added tool for managing groundwater levels and preventing saltwater intrusion. Reasonable application of injection technology for this purpose would be considerably less ambitious than the former proposal to inject up to 5,000 gallons per minute (gpm) of diverted Soquel Creek streamflow.

***Implications for Environmental Assessment*** – This report and its referenced data provide the hydrologic understanding and base of information needed for a programmatic EIR of SCWD's plans for conjunctive use. One major yet unavoidable gap in our understanding is the uncertain location of the saltwater interface offshore of the Purisima area. Also, the effects of groundwater pumping on surface water are difficult to quantify. This limitation is not critical to the EIR objectives, however, because conjunctive use will decrease, not increase, pumping, and does not in and of itself involve the redistribution of pumping to new locations.

Given some uncertainty regarding sustainable yield and possible interruptions in supplemental supply, a use-curtailment mitigation measure may be needed in the event that groundwater levels decline and persist at problematic levels (e.g., as a result of increased groundwater pumping by others, severe drought, or the unknown and unprecedented consequences of climatic change).

Project-specific EIRs and ongoing groundwater management may require development of a suitable groundwater model.

***Additional Data Needs*** – The report describes a number of potential data needs that came to light during the course of this study. These include aquifer tests, spinner logs, groundwater age dating, baseflow surveys, and additional monitoring wells, as described in Section 8.5.3.

***Additional Analysis and Modeling*** – Continued expert analysis and the development of one or more analytical tools are needed to further assess the conditions under which saltwater intrusion is likely to occur along the Soquel-Aptos coast. Additional analysis is needed to establish the groundwater-level objectives needed to prevent intrusion, the pumping reductions needed to achieve these levels, and the corresponding sustainable yields of the basin subareas.

The complexity of the groundwater system hinders the consideration of the multiple factors involved. One approach is to subdivide the coastline into a number of segments, one for each coastal monitoring well. The salient features of each segment can be generalized by a local conceptual model, which in turn can support the development of a relatively simple numerical model for each segment. These models can then be used to provide improved estimates of the groundwater-level goals for each segment of coastline. Alternatively, a calibrated numerical model of the entire Soquel-Aptos basin, or possibly separate models for the Purisima and Aromas areas, has the advantage of full three-dimensional representation of the aquifer system, the groundwater mass balance, the influence of head-dependent boundaries, and the spatial and temporal variations of hydraulic stresses.

SCWD is currently updating the numerical code of its IGSM model. In addition to updating the model files, the assumptions underlying the IGSM model need to be evaluated relative to this conceptual model. Also, the capabilities of the model should be assessed relative to SCWD's modeling needs. That evaluation may conclude that further modifications of the model are warranted. Alternatively, there may be some efficiency in developing a new model on the basis of this conceptual model and the experience gained from the IGSM.

Potential uses for a calibrated model include predicting water level responses to pumping, assessing the risks of saltwater intrusion, and evaluating sustainable yield; estimating the length of time that groundwater levels may fluctuate below target levels without adverse consequences; evaluating potential groundwater impacts from the planned use of the Beltz wells; guiding the preparation of groundwater-level contour maps; evaluating the source of groundwater pumped from wells and the fate of groundwater recharge; optimizing the locations of new wells and the distribution of pumping from all wells; and, providing the analyses needed for project-specific EIRs.

***Response to Questions Posed at the May 4, 2004 SCWD Board Meeting*** – The executive summary concludes with direct responses to seven sets of questions posed at the May 4, 2004 SCWD Board meeting and provided to us in writing by the District manager. These responses are based on the contents of this report and thus are somewhat redundant with earlier portions of this executive summary and the conclusions presented Section 8.

1. *Is the developable yield estimate of 4,870 ac-ft/yr that was established for the Draft Integrated Resources Plan [Montgomery Watson, 1999b] still reasonable? If not, can an adjusted amount be developed using the conceptual model?*

The previously estimated "developable yield"[1] of 4,870 ac-ft/yr consists of 3,070 ac-ft/yr from the Purisima area (Service Areas I and II) and 1,800 ac-ft/yr from the Aromas area (Service Areas III and IV). The 3,070 ac-ft/yr value represents SCWD's portion of a previously estimated total sustainable yield for the Purisima area of 6,230 ac-ft/yr (Montgomery Watson, 1999a). Similarly, the 1,800 ac-ft/yr value represents SCWD's portion of an unspecified total Aromas area yield (SCWD, 1998). Inasmuch as SCWD has no control over groundwater production by others, its assumed portion of these estimated yields could be negatively impacted by others' increased production.

Using a simple mass balance approach, this report is unable to provide a firm estimate of groundwater yield. Highly approximate estimates are provided, and these can be improved in subsequent analyses that build on the information and interpretation provided by this report. Ideally, a calibrated groundwater flow model consistent with this conceptual model is needed to accurately account for head-dependent flows and spatial and temporal variability.

We assume that sustainable groundwater yield is limited by total recharge, maintaining baseflows, and avoiding the potential for saltwater intrusion. Given that impacts to baseflow from groundwater pumping have been essentially unmeasurable, our evaluation of sustainable yield under past and current conditions is based primarily on saltwater intrusion.

Based on our review of coastal groundwater levels, groundwater production, and saltwater intrusion indicators, we estimate SCWD's sustainable yields in contrast to its current average production of about 3,400 ac-ft/yr from the Purisima area and 2,100 ac-ft/yr from the Aromas Area. Our preliminary rough estimates of appropriate pumping reductions suggest that SCWD's sustainable production does not exceed 3,000 and 1,800 ac-ft/yr for the Purisima and Aromas areas, respectively, and is probably somewhat less. Although these estimated limits are consistent with the previous estimates of developable yield, we are concerned that they may be too high rather than too low given the level of uncertainty.

If coastal groundwater levels do not rise to satisfactory levels, or if other pumpers increase their production, greater reductions may be necessary. Also, it may be possible to enhance existing yields through further redistribution of pumping. Meanwhile, more detailed analysis and groundwater modeling may provide improved estimates of target groundwater levels, sustainable production levels, and necessary pumping reductions. The experience gained from restoring groundwater levels and monitoring intrusion indicators will provide the ultimate indication of sustainable yield.

2. *Can coastal groundwater level goals be established for different areas? If so, would these goals and the projected demand provide sufficient information from which to estimate annual use of the supplemental supply source? Could these goals then become an ongoing groundwater management tool for actual operation of the conjunctive use program?*

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[1] The qualifier "developable" is potentially misleading since the combined yield of existing, developed wells already exceeds this amount. Alternatively, we use the term "sustainable yield."

Consistent with estimated hydraulic gradients needed to prevent saltwater intrusion, SCWD needs to establish preliminary groundwater level objectives for all coastal monitoring wells, and then modify these over time based on new information and additional analysis. Relevant factors for estimating these groundwater level goals include aquifer depth, thickness, structure, and hydraulic properties; the degree of aquifer confinement; potential interactions among multiple aquifer and aquitard layers; distances from the coast and seafloor outcrops; proximity to production wells; relations among historical water levels, gradients, pumping, and saltwater-intrusion indicators; application of the Ghyben-Herzberg relation; estimated or known locations of the saltwater interface; and the results of groundwater modeling.

Establishing such targets may be relatively straightforward for the Aromas area given documented relations between water levels, pumping, and evidence of intrusion. This also may be the case for shallow portions of the Purisima Formation, such as where the Hillcrest and Seacliff wells once operated. Establishing groundwater level objectives for deeper portions of the Purisima Formation is more difficult because of the strong anisotropy of the layered aquifers and uncertain and/or weak evidence of past or ongoing intrusion. While preliminary objectives can be established, groundwater modeling may be needed to finalize these goals, including the allowable time that water levels may fluctuate below target levels (e.g., during supplemental supply interruptions).

Given these water level objectives and SCWD's water demand projections, relationships between pumping and groundwater levels are needed to help estimate the sustainable groundwater yield and the needed supply of supplemental water. Unfortunately, several factors obfuscate the recognition of empirical relations between pumping and water levels. First, there is a significant degree of data uncertainty due to noise, error, apparent inconsistencies, and spatially variable conditions. As such, apparent correlations between water levels and pumping may be more or less coincidental and/or locally unique and difficult to generalize. Second, data are sparse for early periods when the greatest changes in pumping occurred. Thus, the data record does not reflect the full range of stresses needed to reveal these relationships. Third, groundwater levels are influenced by the cumulative effects of both near and distant wells, and both recent and past pumping, so that the effect of changing one well's pumping is difficult to interpret. And fourth, groundwater levels are strongly influenced by head-dependent boundaries, and thus may change relatively little when pumping increases or decreases. A calibrated groundwater model can compensate for the latter two factors, and would thus provide a valuable tool for answering "what if" questions relating to the effects of increased or decreased pumping.

Through monitoring, experience, analysis, and refinement, it is reasonable to expect these groundwater level goals to provide an ongoing groundwater management tool for operating the conjuctive use program.

3. *Is 2,000 ac-ft/yr a reasonable available supply to balance the basin and meet projected demand? Would approximately 1,000 ac-ft/yr of supplemental supply from a conjunctive use program appear to be sufficient to restore groundwater basin balance in the near-term (first 10-15 years)?*

With expected conservation savings, SCWD projects a water demand of 6,080 ac-ft/yr by 2050 (see Figure 8-1). Assuming its sustainable groundwater yield is about 4,800 ac-ft/yr, a supplemental supply of nearly 1,300 ac-ft/yr will be needed by 2050. Thus, the planned supplemental supply of 2,000 ac-ft/yr appears adequate for meeting projected demand, with some margin of safety in the event that demand is greater, the sustainable groundwater yield is determined to be less, and/or a greater supplemental supply is needed at times to compensate for supply interruptions.

SCWD projects that meeting future water demand will require less than 1,000 ac-ft/yr of supplemental water until about 2040, again assuming conservation savings (Figure 8-1). Thus, a total supplemental supply of 2,000 ac-ft/yr will provide 1,000 ac-ft/yr or more in excess of growth needs that may be used to "restore the groundwater basin balance" during the near term.

The intention of the water-level objectives is to achieve the hydraulic gradients needed to prevent saltwater intrusion. At suitable pumping rates, water levels will gradually reach an equilibrium consistent with these goals. It may be desirable to implement larger initial reductions in pumpage to more quickly achieve these goals. For example, initially large pumping reductions may be appropriate in the Aromas area where an alarming rate of saltwater intrusion poses a serious threat to continued SCWD production. Initially large pumping reductions will provide a valuable verification of suitable cause-and-effect relations between pumping and desired water levels, as well as indicate opportunities for further modification of pumping rates. This management approach will undoubtedly involve an element of trial-and-error over some period of time.

Restoring the groundwater resource could include aggressively pushing the freshwater-saltwater interface back rather than simply preventing further onshore movement. To push the interface offshore as quickly as it migrated toward shore requires an equal but opposite hydraulic gradient. The feasibility of doing so varies as a function of how low water levels had been versus how high they can be raised relative to sea level. Groundwater levels influenced by pumping have the potential to be drawn down quite low, whereas there may be limits on how high water levels can be raised. Furthermore, offshore storage will increase more slowly than the rate of supplemental water use because of increased groundwater discharge to the ocean. The slow reversal of cation-exchange processes also delays pushing back the interface. Because the supplemental supply will have a significantly greater cost than the groundwater production it replaces, decisions regarding initial pumping reductions will require careful analysis and consideration.

Saltwater intrusion in SCWD's southern Aromas area is part of an ongoing regional problem that extends into Pajaro Valley. The eventual implementation of both PVWMA's BMP and SCWD's proposed plans for conjunctive use might be unable to prevent the near-term saltwater degradation of SCWD's southeastern-most wells. SCWD may need to consider additional, more immediate measures, whether on its own or in cooperation with PVWMA, such as facilitating the reduction of other pumping in the Aromas area and adjacent areas of Pajaro Valley.

4. *Do the conjunctive use options provide sufficient flexibility to reduce or expand the annual yield as needed to maintain desirable groundwater levels?*

As discussed in response to question 3 above, the planned 2,000 ac-ft/yr supplemental supply appears to have some margin of safety given water demand and conservations projections through 2050. Clearly, either the regional desalination plant or a Pajaro Valley groundwater transfer could be utilized less if indicated by favorable groundwater conditions. Use of the desalination plant has both infrastructure and institutional limitations (e.g., plant and pipeline capacity, City of Santa Cruz needs during critical drought periods). Potential hydrogeologic, infrastructure, and institutional limits may exist for groundwater transfers from Pajaro Valley, and these need to be evaluated further. Specifically, the capacity of the Pajaro Valley aquifer zones and wells expected to supply SCWD need to be evaluated, especially with regard to their operation during sustained droughts.

5. *Is there enough information to develop mitigation measures should the groundwater basin not respond as predicted or if there is a prolonged drought or other substantial climatic change?*

As discussed above, the planned 2,000 ac-ft/yr supplemental supply appears to provide some margin of safety given water demand and conservations projections through 2050. Thus, full use of the 2,000 ac-ft/yr for prevention of saltwater intrusion constitutes one potential mitigation measure. With anticipated conservation measures implemented during the next decade, and for all new development thereafter, future demand is not projected to exceed current demand until about 2030 (Figure 8-1). If at that time the planned supplemental supply is insufficient for the purpose of mitigating adverse environmental impacts associated with groundwater pumping, further growth could be curtailed until additional supplemental supplies are developed. Use-curtailment measures could be implemented in the worst-case event that the supplemental supply is inadequate to prevent adverse impacts.

The potential effects of climatic change are unprecedented and thus difficult to assess. In the event that a severe drought occurs after many years of supplemental water use, some replenishment of both onshore and offshore groundwater storage is expected to have occurred by then (e.g., pushing the saltwater interface seaward). This will allow a period of groundwater production in excess of the average sustainable yield if needed to compensate for diminished recharge and potential supplemental supply interruptions.

6. *Is there enough information to evaluate environmental impacts to ground and surface water sources?*

This report and its referenced data provide the hydrologic understanding and base of information needed for a programmatic EIR of SCWD's plans for conjunctive use. The documented historical conditions span several decades and include a variety of climatic and cultural conditions. One major yet unavoidable gap in our understanding is the uncertain location of the saltwater interface offshore of the Purisima area.

The effects of groundwater pumping on surface water are difficult to quantify because the combined effect of other factors has a collectively greater influence. This limitation is not critical, however, because the proposed conjunctive use will decrease, not increase, pumping, and does not in and of itself involve the redistribution of pumping to new locations.

7. *Do we know enough and have enough information and understanding for the EIR? Do we know enough and have enough information and understanding for the groundwater basin management program?*

Our existing information and understanding appears adequate for the planned programmatic EIR. For ongoing groundwater basin management, additional analysis is needed to establish groundwater level goals, reevaluate estimates of sustainable yield, and refine estimates of supplemental water needs. Development of a suitable groundwater model is desirable for these purposes and the analyses needed for project-specific EIRs.

# Groundwater Assessment of Alternative Conjunctive Use Scenarios
# Soquel Creek Water District

# Technical Memorandum 2
# Hydrogeologic Conceptual Model

# 1 Introduction

## 1.1 Background

In its July 2003 Request for Proposals (RFP) entitled *Groundwater Basin Assessment of Various Conjunctive Use Water Supply Scenarios*, Soquel Creek Water District (SCWD or District[2]) stated the following regarding its groundwater supplies and plans to implement conjunctive use:

- Since the late 1980s, groundwater levels have been below sea level at least seasonally in portions of the Purisima aquifer along the coast between Capitola and Aptos. This conflicts with the District's management goal of maintaining groundwater levels above sea level as much as possible to protect against the possibility of saltwater intrusion.
- Beginning in the early 1990s, there has been some apparent landward movement of the freshwater-saltwater interface within the Aromas aquifer, despite coastal groundwater levels consistently above sea level. This saltwater encroachment is attributed to depressed groundwater levels in the adjacent Pajaro Valley.
- None of SCWD's production wells has been impacted by saltwater intrusion. However, the following actions are intended to prevent future intrusion:
  - Develop a supplemental supply that will allow SCWD to reduce its current rate of production by 600 acre-feet per year (ac-ft/yr) and meet future water demands without further increases in groundwater production.
  - For the Aromas area, the Pajaro Valley Water Management Agency (PVWMA) is implementing a Basin Management Plan (BMP) to recover depressed coastal groundwater levels south of La Selva Beach.
- In conjunction with additional conservation measures and demand management strategies, the objectives of the planned supplemental supply include:
  - Allowing local groundwater levels to recover, counteracting the potential for seawater intrusion.
  - The conjunctive use of independent water sources during anticipated climatic cycles.
  - Up to 2,000 ac-ft/yr of increased supply, the amount needed to offset projected future shortfalls and the estimated 600 ac-ft/yr of current overdraft from the Purisima aquifer.
  - Managing other potential groundwater-use impacts at non-significant levels.
  - Providing for a sustainable, long-term water supply.
- Four supplemental water supply options have been identified, each with an intended yield approaching 2,000 ac-ft/yr:
  1. Shared development and use of a City of Santa Cruz desalination plant.

[2] This report uses "District" minimally to avoid confusion with the Central Water District. The acronym SCWD should not be confused with the City of Santa Cruz Water Department.

2. Shared development of a Watsonville wastewater reclamation plant in exchange for a supply of potable groundwater conveyed from Pajaro Valley.
3. Direct use of a Soquel Creek diversion and/or underground storage of diverted flows by groundwater injection.
4. Enhanced recharge of rainfall and runoff within existing SCWD groundwater recharge areas.[3]

The first two alternatives are regional in nature, whereas the latter two are local to the Soquel-Aptos groundwater basin.

The RFP stated that the purpose of the groundwater basin assessment was to evaluate and screen these alternatives, assist with the selection of one or more preferred alternatives, and support preparation of an environmental impact report (EIR). The RFP recognized that the alternatives evaluation would require some sort of analytical tool or tools. Inasmuch as the District's existing Integrated Ground and Surface Water Model (IGSM) required significant modification, the need for some type of alternative analytical tool(s) was anticipated. Later, the detailed analysis of one or more preferred alternatives could be conducted with the modified IGSM or a replacement model derived from any tools developed for the alternatives evaluation.

As the groundwater basin assessment began in November 2003, the study objectives were effectively broadened in light of the following:

- SCWD expressed uncertainty regarding the assumed sustainable yield of the Purisima aquifer. This in turn created uncertainty as to whether a supplemental supply of 2,000 ac-ft/yr might be too small or too large.
- The planned supplemental supply was intended to limit SCWD groundwater pumpage to 3,070 ac-ft/yr from the Purisima area and 1,800 ac-ft/yr from the Aromas area. However, SCWD expressed concern that it might be overlooking potential problems with the Aromas aquifer that would require additional action.
- For these reasons, the groundwater basin assessment was tasked, as part of its alternatives assessment, to evaluate the District's sustainable groundwater yield from both the Purisima and Aromas aquifers.
- The City of Santa Cruz Integrated Water Plan (2003) includes use of its Beltz wellfield in conjunction with its proposed desalination plant during drought periods. Because the Beltz wells draw from the Purisima aquifer just west of the SCWD service area, SCWD expressed concern that such use might exacerbate overdraft and necessitate a larger supplemental supply or other mitigation measures. Thus, the groundwater basin assessment was tasked with evaluating SCWD's groundwater situation in the context of the Santa Cruz's planned use of its Beltz wells.

Then, the following developments occurred during the course of this basin assessment:

- Studies for the Soquel Creek diversion alternative addressed the feasibility of groundwater injection (Williams, 2004) and potential yield limitations imposed by fish bypass flows

[3] The use of satellite wastewater reclamation plants was included as a possible component of this and/or other alternatives.

(Entrix, 2004). At its March 16, 2004 meeting, the SCWD Board of Directors voted to discontinue consideration of the diversion alternative.

- Projections of near-term water-supply shortfalls were reduced based on improved estimates of potential water savings from conservation.
- In an April 2004 memorandum to the SCWD General Manager, the groundwater assessment team's lead hydrogeologist concluded the following (Johnson, 2004b):
  - The proposed enhancement of groundwater recharge should not be considered as a conjunctive-use project. Such measures may introduce more water into the groundwater system and may enhance the long-term average yield of streams and wells. However, enhanced recharge would not provide SCWD with the flexibility to adjust pumping, when and where necessary, to achieve groundwater-level objectives.
  - In answer to the question, "Is a supplemental supply of the magnitude of one of the regional alternatives needed?", the answer was yes, SCWD should continue to pursue such a supplemental supply based on the findings of the groundwater assessment to date. However, determining the amount of additional supply needed requires continued analysis.

  Based on these recommendations, the SCWD Board of Directors decided to continue pursuing a supplemental water supply for conjunctive use, focusing on the two regional alternatives.

The objectives of the groundwater basin assessment have thus evolved between the release of the RFP and the present. The fundamental assumption and question had been:

- The District needs up to 2,000 ac-ft/yr of supplemental water to achieve District-wide pumping of approximately 4,870 ac-ft/yr (3,070 ac-ft/yr from the Purisima area and 1,800 ac-ft/yr form the Aromas area).
- Among the four alternatives, which are best suited for conjunctive use given the existing groundwater yield?

The revised questions are:

- What *is* the nature and yield of the District's existing groundwater supply?
- Does a conjunctive use project need to address the Aromas aquifer?
- How does use of the Beltz wells impact SCWD's groundwater supply?
- How much supplemental water is needed?

Selection between the remaining two alternatives has become less of a groundwater issue because both essentially import "new" water, their potential yields are roughly equal, and both are more or less susceptible to interruption.[4] Furthermore, the analyses originally envisioned for comparing alternatives have been unviable given uncertainty about underlying assumptions and fundamental questions about groundwater yield.

In conclusion, there has been considerable uncertainty regarding the fundamental nature of the groundwater system and a broad range of critical groundwater issues. These issues extend

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[4] In the case of desalination, interuptions would occur when Santa Cruz required the entire plant yield during critical drought periods. In the case of Pajaro Valley groundwater, there are uncertainties about how and when transfers could occur.

geographically from Live Oak, to La Selva Beach, beyond into Pajaro Valley, and inland throughout the Soquel-Aptos basin. A comprehensive hydrogeologic assessment is needed to serve as the basis for defining these issues and supporting the analyses needed to address them. Fulfilling these needs has evolved into a primary goal of this current phase the Soquel-Aptos groundwater basin assessment.

## 1.2 Objectives

This hydrogeologic conceptual model is a comprehensive synthesis of available information and knowledge relevant to understanding the Soquel-Aptos groundwater system. It serves as the foundation upon which to define groundwater issues, formulate potential solutions, and develop and apply methods of analysis.

The objectives of this report include:

- Synthesizing more than 35 years of groundwater data and investigations.
- Articulating the critical groundwater management issues (i.e., saltwater intrusion, aquifer-stream interactions, groundwater yield, the role of conjunctive use, the need for supplemental water).
- Evaluating these issues using standard means of expert interpretation, and presenting these conclusions in the context of past expert interpretations.
- Identifying data needs and issues requiring additional, more sophisticated analysis.
- Providing the knowledge base and assumptions needed to develop and apply more sophisticated methods of analysis (e.g., a revised IGSM model or other groundwater flow model).

## 1.3 Study Area

The study area encompasses the aquifer zones that contribute to SCWD's existing groundwater supply, extended outward to suitable hydrogeologic boundaries (Figure 1-1). This 66-square-mile area spans eastward from Branciforte Creek; through the developed areas of eastern Santa Cruz, Live Oak, Soquel, Capitola, and Aptos; inland towards the Zayante fault; and, southeast through Rio Del Mar and La Selva Beach, and into the western margin of Pajaro Valley. As such, it does not comprise a single, well defined hydrogeologic basin. However, as the contiguous groundwater source for SCWD, it is commonly referred to as the "Soquel-Aptos basin."

## 1.4 Previous Work

Previous assessments of Soquel-Aptos groundwater conditions have included three USGS studies (Hickey, 1968; Muir, 1980; Essaid, 1992), an independent study by Thorup (1981), and consulting studies prepared for SCWD (Luhdorff and Scalmanini Consulting Engineers [LSCE], 1981-2004; Montgomery Watson, 1998). The collective work of LSCE served as the underlying conceptual model for two previous modeling studies (Essaid, 1992; Montgomery Watson, 1998). Section 9 of this report provides a comprehensive bibliography of relevant past work.

## 1.5 Available Data

Table 1-1 summarizes relevant data available from sources other than referenced reports. Much of the information used in this report pertains to wells. Tables 1-2, 1-3, and 1-4 respectively provide summaries of SCWD production wells, monitoring wells, and other area production wells. Figure 1-2 is a map showing current well locations and the SCWD boundaries.

## 1.6 Report Organization

Following this introduction, Section 2 presents the hydrogeologic framework of aquifer units contributing to SCWD's groundwater supply. Section 3 presents an analysis of aquifer and aquitard properties. Section 4 describes the occurrence and movement of groundwater as evidenced by available groundwater level and pumping data. Section 5 defines and estimates the various components of the groundwater budget. Section 6 evaluates the potential for saltwater intrusion. Section 7 assesses the potential for stream-aquifer interactions. And, Section 8 concludes with the key findings of the conceptual model and recommendations regarding conjunctive use and needed additional work. Tables and figures are presented at the end of each section. Appendix A presents a detailed review of previous assessments of stream-aquifer interactions.

## 1.7 Project Team

The following team collaborated in the preparation of this report. The primary focus of each team member is indicated. However, each team member reviewed the entire report and concurs with its overall content, conclusions, and recommendations.

| Team Member | Affiliation | Primary Focus |
|---|---|---|
| Nicholas M. Johnson, Ph.D., R.G., C.Hg. | independent consultant, San Francisco, CA | Sections 2, 3, 4, 5, 6, & 8 |
| Derrik Williams, R.G., C.Hg. | independent consultant, Oakland, CA | Sections 5 and 6; groundwater injection |
| Eugene B. (Gus) Yates, R.G., C.Hg. | independent consultant, Berkeley, CA | Sections 4, 5, 6, and 7; Appendix A |
| Gordon Thrupp, Ph.D., R.G., C.Hg. | S.S. Papadopulos & Associates, San Francisco, CA | Section 3; IGSM |

## 1.8 Acknowledgements

The project team gratefully acknowledges the assistance of SCWD staff for fulfilling voluminous data requests and fielding a broad range of questions; guidance and feedback from the SCWD General Manager, Laura Brown, and SCWD Board of Directors; collaboration with SCWD's other consultants at Environmental Science Associates, Black and Veatch, Entrix, and Linsley, Kraeger Associates; collaboration with City of Santa Cruz Water Department staff and consultant, Curtis Hopkins; data provided by Clarke Wales, General Manager of the Central Water District; and assistance from Santa Cruz County staff John Ricker, Mike Sapanor, and Mike Cloud.

# 2 Hydrogeologic Framework

The nature and structure of the study area's hydrogeologic units are described in Sections 2.1 and 2.2. Section 2.3 presents a revised hydrostratigraphic model and Section 2.4 defines the study area's relevant hydrogeologic boundaries and subareas.

## 2.1 Geologic Units

SCWD wells produce groundwater from aquifer zones within two geologic formations, the Purisima Formation and the Aromas Red Sands (abbreviated elsewhere in this report by their geologic map symbols, "Tp" and "Qa", respectively). The Purisima Formation is exposed throughout the study area except where overlain by the Aromas Sands east and southeast of Aptos, and by relatively shallow alluvial and terrace deposits elsewhere (Figure 2-1).

Stratigraphically, the Purisima Formation is underlain by a sequence of older marine formations, including the Santa Cruz Mudstone, Santa Margarita Sandstone, Monterey Formation, Lompico Sandstone, Butano Sandstone, and several other older formations overlying granitic and metamorphic basement rock. Within the study area, most of these older formations were removed by erosion prior to deposition of the Purisima Formation such that the base of the Purisima Formation is generally within a few hundred feet or less of basement rock.

### 2.1.1 Purisima Formation (Tp)

The Purisima formation is a consolidated to semi-consolidated marine sandstone with siltstone and claystone interbeds. It has an uneroded total thickness of roughly 2,000 ft. Locally, the Purisima Formation dips from west to east such that (1) only remnants of its lower-most strata occur along ridge tops west of the study area and (2) it becomes deeply buried beneath Pajaro Valley to the east. The Purisima Formation also occurs within a tightly folded syncline north of the Zayante fault along the upper portions of the Soquel and Aptos creek watersheds.

Hickey (1968) subdivided the Purisima Formation into three hydrostratigraphic units in the Soquel-Aptos area, designated from oldest to youngest as A, B, and C. These units were not formally correlated and their designations appear to have been applied inconsistently relative to the stratigraphy as currently defined.[5]

The current stratigraphic model resulted from SCWD's drilling of eight exploratory test holes in 1983. Based on an interpretation of the associated geophysical logs, LSCE (1984a) correlated at least a dozen distinctive marker beds within nearly 1,200 ft of strata. Bounded between six of these markers, LSCE designated five units labeled A through E from oldest to youngest. Additionally, LSCE designated the zones below and above this package as unit AA and unit F, respectively.

LSCE's designated units provide a convenient basis for subdividing the formation, although not necessarily in a consistent hydrostratigraphic sense. Fine-grained horizons occur at the top, bottom, and/or middle of some units, and are absent in others. This is counter to the statement that each unit is an aquifer "confined by the claystone or siltstone interbeds between them" (LSCE, 1984a, p. 24), a conceptual "layercake" of aquifers and aquitards subsequently assumed by others (e.g., Todd Engineers, 2001; Fugro West, 2001). Although the units do not define a regular or unique sequence of aquifers and aquitards, they do capture the overall layered nature of the formation. The lateral extent of lithologic homogeneity within units is probably limited, although certain horizons do have a

[5]This conclusion is partially based on a comparison of the stratigraphic units assigned to particluar wells logs by Hickey (1968, Figure 3) and LSCE (1984, Sheets 10 and 11).

tendency to be relatively fine- or coarse-grained. Despite probable discontinuities, the cumulative effect of the many fine-grained zones is sufficient to account for the generally semi-confined to confined groundwater conditions.

Table 2-1 provides the depths, elevations, and thicknesses of Purisima units evident from our review of 28 geophysical well logs and 26 available cross sections (Hickey, 1968; Johnson, 1980; Thorup, 1981; LSCE, 1984a, 1987a, 1987b; Fugro West, 2001; McLaughlin et al., 2001; Cloud, 2004). Figure 2-2 is a schematic illustration summarizing the characteristic hydrostratigraphic features evident from the available geophysical logs. Figure 2-3 is a cross section summarizing the relationship of selected production and monitoring wells to the various stratigraphic units (see Figure 2-1 for line of section). Consistent with this interpretation, Tables 1-2 through 1-4 indicate which stratigraphic units each production and monitoring well are screened across.[6]

These units and their characteristic features are described in the following paragraphs, starting at the base of the stratigraphic column and working upwards, from oldest to youngest.

***Unit "Tp?" (< 200 ft thick) –*** The base of unit AA, the Purisima Formation's deepest defined unit, is poorly defined. The lithology becomes uniformly fine-grained beneath the lowermost coarse-grained layers of unit AA. Whether to group this interval with unit AA, a separately defined unit at the base of the Purisima, an older fine-grained formation such as Santa Cruz Mudstone or Monterey Formation, or possibly weathered schist basement rock, is uncertain. In aggregate, this lower fine-grained material is labeled "Tp?" in the remainder of this report. In logs sufficiently deep, the bottom of this fine-grained sequence is marked by the highly resistive signature of an underlying sandstone (e.g., Santa Margarita or Lompico sandstones, labeled "Tu") or granitic basement rock ("gr").

***Unit AA (200-300 ft thick) –*** Unit AA is distinguished primarily as the zone below unit A, a well-defined aquifer. Directly underlying unit A is a fine-grained zone 20 to 70 ft thick followed by a sequence of interbedded, moderately coarse- and fine-grained zones 10 to 30 ft thick. A distinct coarse-grained zone, if present, commonly occurs toward the top of unit AA with a thickness of 20 to 80 ft. Below this occurs another fine-grained marker, and possibly one more distinct but thinner coarse-grained zones. Omitting the lower fine-grained "Tp?" zone, unit AA appears to range from less than 200 to more than 300 ft thick, and averages about 220 ft thick among the available logs (Table 2-1).

***Unit A (~250 ft thick) –*** Unit A is the thickest and most consistently coarse-grained aquifer zone locally within the Purisima Formation. This unit is further distinguished by a claystone marker that defines the base of unit B. Unit A typically consists of an upper and a lower aquifer zone. The lower zone tends to be more coarse-grained and slightly thicker (~120-140 ft). Where uneroded, the total thickness of unit A ranges from 200 to 280 ft, and averages about 250 ft. Aquifer zones in unit A appear less pronounced at some locations away from existing production wells (e.g., SC-11).

***Unit B (200-260 ft thick) –*** The 25- to 45-ft thick claystone marker at the base of unit B is the most highly correlated feature within the local Purisima stratigraphy. Above it lies a coarse-grained unit about 20 to 30 ft thick, and then another distinct fine-grained zone up to 70 ft thick. The upper portion of the unit includes a coarse-grained zone 20 to 80 ft thick and additional fine-grained interbeds. As the units were originally defined in SCWD test-hole logs (LSCE, 1984a), a thin fine-

[6] These aquifer designations are different for several wells compared to those assigned by Montgomery Watson et al. (1998).

grained zone (≤ 20 ft) occurs either at the top of unit B or the bottom of unit C. Unit B ranges in thickness from 200 to 260 ft.

***Unit C (100-130 ft thick) –*** Unit C has a moderately coarse-grained zone up to 80 ft thick near its center. A distinct coarse-grained zone 15 to 20 ft thick occurs at the top of the unit, separated from the middle zone by a 5- to 10-ft thick fine-grained zone. Overall, unit C ranges from 100 to 130 ft thick.

***Unit D (120-160 ft thick) –*** The lower 60 to 80 ft of unit D is predominantly fine grained, with one or two minor coarse grained intervals. The upper 40 to 80 ft is relatively coarse grained, with one or two prominent zones. The total thickness ranges between 120 and 160 ft.

***Unit E (~160 ft thick) –*** Where encountered in the east and southeast portions of the study area, unit E averages about 160 ft thick, is moderately coarse grained overall, and is capped with a fine-grained zone about 20 ft thick.

***Unit F (>800 ft thick) –*** Unit F is the unsubdivided upper portion of the Purisima Formation. It thickens as it becomes less eroded to the east and southeast, becoming more than 800 ft thick where capped by the Aromas Sands at the margin of Pajaro Valley.

The lower portion of unit F is encountered as a shallow unit near Aptos. At its base it has a coarse-grained zone 40 to 60 ft thick, above which is a fine-grained zone 20 to 40 ft thick, and followed by a coarse-grained zone more than 100 ft thick. The remainder of the unit appears to include alternating moderately coarse- and fine-grained zones.

Purisima unit F is encountered as a relatively deep unit in the Aromas area (labeled "QTp" in a study for PVWMA by LSCE [1987a]). The contact with the overlying Aromas Sands is an angular unconformity,[7] and thus lacks a consistent nature and is difficult to identify. Furthermore, information about the unit at depth is obscured where geophysical logs encounter saline water in pilot holes drilled between Aptos and La Selva Beach.

In their work for SCWD, LSCE generally refer to the subsurface as consisting entirely of Aromas Sands southeast of monitoring-well cluster SC-A1. Other work, including this study, interprets the occurrence of Purisima Formation within the lower depths of SCWD's Aromas-area wells (e.g., Thorup, 1981; LSCE, 1987a; Montgomery Watson et al., 1998). The precise contact between these formations remains open to further refinement.

***Summary*** – In summary, the Purisima units have the following distribution of uneroded thicknesses (in feet):

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[7] i.e., the essentially flat-lying Aromas Sands overlie upturned beds of the Purisima Formation that have been truncated by erosion.

| | Unit | Average | Range |
|---|---|---|---|
| Top | F | >800 | |
| | E | 160 | 130 - 180 |
| | D | 140 | 120 - 160 |
| | C | 110 | 100 - 130 |
| | B | 240 | 200 - 260 |
| | A | 250 | 200 - 280 |
| | AA | 220 | <200 - >300 |
| Bottom | Tp? | 0 - 200 | |
| | Sum A-E | 900 | |
| | Sum AA-E | ~1,100 | |
| | Sum AA-F | ~2,000 | |

### 2.1.2 Aromas Red Sands (Qa)

The poorly consolidated Aromas Red Sands consist of interbedded fluvial, marine, and eolian sands with lenses of silt and clay. As a result of this complex depositional history, the formation contains significant heterogeneities. The Aromas Sands overlie the Purisima Formation in the hills and coastal terraces east and southeast of Aptos. SCWD monitoring and production wells from Aptos to La Selva Beach encounter approximately 200 to 500 ft of Aromas Sands above Purisima unit F (Table 2-1). LSCE (1987a) subdivided the Aromas Sands into an upper and a lower unit within Pajaro Valley. Inflections in the geophysical logs of all but the northern-most (SC-A1) of SCWD's five Aromas-area monitoring wells appear to support the local subdivision of the Aromas Sands into upper and lower coarse-grained zones, averaging about 225 and 175 ft thick, respectively. A large portion of the upper zone may be unsaturated, especially where the water table is drawn down to near sea level. SCWD's Aromas-area production wells are screened in the lower Aromas Sands only.

Whereas SCWD's Purisima monitoring wells are labeled corresponding to each well's screened stratigraphic unit (e.g., SC-1A is screened in Purisima unit A), the labeling of the Aromas-area monitoring wells simply indicates relative depth within each monitoring well cluster (e.g., SC-A1A is deeper than SC-A1B), and do not correlate from well to well or to unique stratigraphic units (Figure 2-4). At clusters SC-A2, -A3, and -A4, the "A" and "B" piezometers were installed respectively below and above the saltwater-freshwater interface.

### 2.1.3 Other Units

Among the older sedimentary formations underlying the Purisima Formation, the Monterey Formation and the Santa Cruz Mudstone may be grouped with the basement rock as essentially non-water bearing. However, unlike the basement rock, these older mudstones and shales may be difficult to distinguish from the fine-grained bottom of the Purisima Formation. Conversely, the occurrence of Butano, Lompico, and Santa Margarita sandstones could constitute a lower extension of the aquifer system (abbreviated as "Tu" for undifferentiated sandstone of Tertiary age). The latter two sandstones serve as productive aquifers elsewhere in the region (e.g., Scotts Valley). Only one of the reviewed production wells appears to be screened in the older sandstone unit (SCWD's Main Street well).

Surficial deposits overlying the Purisima Formation include alluvial and terrace deposits. These deposits are relatively shallow and their water resources significance is minor other than as conduits for recharge and stream-aquifer interaction.

### 2.1.4 Offshore Geology

Sediment mapping of the Monterey Bay seafloor with acoustic imagery has distinguished areas with and without unconsolidated deposits overlying the Purisima Formation (Eittreim et al., 2000, 2002). This work updates previous mapping by Greene (1977). Exposures of bare Purisima Formation are widespread immediately offshore, particularly along Opal Cliffs and Pleasure Point (Figure 2-5a).

A band of unconsolidated deposits extending offshore from the mouth of Soquel Creek appears to be an infilled paleochannel cut into the Purisima Formation (Figure 2-5a). Unpublished seismic reflection data suggest a fill depth of as much as 65 ft (i.e., 20 m; B. Jaffe/USGS, personal communication with R. Anima/USGS, as relayed to N. Johnson, March 11, 2004). One or two other possible pale channels occur in parallel to the east (as does another to the west extending from the mouth of the San Lorenzo River). These features trend southwest toward the former shoreline at lower sea level. The topography of ancestral canyons once associated with these channels has been planed-off by surf-zone erosion (i.e., this will be the next coastal terrace once uplifted relative to sea level).

The Aromas Sands are difficult to distinguish acoustically and may be exposed more extensively offshore in areas interpreted as "mud and fine sand" (Eittreim et al., 2002; Figure 2-5a). Given the relatively shallow water depth (generally <80 ft), the deposits labeled "Qmud" may be assumed to be more sand and less mud, including the deposits that fill the paleochannels off Soquel Creek (B. Jaffe/USGS, personal communication, March 11, 2004).

## 2.2 Geologic Structure

South of the Zayante fault, the Purisima Formation generally dips 2 to 5 degrees to the east-southeast. This structure is indicated by the mapped strike and dip of exposed bedding (e.g., Hickey, 1968) and the correlation of marker beds between borehole logs (LSCE, 1984a). Near the fault, the structural dip becomes steeper and more southward, reflecting a component of upward movement along the fault zone.

A more recent compilation of geologic mapping for Santa Cruz County exhibits a different pattern of strike and dip symbols for the Purisima Formation in the Soquel-Aptos area (Brabb, 1989, 1997). This map shows the dip to be southward along area streams including Rodeo Gulch, Aptos Creek, and Trout Gulch, and omits previously published observations of east-southeast dipping beds along the coastal cliffs and inland. It is difficult to reconcile most of these southward-dip orientations with the east-southeast dipping structure that is otherwise interpreted. There are relatively few well logs suitable for correlation inland of the coastal terrace. However, LSCE (1984a) did interpret an east-southeast dip between Soquel and Valencia creeks using inland boreholes SC-10, SC-11, and SC-12 (see their cross section B-B').

For this study, we prepared an original set of geologic structure maps for the area south of Zayante fault to address the following objectives:

- Evaluate the apparent structural discrepancy introduced by Brabb's geologic map.
- Resolve with some detail and accuracy the outcrop pattern of the various Purisima units (to help assess the nature and fate of direct groundwater recharge).
- Provide the structural information needed for groundwater modeling. Available maps from previous studies (e.g., Hickey, 1968; Thorup, 1981) do not reflect newer data; are of an unusable scale (e.g., Essaid, 1991); and/or lump together units that may be more appropriately treated as individual layers (e.g., Montgomery Watson et al., 1998).

North of the Zayante fault, the Purisima Formation is tightly folded within the narrow, southeast-trending Glenwood Syncline. Groundwater probably flows southward across portions of the fault, but the syncline structure itself has limited significance to SCWD's groundwater system, and thus is not contoured in the figures introduced below.

Appendix B presents a complete set of our interpreted geologic structure maps with the supporting data posted on each map. Selected maps without the posted data are presented in the following discussion.

### 2.2.1 Top of Basement Rock

Granitic basement rock has been encountered by at least seven Soquel-Aptos borings (Table 2-1) and several oil test wells to the east in Pajaro Valley. Depths to basement rock beneath shallower wells have been interpolated along geologic cross sections (LSCE, 1984a, 1987a; Cloud, 2004). Additionally, metamorphic and granitic basement rocks are exposed at several locations along the western and northern margins of the study area, i.e., along Branciforte Creek, its tributaries, and the southern flank of the Zayante fault zone (Figure 2-1). Where other formations underlie the Purisima Formation, the occurrence of basement rock may be inferred at depths below these formations. Offshore, the top of basement rock was contoured by Greene (1977).

Boreholes encounter the basement rock with increasing depth from west to east, ranging from approximately 200 ft below mean sea level (ft msl) at the Thurber Lane northern test hole, to about –800 ft msl at SC-11, and about –2,400 ft msl at the Texaco-Pierce oil test well (see Figure B-1 for well locations). Minimum depths are also inferred from deep borings that did not encounter basement rock (e.g., SC-8).

The basement rock is sufficiently shallow along the western margin of the study area to be exposed at the bottom of stream canyons. Branciforte Creek cuts through the bottom of the Purisima Formation and approximately 100 ft of Santa Margarita Sandstone upstream of its confluence with Carbonera Creek, exposing both quartz diorite (i.e., granitic rock) and schist. Its Granite Creek tributary cuts through the Purisima Formation and underlying Santa Cruz Mudstone to expose granitic rock. Further upstream, Branciforte Creek exposes granitic rock directly beneath the Purisima Formation. The headwaters of Branciforte Creek in Blackburn Gulch expose at least 200 ft of Lompico Sandstone beneath the Purisima Formation with no sign of basement rock (Figure 2-1).

The granitic basement is uplifted along the southern flank of the Zayante fault zone such that it is exposed directly beneath the Purisima Formation where the fault intersects the main stem and West Branch of Soquel Creek, and Bridge Creek in the Aptos Creek watershed (Figure 2-1).

Strike and dip readings from exposed Purisima Formation (e.g., Hickey, 1968) may be applicable to much of the basement-rock surface given that (1) the Purisima Formation essentially overlies basement rock across most of the study area and (2) the Purisima units appear to have generally uniform thicknesses.

Figure 2-6 presents our contour map of the estimated top of the granitic basement south of the Zayante fault. Near the coast, this surface generally dips 2.5 to 4 degrees to the east-southeast and descends to an elevation of –2,400 ft msl east of La Selva Beach. A narrow basement ridge occurs along the Zayante fault, and a basement trough extends northwest beneath Blackburn Gulch. This map is consistent with available information and the overall trend of earlier published maps (Hickey, 1968; Greene, 1977; Thorup, 1981; Essaid, 1991). Given that it is an erosional surface, the actual basement surface probably has local topographic irregularities. As drawn, however, the map provides a useful base for conceptually stacking the Purisima units.

Two units are distinguished in the zone above the granitic basement rock and below the poorly defined base of Purisima unit AA: (1) an older sandstone (unit "Tu") and (2) a fine-grained zone (unit "Tp?") that may include the base of the Purisima Formation and/or older fine-grained formations such as the Santa Cruz Mudstone and Monterey Formation.

### 2.2.2 Purisima Units

Figure 2-7 is a contour map of the estimated bottom of Purisima unit AA. By default, this surface generally mimics the basement contours given that few wells provide a clear indication of the Purisima's base. The contours are consistent with the Purisima's direct contact on basement rock in the upper Soquel and Aptos watersheds; the occurrence of about 100 ft of older sedimentary rocks above the basement along lower Branciforte Creek and elsewhere; and the occurrence of several hundred ft of older sedimentary rock (e.g., Lompico Sandstone) that fill the structural trough beneath Blackburn Gulch.

Figure 2-8 presents contours representing the estimated top of unit AA (i.e., the bottom of unit A). This contact is inferred in part from 16 well and test-hole logs (Table 2-1). For wells where the top of unit AA has been eroded, we estimated structural elevations by extending contacts on available cross sections above ground (Table 2-1). This helped identify where the structure surface intersects the ground surface, as is necessary to delineate the outcrop area of unit AA.

We used a similar procedure to estimate contours along the top of unit A as shown in Figure 2-9. Where the unit is exposed, the contours represent its eroded outcrop surface. Units B through E are each of sufficiently uniform thickness that we estimated their top surfaces by adding their average cumulative thicknesses to the top of unit A. Figure 2-10 is a map of the estimated outcrop areas for each unit.[8]

The structure maps are consistent with most of the available data with the exception of the seemingly anomalous strike and dip orientations shown by Brabb (1989, 1997). Seafloor acoustic (side-scan sonar) images of the Purisima Formation outcrop reveal the bedding of truncated strata partially obscured by seafloor rubble (Eittreim et al., 2002). These lineations are consistent with the interpreted strike of the dipping units (Figure 2-5b). Dipping beds consistent with the interpreted structure also are evident in seismic reflection profiles of the upper 150 ft of rock beneath the seafloor (B. Jaffe, personal communication with R. Anima/USGS, as relayed to N. Johnson, March 11, 2004).

### 2.2.3 Bottom of Aromas Sands

The estimated bottom of the Aromas Sands can be inferred from mapped geologic contacts with the underlying Purisima Formation, and available cross sections and well logs. An inspection of mapped contact elevations (Brabb, 1997) suggests a fairly irregular, erosional surface. Preparation of a contour map of this surface was begun for this report but not finalized.

### 2.2.4 Faults

The Zayante fault serves as a basin boundary along the segment northwest of Soquel Creek, and probably affects groundwater flow where it extends through the basin southeast of Soquel Creek (see Section 2.4.3). The San Gregorio fault lies at least 20 miles offshore in Monterey Bay. No other named fault traverses the basin.

[8] The estimated outcrop areas in Figure 2-10 are for the hydrostratigraphic units defined in Section 2-7.

Some USGS maps (e.g., Hanson, 2003) show segments of three closely spaced faults, both observed and inferred, that extend west-northwest along Larkin Valley, follow State Route 1 between Freedom and Rio Del Mar boulevards, and cross the lower portion of Valencia Creek toward Aptos. An extension of this trend to the west-northwest places it approximately along the inland boundary of the Soquel-Aptos coastal terrace. Such a fault could affect groundwater movement toward aquifer zones pumped by SCWD.

Numerous minor faults are evident in cliff exposures of the Purisima Formation between Pleasure Point and Capitola (Griggs and R. Johnson, 1979). Offshore imaging also suggests fault traces perpendicular to the coast near Capitola (B. Jaffe/USGS, personal communication with R. Anima/USGS, as relayed to N. Johnson, March 11, 2004). The cumulative effect of such faulting may be to offset permeable strata and lower effective horizontal hydraulic conductivities.

## 2.3 Hydrostratigraphic Units

As summarized in the following table, Table 2-2 and Figures 2-2 and 2-11 present a proposed hydrostratigraphic interpretation for conceptualizing the distribution of hydrogeologic properties and pumping stresses.

| Proposed Hydrostratigraphic Units | | Typical Thickness (ft) |
|---|---|---|
| 1 | Upper Aromas Aquifer ($Qa_U$) | 225 |
| 2 | Lower Aromas Aquifer ($Qa_L$) | 175 |
| 3 | Aquifer F | 150-500+ |
| 4 | Aquifer DEF | 330 |
| 5 | Aquitard D | 80 |
| 6 | Aquifer BC | 200 |
| 7 | Aquitard B | 150 |
| 8 | Aquifer A | 250 |
| 9 | Aquifer AA (aquitard at top) | 150-300 |
| 10 | Aquitard "Tp?" | 0-200 |
| | Aquifer Tu | 0-300 |

The ten interpreted hydrostratigraphic units split and combine the various Purisima and Aromas stratigraphic units into aquifer and aquitard zones consistent with the interpreted geophysical logs and the overall distribution of well screens. From top to bottom, the hydrostratigraphic units are defined as follows:

- The informally recognized upper and lower units of the Aromas Sands ($Qa_U$ and $Qa_L$) comprise two aquifer zones. It appears that none of the SCWD production wells is screened in the upper Aromas.
- The upper portion of Purisima unit F is designated aquifer F, and is screened by most of SCWD's Aromas-area wells and other deep wells in Pajaro Valley. The SCWD wells appear to draw from a dual aquifer consisting of the lower Aromas and upper Purisima. This portion of Purisima aquifer F is generally not screened or encountered by SCWD's other, Purisima wells. Little hydraulic communication is expected between the District's Purisima and Aromas-area wells through unit F due to distance, stratigraphy, and an intervening, generally coastward groundwater gradient.
- The lower portion of Purisima unit F, all of Purisima unit E, and the upper portion of Purisima unit D are grouped into aquifer DEF, a zone screened by wells to the west of Aptos Creek. A

group of older, shallow wells were screened in just the upper portion of this zone, referred to as aquifer EF (e.g., the Hillcrest and Seacliff wells).

- Few production wells are screened in the fine-grained lower portion of Purisima unit D, designated aquitard D.
- Purisima unit C is grouped with the upper portion of Purisima unit B to form aquifer BC, which includes some thin aquitards.
- Few production wells are screened in the fine-grained lower portion of unit B, designated aquitard B.
- Purisima unit A forms the distinct and highly permeable aquifer A.
- Purisima unit AA is screened by few wells and has an aquitard along its top.
- Where present, fine-grained sediments near the base of the Purisima (labeled "Tp?") form a basal aquitard and one or more older sandstones (Tu) forms a basal aquifer. For modeling purposes, the two basal units may be combined through parameter weighting and/or lateral zonation into a single bottom layer.

A former study also combined units D, E, and F (Montgomery Watson et al., 1998) and, along with another previous study (Essaid, 1992), combined units A and AA. However, the well defined and highly permeable unit A warrants recognition as a separate aquifer zone. Neither of these two previous modeling studies identified distinct aquitard zones.

## 2.4 Hydrogeologic Boundaries and Subareas

The hydrogeologic boundaries defined below attempt to isolate the Soquel-Aptos groundwater system by minimizing the potential for cross-boundary subsurface flows. In this way, most of the basin's groundwater recharge and discharge occur within these boundaries. Such natural boundaries facilitate the evaluation of the groundwater balance and the potential basin-wide effects of various groundwater stresses (e.g., pumping and droughts).

### 2.4.1 Bottom and Top Boundaries

The occurrence of granitic or metamorphic rock (i.e., basement rock) or uniformly fine-grained sedimentary rock (e.g., Monterey Formation or Santa Cruz Mudstone) is the assumed bottom of the groundwater system. This boundary may be poorly defined locally where the Purisima Formation grades into finer grained material within or below unit AA. Furthermore, the depth to basement rock is mostly inferred to the east as it becomes deeper than most wells.

The water table, perennial-stream beds, and the ocean floor define the top of the groundwater system.

### 2.4.2 Western Boundary

The western hydrogeologic boundary follows Branciforte Creek from its headwaters downstream to the San Lorenzo River, and then along the river to its mouth at the ocean (Figures 1-1 and 2-1). As described in Section 2.1.1, Branciforte Creek cuts through the bottom of the Purisima Formation and into basement rock along much of its course. For this reason, local groundwater flow is expected to discharge to the creek rather than pass beneath it. Along its headwaters in Blackburn Gulch, Branciforte Creek cuts through the Purisima into Lompico Sandstone. Although there is a potential for subsurface flow through the Lompico Sandstone, topographic influences on groundwater gradients and discharge, and limited recharge areas in the upper watershed, suggest this is minimal. Although the Purisima Formation underlies the lower San Lorenzo River, elevations are near sea level and there is little potential for a groundwater gradient across the river. Others have adopted a relatively similar western boundary for the Soquel-Aptos basin (e.g., Essaid, 1991; Montgomery Watson et al., 1998).

### 2.4.3 Northern Boundary

Selection of an appropriate northern boundary is complicated by the southeast trending Zayante fault. Upturned stratigraphy south of the fault and west of the main branch of Soquel Creek has resulted in the removal of the Purisima Formation by erosion, and exposure of underlying Butano Sandstone and granitic basement. The water-bearing properties of the Butano Sandstone are limited (Johnson, 1980), and the geologic structure and topography are not conducive to groundwater flow from the Butano into the Purisima. Furthermore, the granitic high just south of the fault is a likely barrier to groundwater flow from units folded within the Glenwood Syncline north of the fault. For these reasons, the Purisima Formation outcrop just south of the fault is selected as the northern boundary of the Soquel-Aptos basin west of Soquel Creek (Figure 2-1). Montgomery Watson et al. (1998) selected a similar boundary, but without documented explanation.

East of Soquel Creek, offset blocks of Purisima Formation occur side by side across the Zayante fault. These blocks have their own distinctive structures and may contain different portions of the Purisima stratigraphy. Several previous studies have treated this segment of fault as a groundwater basin boundary (Hickey, 1968; Johnson, 1980; Muir, 1980; Essaid, 1991). As cited by these studies, this interpretation harkens back to a 50-year-old water-level map suggesting preferential groundwater flow southeast through the Glenwood Syncline north of the fault, and little or no flow across the fault (California State Water Resources Board [SWRB], 1953). In this case, groundwater movement north of the fault would bypass the lower Soquel and Aptos watersheds by flowing from the upper Bean Creek watershed in the San Lorenzo basin to the Corralitos Creek watershed in the Pajaro basin. Although the potential for some groundwater flow across the fault was acknowledged, these studies assumed the amount was highly uncertain and probably minor.

There is little topographic gradient to drive groundwater flow southeast through the syncline across the upper Soquel and Aptos creek watersheds. Southward flow must traverse steeply dipping beds within the Glenwood Syncline, cross the fault, and find entry into permeable zones south of the fault. Nevertheless, there is a substantial gradient south toward the ocean, and flow may occur more readily in near-surface weathered and fractured zones. Additionally, the depth of juxtaposition across the fault increases as the southern block of Purisima thickens to the southeast. For these reasons, we include the block of Purisima north of the fault and southeast of Soquel Creek as part of the Soquel-Aptos groundwater basin. The boundary selected by Montgomery Watson et al. (1998) appears to reflect a similar assumption. In subsequent analyses, the significance of this area may be modified by adjusting recharge, fault zone, and aquifer property assumptions.

### 2.4.4 Eastern Boundary

Selection of a well-defined eastern boundary is difficult because SCWD's southeastern most wells lie within the Pajaro Valley's western margin. Groundwater recharged into the Aromas Sand hills east of Aptos and north of La Selva Beach has potential gradients toward both the coast and pumping centers in Pajaro Valley. Montgomery Watson et al. (1998) addressed this issue by extending the study area boundary nearly to the Pajaro River (through incorporation of their Pajaro Valley model). Todd Engineers (2002) delineated a recharge area for SCWD's Aromas-area wells that may too closely border the southeastern-most wells. Other previous studies focused only on the Purisima aquifer (e.g., Essaid, 1991).

For this study, we assume a boundary that follows the western drainage divide of the Corralitos Creek watershed; curves west across Larkin Valley, encompassing a portion of the Harkins Slough watershed; and intersects the coast southeast of La Selva Beach (Figures 1-1 and 2-1). Groundwater contour maps of Pajaro Valley under non-drought conditions suggest such a boundary (PVWMA, 2001), and planned groundwater replenishment may support this boundary under future conditions. Our yield assessment for SCWD's Aromas-area wells considers the potential for groundwater flow across this boundary during drought conditions.

### 2.4.5 Southern Boundary

The southern study area boundary assumed by previous studies has ranged from about one-half mile offshore (e.g., Montgomery Watson et al., 1998) to 20 miles offshore (Essaid, 1992). The 1992 study discounted the threat of saltwater migration from the distant submarine canyon walls, but concluded that "the most immediate potential cause for seawater intrusion is pumping from shallow Purisima units near the coast that could induce downward leakage of seawater through ocean floor outcrops" (Essaid, 1992, p. 29). Given the Purisima Formation's dip perpendicular to the coast, all of the units are "shallow" at some point along the coast. For these reasons, our assumed boundary encompasses the seafloor exposures of Purisima Formation mapped by Eittreim et al. (2000, 2002) that occur within two miles south of Pleasure Point (Figure 2-5a).

### 2.4.6 Subareas

Given the boundaries defined above, the study area consists of the following hydrogeologic subareas (Figure 2-12):

| Subarea | Area ($mi^2$) | Description | Hydrogeologic Significance |
|---|---|---|---|
| Central Purisima | 34 | south of Zayante fault to coastal terrace | precipitation recharge, groundwater discharge to streams, rural groundwater production |
| North Purisima | 7.4 | north of Zayante fault, east of Soquel Creek | |
| Purisima Terrace | 10.2 | coastal terrace south of Purisima outcrop | mostly municipal groundwater production, urban recharge, discharge to streams |
| **Purisima Area** | **52** | | |
| Aromas Sands | 12.0 | outcrop area within study area | precipitation recharge, rural and municipal groundwater production |
| Aromas Terrace | 2.4 | coastal terrace south of Aromas outcrop | municipal and private groundwater production, suburban recharge |
| **Aromas Area** | **14.4** | | |
| **Onshore Total** | **66** | | |
| Offshore | 26 | | groundwater discharge |
| **Total** | **92** | | |

These subareas are generally grouped into a "Purisima area" which supplies groundwater to SCWD Service Areas I and II, and an "Aromas area" which supplies District Service Areas III and IV. Groundwater produced from the Aromas area is partially derived from Purisima unit F, but with relatively minimal interaction with groundwater in the Purisima area.

# 3 Aquifer and Aquitard Hydraulic Properties

Reasonable estimates of various hydraulic properties are essential for understanding and predicting groundwater flow, particularly in response to pumping wells. These properties include:

- Whether an aquifer behaves as confined, semi-confined, or unconfined – An unconfined aquifer's saturated thickness varies with the fluctuation of its water table. A confined aquifer is fully saturated below a confining, low-permeability layer (i.e., aquitard). Semi-confined conditions occur where the aquifer is at least partially supplied by leakage through the aquitard (or semi-confining layer).
- Hydraulic conductivity ($K$) is the proportionality constant between the rate of groundwater flow and the hydraulic gradient; i.e., groundwater flow equals the hydraulic conductivity times the gradient times the cross-sectional area of flow. Within a hydrogeologic unit, horizontal hydraulic conductivity ($K_H$) is typically much larger than the effective vertical hydraulic conductivity ($K_V$) due to layering. This report uses units of feet per day (ft/day) for hydraulic conductivity.
- Transmissivity ($T$) is the capacity of a unit-width of aquifer to transmit water through its entire thickness as a function of the hydraulic gradient; it equals hydraulic conductivity times aquifer thickness, $b$ (i.e., $T = K \times b$). Groundwater flow equals transmissivity times the hydraulic gradient times the width of flow perpendicular to the gradient. This report uses transmissivity units of square feet per day ($ft^2$/day).[9] Most methods for estimating aquifer properties provide values of transmissivity, from which horizontal hydraulic conductivity is estimated as $K = T \div b$.
- The storativity, or storage coefficient ($S$, dimensionless), is the volume of water released from aquifer storage per unit surface area given a unit decline in hydraulic head. Under confined conditions, this property is entirely a function of the compressibility of both water and the aquifer matrix. On a unit volume basis, it is referred to as "specific storage", $S_s$ (1/ft), and has a value of approximately $1 \times 10^{-7}$ per vertical foot of aquifer due to the compressibility of water alone. Thus, for a 100-ft thick confined aquifer, the storativity has an approximate minimum value of $1 \times 10^{-5}$ (i.e., $S = S_s \times b$) (Heath, 1983).
- Specific yield ($S_y$, dimensionless) is the volume of water that drains under the influence of gravity per unit volume of saturated rock (i.e., the storage coefficient under water-table conditions). It's value is somewhat less than the aquifer porosity, typically ranging from 0.01 to 0.25 (i.e., 1 to 25 percent).
- The apparent storage coefficient under semi-confined conditions is influenced by aquitard leakage and attains values greater than 0.001.

The following types of information are available for interpreting the hydraulic properties of the Soquel-Aptos aquifer-aquitard system:

- Aquifer test time-drawdown data – defined here as recorded changes in groundwater level during a relatively long-duration pumping period (e.g., ≥24 hours) observed in one or more observation wells other than the pumping well. Ideally, water levels are static prior to the test, the pumping rate is known and held constant, and the water-level recovery following the pumping period is also recorded. The interpretation of such data can provide estimates of transmissivity, storage coefficient, and the vertical hydraulic conductivity of the aquifer and/or bounding aquitard ($K'$).

[9] Another common unit of transmissivity is gallons per day per foot (gpd/ft), for which values are 7.48 times greater than when expressed in $ft^2$/day.

Because of the number of variables being estimated, data from multiple observation wells are needed to constrain the solution. Data from three aquifer tests with single observation wells are available for the Tu/AA and A aquifer zones.

- Pump test time-drawdown data – defined here as water-level changes during a relatively short pumping period (e.g., 6 to 12 hours) observed in the pumping well only. Such data generally provide reliable estimates only of transmissivity. Pump tests with six or more hours of data are available for four area wells completed in the A, BC, and F/Qa aquifer zones.
- Specific capacity ($S_c$) – the yield of a well per foot of drawdown after a reasonably long pumping period. Rough estimates of transmissivity may be calculated from reported specific capacities. Various measurements of specific capacity are available for all of the District wells.
- Experience from prior groundwater modeling – the hydraulic properties assumed by a numerical groundwater flow model are typically based on a hydrogeologic conceptual model and/or calibrated to available groundwater level and discharge data. Such calibrations are "non-unique", however, meaning that different sets of parameter values may provide similar levels of calibration. Calibrated models have been prepared for both Soquel-Aptos and Pajaro Valley.

## 3.1 Analytical Methods

This section briefly describes pertinent aspects of the analytical methods relevant to this study.

### 3.1.1 Confined-Aquifer Solutions

***Cooper-Jacob Method –*** The Cooper-Jacob (1946) method is the simplest technique for estimating transmissivity and storativity from time-drawdown or time-recovery data. It involves fitting a straight line to data points where time is plotted on a logarithmic scale and drawdown is plotted on an arithmetic scale. When the solution method is unspecified in previous work, it may be presumed that the Cooper-Jacob method was used. Despite its common use, this approach has the following limitations and is not used in the current study.

1. It is valid only after pumping for a period of time $t^*$ equal to the following expression (Walton, 1987):[10]

   $$t^* = (r^2 \times S \times 1{,}440) / (4 \times T \times u)$$

   Data are valid only at relatively large times as the distance from the pumping well increases. This limitation may require discounting a substantial portion of test data.
2. It does not handle multiple pumping rates, such as from "step tests."
3. It does not account for "partial penetration" of the aquifer by the pumping or observation wells.
4. It ignores information provided by departures from a straight-line (i.e., semi-log) fit, and may misinterpret flattened curves related to leaky or unconfined conditions.

***Theis Method for Confined Aquifers –*** The Theis (1935) method is appropriate for estimating transmissivity and storativity from drawdown in a confined aquifer. Like the Cooper-Jacob method, it may provide erroneous results under leaky and unconfined conditions.

As with the other methods described below, available software allows consideration of drawdown and recovery data together, variable pumping rates, and partial aquifer penetration. Partial penetration results in three-dimensional flow and increased drawdown. It influences the solution

[10] A explanation of symbols and their units is provided following the Table of Contents.

significantly when an observation well is within a distance $r_p$ of the pumping well defined as follows (Hantush, 1964):

$$r_p = (1.5 \times b) / (K_V/K_H)^{1/2}$$

### 3.1.2 Leaky Aquifer Solutions

***Hantush-Jacob Method for Leaky Aquifers –*** The Hantush-Jacob (1955) method accounts for semi-confined aquifer conditions assuming steady leakage through an aquitard (i.e., no release from aquitard storage). The rate of drawdown is less than predicted by the Theis equation and eventually diminishes to zero. Continued drawdown is unnecessary once the cone of depression is large enough to induce leakage sufficient to sustain the rate of pumping. When pumping stops, water levels recover more rapidly than predicted by the Theis equation. The hydraulic conductivity of the aquitard may be estimated using the solution parameter $r/B$:

$$K' = [T \times b' \times (r/B)^2]/r^2 = (T \times b')/B^2$$

***Hantush Method for Leaky Aquifers –*** The Hantush (1960) method is also for semi-confined conditions but accounts for aquitard storage. The hydraulic conductivity of the aquitard may be estimated using the value of solution parameter β:

$$K' = (16 \times \beta^2 \times b' \times T \times S)/(r^2 \times S')$$

***Moench Method for Leaky Aquifers –*** The Moench (1985) method for leaky aquifers accounts for initial storage in the wellbore and is otherwise similar to the Hantush-Jacob solution in solving for aquitard hydraulic conductivity.

### 3.1.3 Unconfined Aquifer Solutions

***Neuman Method for Unconfined Aquifers –*** The Neuman (1975) method accounts for the effects of delayed drainage under unconfined conditions. It solves for transmissivity, storativity, specific yield, and a parameter β. The storativity reflects the aquifer's initial confined response prior to the delayed contribution of specific yield. The ratio of vertical to horizontal aquifer hydraulic conductivity can be estimated as:

$$K_V/K_H = \beta \times (b^2/r^2)$$

The effects of delayed drainage are significant for times shorter than $t_d$:

$$t_d = (5 \times b \times S_y \times 1{,}440)/K_v$$

Due to its accounting of three-dimensional flow, this method can provide some insight regarding vertical hydraulic conductivity under non-unconfined conditions (e.g., leaky). The Neuman method is preferable to modified versions of the Theis and Cooper-Jacob solutions for unconfined conditions.

### 3.1.4 Transmissivity Estimates from Specific Capacity

The specific capacity of a pumping well, expressed as gallons per minute per foot of drawdown (gpm/ft), depends on the hydraulic characteristics of both the well and the aquifer. Assuming that a reasonably small portion of drawdown is attributable to well losses, the following rule of thumb is often used for estimating transmissivity from specific capacity (Heath, 1983; Driscoll, 1986):

$$T\text{ (gpd/ft)} = S_c \times 2{,}000 \text{ (confined) or } S_c \times 1{,}500 \text{ (unconfined)}$$

Dividing by 7.48 converts this estimate to the transmissivity units used in this report ($ft^2$/day). Based on the Theis equation, the "2,000" factor, $f$, can be tailored to expected conditions as follows:

$$f = [W(u)/(4 * \pi)] * 1{,}440$$

where W($u$) is the Theis well function, $u$ is defined as

$$u = (r_w^2 * S)/(4 * T * t)$$

$r_w$ is the effective well radius, $t$ is the time since pumping began, and $T$ is an initial guess of transmissivity. Thus, aside from the effect of well losses, $f = 2{,}000$ is essentially correct for particular combinations of pumping duration, well radius, transmissivity, and storativity (e.g., $t$=1 day, $r$=0.5 ft, $T \approx 4{,}000$ ft$^2$/day, and $S$=$1\times10^{-3}$). Other factors being equal, using $f = 2{,}000$ will over estimate transmissivity for (a) shorter pumping periods, (b) smaller values of actual transmissivity, or (c) greater values of storativity, and under estimate transmissivity in the reverse sense. Nevertheless, this method provides useful rough estimates. Furthermore, $f$ can be tailored to local conditions using preliminary estimates of $T$ and $S$ derived from other sources.

As with any estimate of transmissivity, an appropriate aquifer thickness must be assumed to estimate hydraulic conductivity from $K = T/b$. Depending on conditions, an effective aquifer thickness may equal (a) the combined length of well screen, (b) the distance between the upper-most and lower-most well screens, or (c) the distance between aquifer top and bottom.

## 3.2 Time-Drawdown Analyses

This section presents our analysis of time-drawdown data for six SCWD production wells and three wells operated by the City of Santa Cruz. Interpretation of these data provide hydraulic property estimates for the Tu/AA, A, BC, and F/Qa aquifer zones. Property estimates from time-drawdown data interpreted by others are available for an additional two SCWD wells.

### 3.2.1 Main Street Well

Eight- and 72-hour aquifer tests were conducted on the District's Main Street well in July 1986 and May 1991, respectively (LSCE, 1991; 1995a). During each test water levels were recorded in the pumping well and monitoring wells SC-18A and SC-18AA at a distance of 39 ft. During the latter test water levels were also monitored in SC-10A and SC-10AA at a distance of approximately 6,800 ft. Figure 3-1 provides a schematic representation of these wells and the aquifer zones they encounter.

Based on the stratigraphic interpretation presented in Section 2, the Main Street well is screened in Purisima unit AA, an underlying, relatively fine-grained zone (Tp?), and an older sandstone (Tu) above the granitic basement.[11] Consistent with this interpretation, SC-18A is actually screened in unit AA (although its gravel pack extends up into unit A) and SC-18AA is screened in the older sandstone. The Main Street well's continuous gravel pack interconnects all of these units with an overlying portion of unit A that extends to near the ground surface.

The Main Street well has one of the highest yields among the Purisima wells, and a high specific capacity similar to wells completed in the highly permeable A aquifer. The few wells completed in unit AA, and the lithology of AA, do not suggest that it is highly productive. No other area well is known to be screened in the older sandstone and its local aquifer characteristics are unknown. Thus, it is unclear to what degree the Main Street well derives its high yield from unit A via the gravel pack or from the older sandstone. A downhole flow meter test could help determine the relative contribution of each zone to the well's production. Without such information, it is difficult to apportion the hydraulic properties interpreted from the aquifer tests to the various zones, and limits

[11] Inferred by some to be Santa Margarita Sandstone (J. Scalmanini/LSCE, personal communication with L. Brown/SCWD, as relayed to N. Johnson).

the feasibility of estimating vertical hydraulic conductivities. Although appearing to show some response during the latter test, the SC-10 monitoring wells are located at too great a distance from the Main Street well for an ideal analysis.

Figures 3-2 through 3-4 present our analyses of the May 1991 time-drawdown data and Table 3-1 summarizes the Main Street well aquifer-test interpretations by this and previous studies.

***Response at SC-18AA* –** Figure 3-2 presents our analysis of the time-drawdown data recorded in SC-18AA. The Theis solution fits the data very well, indicating that the 30-ft clayey interval at about –200 ft msl is an effective confining layer. Thus, in this area, the deeper zones encountered by the Main Street well (Tp? and Tu) constitute a confined aquifer into which leakage from overlying aquifers is relatively minor.

The Theis solution indicates a transmissivity of about 3,600 $ft^2$/day and storativity of 0.0015. This transmissivity agrees closely with the 3,700 $ft^2$/day estimated from the test period's specific capacity (Table 3-1).

A range of hydraulic conductivity estimates is possible because the Main Street well is screened in multiple zones and is fully gravel packed. Alternative assumptions for aquifer thickness suggest average hydraulic conductivities ranging from 6 to 12 ft/day.

An estimated range of aquitard hydraulic conductivities is also possible depending on how the overlying zones are interpreted. We estimate a value of about 0.01 ft/day assuming deep leakage is controlled by the lowermost 30-ft aquitard in unit AA.

***Response at SC-18A* –** As shown in Figure 3-3, a leaky aquifer solution provides a good fit to the SC-18A drawdown curve, indicating a transmissivity of 3,700 $ft^2$/day and a storativity of 0.007. The flattening of the late-time drawdown data and departure from the Theis curve is consistent with leakage from overlying aquifer A. Estimates of effective aquitard thickness from 30 to 200 ft provide a range of possible values of vertical hydraulic conductivity from 0.1 to 0.8 ft/day.

***Response at SC-10AA and SC-10A* –** At a distance of approximately 6,800 ft from the Main Street well, water levels in SC-10AA responded to the May 1991 test with an apparent 2.5 ft of drawdown (Figure 3-4); no net change was recorded at SC-10A. Analysis of the apparent drawdown in SC-10AA is consistent with the aquifer properties estimated from SC-18AA (Table 3-1).

### 3.2.2 Beltz Wells

The City of Santa Cruz operates three production wells, Beltz 7, 8, and 9, in the Live Oak area west of SCWD. Figure 3-5 presents the well profiles relative to the Purisima stratigraphy interpreted in Section 2 (including inactive Beltz 6). All of the wells are screened in the lower half of aquifer A, an exceptionally homogeneous and coarse-grained zone, as discussed in Section 2.1.1. Beltz 7 is screened at the bottom of this zone and the top of the underlying AA unit.

Beltz 8 and 9 were each tested for approximately 34 hours during early 1998. At a distance of 38 ft, inactive Beltz 6 was used as an observation well during the Beltz 8 test. Drawdown data were collected from Beltz 7 for less than 20 minutes in June 2002. Figures 3-6 through 3-9 present our analyses of the time-drawdown data, and Table 3-2 summarizes the interpretation of these results by this and previous studies.

***Beltz 8 and 9 Tests* –** As shown in Figures 3-6 through 3-8, we used the Moench leaky-aquifer method to analyze the Beltz 8 and 9 tests. Along with the other solutions presented in Table 3-2, the probable average and range of hydraulic property values are as follows: transmissivity 5,000 (3,600-

6,800) $ft^2$/day; hydraulic conductivity 50 (35-70) ft/day; aquitard hydraulic conductivity 0.01-1.0 ft/day; and storativity 0.0003-0.004.

The hydraulic conductivity estimated for the A aquifer in the vicinity of the Beltz wells is substantially greater than any other Purisima zone in the Soquel-Aptos area. This may be in part because only the lower portion of unit A is present, which is interpreted from geophysical logs to be more permeable than the upper portion of unit A or any other Purisima unit. Furthermore, the permeability of this zone may be enhanced by processes related to its locally shallow depth (e.g., reduced compaction and cementation; weathering; and opened fractures). As a result, the transmissivity is greater than further east where wells encounter a thicker but more deeply buried A aquifer.

***Beltz 7*** **–** Analysis of the brief time-drawdown data for Beltz 7 (Figure 3-9) suggests a transmissivity of less than 200 $ft^2$/day, despite the well's partial completion in the Purisima-A aquifer. While suggesting that the well is highly inefficient, these results appear to confirm leaky aquifer conditions.

### 3.2.3 Other Wells

***Garnet Well*** **–** As summarized in Table 3-3, SCWD's Garnet well was tested for 8 hours following its construction in 1995, with water levels recorded in both it and the Opal 4 well approximately 30 ft away. The Garnet well is screened in the lower 60 percent of the Purisima-A aquifer. SCWD's data plot for this test reports a transmissivity of approximately 4,500 $ft^2$/day (presumably using the Cooper-Jacob method).

Our analysis of the test data is presented in Figures 3-10 and 3-11, and summarized in Table 3-4. Using the Moench and Hantush-Jacob leaky-aquifer methods, we estimate a transmissivity of approximately 3,400 $ft^2$/day, a corresponding aquifer hydraulic conductivity of 17 ft/day, a storativity of about 0.002, and an aquitard hydraulic conductivity of about 0.5 ft/day. Compared to the Beltz wells, the A aquifer near the Garnet well has a greater thickness but lower transmissivity.

***Tannery II Well*** **–** SCWD's Tannery II well is screened across nearly the entire thickness of the Purisima-A aquifer (Figure 2-11). It was tested for 8 hours following its construction in 2001. The District's data plots give an estimated transmissivity of approximately 2,000 $ft^2$/day.

Our analysis of the test data is presented in Figure 3-12 and summarized in Table 3-4. Using the Hantush-Jacob leaky aquifer solution, we estimate a transmissivity of approximately 2,100 $ft^2$/day and hydraulic conductivity of about 9 ft/day. In light of the Beltz and Garnet estimates, the Tannery II results correspond to an eastward declining trend in A-aquifer transmissivity and hydraulic conductivity. Without any observation well data for the Tannery II test, estimates of other properties are less reliable. However, greater confinement is expected as the A aquifer dips deeper to the east.

***Estates Well*** **–** SCWD's Estates well is screened in both the Purisima-A and -BC aquifers (Figure 2-11). It was tested for 7 hours in 1983. Using the Hantush-Jacob method, we estimate a transmissivity of approximately 2,400 $ft^2$/day (Figure 3-13 and Table 3-4). Subtracting the transmissivity estimated for the Tannery II well, this suggests a transmissivity of about 300 $ft^2$/day for the BC aquifer, and a corresponding hydraulic conductivity of about 1 ft/day.

***Madeline Well*** **–** SCWD's Madeline well is screened in only the BC aquifer (Figure 2-11). Our analysis of a 1984 12-hour test indicates a transmissivity of about 240 $ft^2$/day and hydraulic conductivity of about 1 ft/day (Figure 3-14, Table 3-4). This agrees fairly well with the Estates well BC-aquifer estimate. The data are fit equally well by the confined and leaky solutions, suggesting that the BC aquifer is essentially confined at this depth and in this area.

***San Andreas Well –*** SCWD's San Andreas well penetrates the upper and lower Aromas aquifer and more than 200 ft of the underlying Purisima-F aquifer (Figure 2-11). Figure 3-15 and Table 3-4 present three alternative interpretations of its 1991 8-hour test. The Hantush-Jacob leaky aquifer solution excludes the upper Aromas from the aquifer thickness and assumes a 20-ft thick aquitard between the upper and lower zones. It estimates a transmissivity of 4,700 $ft^2$/day and aquifer and aquitard hydraulic conductivities of 13 and about 2 ft/day, respectively. Alternatively, the Neuman unconfined aquifer solution includes the saturated portion of the upper Aromas in the aquifer thickness and accounts for partial penetration of the aquifer since the upper Aromas is not screened. It gives a transmissivity of 6,800 $ft^2$/day and horizontal and vertical hydraulic conductivities of 15 and 1.5 ft/day, respectively. Given the similarity of the estimated hydraulic conductivities, these two methods appear to be essentially equivalent interpretations of the aquifer conditions. Indeed, conditions probably range from unconfined to leaky in the Aromas and semi-confined to confined in Purisima-F. The much higher transmissivity and unreasonable storativity estimated by the Theis (or Cooper-Jacob) method (i.e., 25,000 $ft^2$/day and $\sim 1\times10^{-20}$) demonstrate the problem with assuming fully confined conditions in this case.

***Seascape and Sells Wells –*** SCWD's Seascape and Sells wells were both tested in 1987 and in each case two observation wells were monitored. Similar to the San Andreas well, these are screened in the lower Aromas and the Purisima-F aquifers (Figure 2-11). Estimated transmissivities and storativities were reported for these tests (LSCE, 1987b), but we did not locate plots or tables of time-drawdown data for an independent analysis. The previously estimated transmissivities are 12,000 and about 70,000 $ft^2$/day for the Seascape and Sells wells, respectively. These values are considerably greater than our estimates for the San Andreas well using the Hantush-Jacob and Neuman solutions, and suggest that the Theis or Cooper-Jacob methods may have been inappropriately applied. As discussed in Section 3.3, estimates of transmissivity from these wells' specific capacities range from 5,000 to 10,000 $ft^2$/day.

## 3.3 Transmissivity Estimates from Specific Capacity

Table 3-3 and Tables 3-5 through 3-10 present specific capacity data from a variety of sources for various study-area wells. Using the method described in Section 3.1.4, this section presents a range of transmissivity and hydraulic conductivity estimates derived from these data. These data help support the few estimates derived from aquifer-test data, and provide the only available estimates for otherwise untested aquifer zones (e.g., the Purisima-DEF aquifer). The available data sets include the following:

- Table 3-3 summarizes pump-test records for 10 wells on-file with the District. The associated semi-log time-drawdown plots have been extrapolated (previously or by this study) to provide specific capacities corresponding to 24 hours of pumping. This data set has the advantage of relatively static initial water levels and constant pumping rates.
- Table 3-5 summarizes specific capacities for 25 wells provided in the 1968 USGS report by Hickey. The conditions under which these values were obtained were unspecified.
- Table 3-6 presents a range of specific capacity estimates reported for 17 SCWD wells by two previous studies (Thorup, 1981; LSCE, 1984a). In the latter study, drawdowns were based on differences between in-service pumping levels and seasonal high static levels. The upper range of these estimates appear generally too high compared to the other sets of estimates.
- Table 3-7 presents a representative maximum specific capacity for the Purisima Formation north of the Zayante fault (Johnson, 1980).
- Table 3-8 presents representative specific capacities for 11 SCWD wells (LSCE, 1999).

- Table 3-9 summarizes a range of hydraulic conductivities estimated from the specific capacities of 12 unidentified wells (Essaid, 1992).
- Table 3-10 gives estimated aquifer properties for 24 area wells (Montgomery Watson et al., 1998). To help understand the basis of these transmissivity and hydraulic conductivity estimates, we backed-out the corresponding values of aquifer thickness and specific capacity using the method described in Section 3.1. There are several inconsistencies between the various estimates in this table and our interpretations.

Based on the range of hydraulic property values estimated from aquifer test data (Section 3.2), we used the following values of $f$ (i.e., the "2,000" factor explained in Section 3.1.4) for estimating transmissivity from specific capacity:

- Shallow Purisima-A aquifer (i.e., west from SCWD's Rosedale well): $f$ = 1,900 (conditions are almost as needed for $f$ = 2,000, as indicated by close matches with aquifer test data).
- Deep Purisima-A aquifer: $f$ = 1,800 (compensates for eastward decrease in $T$).[12]
- Purisima-BC aquifer: $f$ = 1,700 (compensates for relatively low $T$).
- Aromas and Purisima-F dual aquifer: $f$ = 1,700 (compensates for relatively high $S$ and larger well diameters).

The following paragraphs summarize transmissivity and hydraulic conductivity estimates for each aquifer zone as derived from the specific capacity data and the aquifer test interpretations discussed previously.

***Older Sandstone (Tu) –*** Of the wells reviewed, the Main Street well is the only one screened in an older sandstone (Tu) below the Purisima AA zone. Because it is also screened in the AA and "Tp?" zones, and has a gravel packed extending up into the A zone, several assumptions are needed to estimate the older sandstone hydraulic properties from the aquifer test results presented in Section 3.2.1. First, we assume that vertical flow through the gravel pack from the A zone is less than 35 gpm, or about 5 percent of the test pumping rate ($Q_p$) (consistent with a similar estimate by Driscoll, 1986). Next, we assume that the Purisima-AA zone has a depth-averaged hydraulic conductivity of 6 ft/day (see discussion under next heading) and that the fine-grained "Tp?" zone has a nominal hydraulic conductivity of 1 ft/day. Assuming the zone thicknesses ($b$) encountered by the Main Street well (Table 2-2), the older sandstone requires a hydraulic conductivity ($K$) of approximately 15 ft/day to achieve a total transmissivity ($T$) of 3,700 ft$^2$/day that was estimated from the aquifer test, as shown in the following table. The estimated hydraulic conductivity could be ±5 ft/day given reasonable alternative estimates for the other units.

| Zone | $b$ (ft) | $K$ (ft/day) | $T$ (ft$^2$/day) | % | $Q_p$ (gpm) |
|---|---|---|---|---|---|
| A | 100 | | 180* | 5% | 35 |
| AA | 220 | 6 | 1,320 | 36% | 260 |
| Tp? | 145 | 1 | 150 | 4% | 30 |
| Tu | 135 | 15 | 2,050 | 55% | 400 |
| Sum | 600 | | 3,700 | 100% | 725 |

(*Effective $T$ based on 5% of total flow through the gravel pack)

[12] Recall from Section 3.1.4 that this method incorporates an initial guess of $T$.

***Purisima-AA*** **–** A transmissivity for the Purisima-AA zone may be estimated as the difference between transmissivities estimated for the Rosedale and Garnet wells, inasmuch as the former is screened in both the AA and A zones and the latter only in the A zone. Using the values from Table 3-3 gives an AA-zone transmissivity of 1,000 $ft^2$/day. A lower value may be appropriate given that the transmissivities estimated from A-zone aquifer tests (Table 3-4) are about 10 percent lower than those in Table 3-3. Dividing by an AA-zone thickness of 150 to 220 ft gives an estimated hydraulic conductivity of 4 to 6 ft/day.

***Purisima-A*** **–** Transmissivities estimated from the specific capacities of several District wells (e.g., Garnet, Opal, Tannery, Maplethorpe, Monterey) compliment the Purisima-A aquifer-test estimates presented in Tables 3-2 and 3-4. As summarized below, these data suggest that the A-zone transmissivity decreases as it dips downward to the east between the Beltz wells and Tannery II well, then remains roughly the same downdip to the Estates well.

| | *T* (ft2/day) | *K* (ft/day) |
|---|---|---|
| Live Oak/Beltz wells | 3,600 - 6,800 | 35 - 65 |
| West Capitola/Soquel (e.g., Garnet well) | 3,000 - 3,500 | 15 - 18 |
| East Capitola/Soquel (e.g., Tannery and Estates wells | 2,000 - 2,400 | 7 - 10 |

***Purisima-BC*** **–** Transmissivities estimated from the specific capacities of SCWD's Madeline and Ledyard wells compliment estimates from the Madeline and Estates aquifer tests (Table 3-4). Values range from 200 to 400 $ft^2$/day, with associated hydraulic conductivities of 1 to 3 ft/day.

***Purisima-DEF*** **–** SCWD's T. Hopkins and Aptos Creek wells produce from the Purisima-DEF aquifer zone, although the latter is also screened in the BC zone. The District's former Hillcrest and Seacliff wells produced from the upper portion of the DEF zone (i.e., units E and/or the lower portion of F). Based on specific capacities reported for these wells, the DEF zone has an overall estimated transmissivity ranging from 300 to 1,500 $ft^2$/day and hydraulic conductivities ranging from 1 to 5 ft/day. Due to the lack of aquifer test data, representative storage coefficients for the DEF aquifer–and its associated degree of confinement–are relatively unknown.

***Purisima-F/Aromas*** **–** SCWD's existing Aromas-area wells are screened in both the lower Aromas and Purisima-F aquifer zones (Figure 2-11). Based on aquifer test and specific capacity data, four of these wells (Country Club, Bonita, San Andreas, and Seascape) appear to share similar aquifer properties, with transmissivities ranging from about 4,500 to 7,500 $ft^2$/day and hydraulic conductivities ranging from 13 to 20 ft/day.

Permeabilities appear to increase in the vicinity of the District's two most southeastern wells, Altivo and Sells. The estimated transmissivity and hydraulic conductivity of the former are 8,600 $ft^2$/day and 26 ft/day, while estimates for the latter are about 10,000 $ft^2$/day and 30 ft/day, respectively.

SCWD's inactive Aptos Jr. High School well,[13] located northwest of the other Aromas-area wells, has an apparently lower transmissivity (~2,000 to 3,700 $ft^2$/day) and hydraulic conductivity (6 to 12 ft/day). This well occurs at the edge of the Aromas Sands outcrop and is essentially a Purisima well.

[13] This well has been referred to as the "Aptos" well in recent years. Previously it was known as the "Aptos School" well among several other names (Table 1-2). We found data for the "Aptos Creek" well mistakenly assigned to the

Several older wells appear to have been screened only in the Aromas Formation (D'Anna, Waugman, and La Selva Beach 1 and 2). Based on specific capacities reported by Hickey (1968), their apparent transmissivities were only 500 to 2,500 $ft^2$/day, with hydraulic conductivities of 2 to 10 ft/day. These values probably reflect high well losses, but may suggest that the District's currently active wells obtain a significant portion of their yield from the underlying Purisima Formation.

The District's old Cliff well appears to have been screened mostly in the Purisima-F zone below the Aromas. Based on information provided by Hickey (1968), its transmissivity was only 1,000 $ft^2$/day with a hydraulic conductivity of about 3 ft/day. If not due to well losses, these relatively low values may suggest a zone of lower permeability locally within the F zone.

It is reasonable to expect spatially variable aquifer properties given the heterogeneity of both the Aromas and Purisima formations. Moreover, it is reasonable to encounter less apparent variability in terms of total transmissivity for relatively deep wells completed in both formations.

Previous interpretations of aquifer test data for the Seascape and Sells wells estimated transmissivities 2 to 7 times greater than estimated by this study (Tables 3-3 and 3-10). As discussed previously (Section 3.2.8), this appears due to an inappropriate assumption of fully confined conditions (i.e., use of the Cooper-Jacob solution). An overestimation of transmissivity is likely to result in an underestimation of drawdown, which could affect the District's efforts to set and achieve water-level objectives.

The variation of aquifer properties among SCWD's Aromas-area wells, both apparent and real, may be due to several factors, including: (a) the heterogeneity of the Aromas Sands; (b) the heterogeneity of the Purisima-F unit, especially given that wells encounter different sections of the formation as it dips from west to east; (c) predominantly Purisima aquifer conditions where the saturated thickness of the Aromas is limited; (d) the superposition of multiple aquifer zones ranging from unconfined to semi-confined; (e) underestimating transmissivity based on the specific capacities of older, inefficient wells; and, (f) overestimating transmissivity by not accounting for leaky or unconfined conditions. Furthermore, the aquifer properties of the Purisima may be somewhat enhanced where overlain by the Aromas Sands due to the relatively high circulation of groundwater under these conditions.

***Purisima Formation North of Zayante Fault –*** As presented in Table 3-7, the transmissivity and hydraulic conductivity of the Purisima Formation north of the Zayante fault is estimated at 450 $ft^2$/day based on a maximum specific yield of 2 gpm/ft for domestic wells in the area (Johnson, 1980). Depending on the assumed aquifer thickness, the hydraulic conductivity ranges from 0.2 to 2 ft/day.

### 3.4 Pajaro Valley Estimates

Table 3-11 summarizes aquifer property estimates from previous groundwater studies of Pajaro Valley. For the most part, these are consistent with the range of estimates for the District's Aromas-area wells, i.e., transmissivities range from about 2,000 to more than 10,000 $ft^2$/day and hydraulic conductivities range from 10 to more than 40 ft/day.

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"Aptos" well in the SCWD data base. SCWD staff have determined that this well should now be referred to as the "Aptos Jr. High School" well.

## 3.5 Modeled Values

Table 3-12 presents the aquifer properties used in eight previous groundwater models of the Soquel-Aptos area and/or Pajaro Valley.

***UCSC Graduate Student Model (Handel et al., 1985)***[14] **–** This single-layer, steady-state model initially assumed a Purisima hydraulic conductivity of nearly 90 ft/day, then reduced it by two orders of magnitude to about 1 ft/day as a result of calibration. Similar to the USGS model described below (Essaid, 1992), the initial high value of hydraulic conductivity was found to cause excessive groundwater flow out to the ocean and an inability to mound groundwater inland.

***Pajaro Valley Model (Bond and Bredehoeft, 1987)* –** This basin-wide model of Pajaro Valley assumed a transmissivity of 13,000 $ft^2$/day for the Aromas aquifer, which corresponds to a hydraulic conductivity of 43 ft/day assuming an aquifer thickness of 300 ft.

***Pajaro Valley Model (Johnson et al., 1988)* –** This three-layer model simulated terrace, alluvial, and eolian deposits, and the upper and lower Aromas Sands. The top, water-table layer was above most well screens. The middle and lower layers had calibrated transmissivities of 13,000 and 7,800 $ft^2$/day, respectively.

***USGS Model (Essaid, 1992)* –** This model began with an "initial-guess" of 8.5 ft/day for the Purisima Formation's overall hydraulic conductivity based on an interpretation of specific capacity data (Table 3-9). As a result of calibration, this value changed to 0.3 ft/day (i.e., lowered by a factor of nearly 30) except for portions of a combined AA/A-zone model layer assigned 14 ft/day. Using values higher than 0.3 ft/day caused excessive groundwater drainage from inland areas where groundwater was expected to mound. The author speculated that the discrepancy between the initial-guess and calibrated hydraulic conductivities was because the specific capacity data were biased to higher permeability units and did not account for the effects of vertical leakage. This model also used very low values of leakance, forcing predominantly horizontal groundwater flow with little interaction between layers.

The current study has found reasonable agreement between aquifer test and specific capacity estimates of transmissivity, and thus questions the low hydraulic conductivities used in the previous model. We also question the lumping of units AA and A into a single 800-ft thick model layer, inasmuch as unit A is an important zone of uniquely high permeability. The inability to calibrate using the initial high values of hydraulic conductivity suggests that permeabilities may decrease inland from existing high-capacity production wells. Furthermore, faulting could offset permeable zones and reduce the effective permeability at sufficiently large scales.

***SCWD IGSM Model (Montgomery Watson et al., 1998)* –** The initial hydraulic properties assumed by this model are summarized in Table 3-10. Similar to the 1992 USGS model, calibration resulted in hydraulic conductivities much lower than expected for layers representing Purisima units (0.02 to 0.5 ft/day), although values up to 50 ft/day were used locally in model layers representing units C through F. Calibrated values of storativity ranged below $1\times10^{-6}$, which is less than reasonable given the compressibility of water (see discussion at the beginning of Section 3). Modeled values of leakance were 2 to 7 orders of magnitude greater than used in the USGS model. Similar to the USGS model, Purisima units AA and A were combined into a single model layer.

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[14] Lead by visiting lecturer, Ken Belitz/USGS.

***Pajaro Valley Model (RMC, 2000) –*** This updated basin-wide model of the Aromas Sands and alluvial aquifers of Pajaro Valley uses hydraulic conductivities ranging from 0.5 to 300 ft/day, resulting in modeled transmissivities of about 150 to 60,000 $ft^2$/day.

***SCWD Aromas DWSAP Model (Todd, 2002) –*** This uncalibrated, steady-state model of the aquifer and recharge area contributing to the District's Aromas-area wells assumed a transmissivity of nearly 30,000 $ft^2$/day, which corresponds to an aquifer hydraulic conductivity of approximately 100 ft/day. These values are about three times greater than interpreted for this area in Section 3.3.

***City of Santa Cruz DWSAP Model (Johnson, 2003) –*** This model of the western Purisima aquifer assumed hydraulic properties roughly equivalent to those interpreted in Sections 3.2 and 3.3. The effective leakance was about an order of magnitude smaller than in the IGSM model. Although not rigorously calibrated, this model successfully simulated the groundwater surface and the local water balance.

## 3.6 Summary and Conclusions

Table 3-13 presents our initial hydraulic-property estimates for the Soquel-Aptos hydrogeologic units. These are reasonably well supported for areas encompassing the available data. However, aquifer properties remain poorly known in large portions of the basin where information is limited.

Specific capacities estimated from private wells (e.g., Table 3-7) and lithologies interpreted from inland test holes and monitoring wells (e.g., SC-11 and SC-12) suggest that highly productive aquifer zones are less common inland of the coastal terrace.[15]

Three previous models of the Soquel-Aptos area have assumed that Purisima aquifer permeabilities are much lower than indicated by available aquifer-test and specific-capacity data (i.e., 3 to 100 times lower) (Handel et al., 1985; Essaid, 1992; Montgomery Watson et al., 1998). Apparently, simulating inland groundwater levels required retarding groundwater outflow with reduced permeabilities. Additionally, relatively low permeabilities were required for model layers that lumped highly productive aquifer zones with less permeable zones (e.g., the combination of units AA and A into a single 800-ft thick layer in the 1992 and 1998 models).

It is difficult to refute the body of evidence supporting higher permeabilities in aquifer zones along the coastal terrace in the vicinity of District wells. These estimates are consistent with the District's sustained, long-term groundwater production. In addressing various groundwater management issues, it is important to accurately reflect these known aquifer properties.

Away from these established aquifer zones, effective permeabilities may decrease for one or more reasons, including changes in formation lithology due to facies changes (i.e., changes in the sedimentary depositional environment) and the effects of faulting.

Data-based estimates of aquifer properties and insights from prior modeling can be honored by zoning aquifer properties within model layers and defining model layers more consistently with the interpreted hydrostratigraphy (as proposed in Section 2.3). The interpreted data suggest that the

[15] Given roughly a century of development in the Soquel-Aptos area, it is reasonable that areas with good aquifer properties coincide with the locations of high capacity wells. This might seem overly coincidental, given that such wells are conveniently located near the populated coast. However, not all populated coastal areas coincide with high capacity production wells (e.g., the City of Santa Cruz), whereas favorable aquifer properties have spurred development in non-coastal areas (e.g., Scotts Valley).

hydraulic conductivity of Purisima aquifer A should be zoned to reflect higher values where it occurs at relatively shallow depths and lower values where it becomes more deeply buried down-dip to the east. A similar trend may occur in other units. Inland areas may require lower permeabilities based on available, mostly empirical, information and past modeling experience.

The analyses presented in this section demonstrate the occurrence of predominantly leaky, semi-confined conditions in Purisima aquifer A from the Beltz wells east to SCWD's Tannery well. The deepest screened zones (including aquifers AA and Tu) are more confined. Purisima aquifer A becomes more confined as it dips down further to the east, as demonstrated by the response of SCWD's Estates well. The Purisima-BC aquifer also is confined where encountered by District wells. The one aquifer test analyzed for the Aromas area suggests that SCWD wells encounter multiple aquifer conditions, ranging from unconfined to leaky conditions in the Aromas Sands to semi-confined and possibly confined conditions in the deeper Purisima-F aquifer. Aquifer test data were unavailable for the Purisima-DEF aquifer.

# 4 Groundwater Occurrence, Movement, and Storage

Groundwater occurs under a wide variety of conditions throughout the study area as a function of its multiple hydrogeologic units, their structure, and their range of aquifer properties. Because of the dipping geologic structure, groundwater conditions grade from unconfined to more fully confined from west to east within each Purisima unit. Groundwater flows through the system from recharge areas toward points of discharge, moving within these units and across contacts between units. Groundwater storage fluctuates with the changing saturated thickness of shallow, unconfined zones, and rather minimally with the changing hydraulic pressure of deep, confined zones. Understanding these aspects of the groundwater system requires an evaluation of groundwater levels and their response to pumping and recharge stresses. This evaluation is also critical to the potential prevention of saltwater intrusion and other pumping impacts through water-level management. Differences in general groundwater quality among the various aquifer zones provide an additional indicator of groundwater movement.

## 4.1 Groundwater Stresses

Groundwater level fluctuations are influenced primarily by variations in pumping and recharge, as discussed in the following subsections.

### 4.1.1 Groundwater Production

Tables 4-1 and 4-2 summarize historical groundwater production for SCWD, the City of Santa Cruz Beltz wells, and the Central Water District (CWD).[16] During recent years, SCWD generally pumps in excess of 5,000 ac-ft/yr (Figure 4-1) and the City of Santa Cruz and CWD each produce roughly a tenth as much. Pumping from private wells is unrecorded but estimated to be several thousand acre-feet per year (see Section 5).

During the past five years, SCWD production has been distributed as follows: 44 percent from Service Area I (Purisima aquifers A and AA, and aquifer Tu); 18 percent from Service Area II (Purisima aquifers A, BC, and DEF); and 38 percent from Service Areas III and IV (Purisima aquifer F and the Aromas Sands). The need for blending to achieve water quality objectives in Service Area IV has resulted in a recent shift in production to Service Area III.

Groundwater production varies during the year as a function of seasonal demand. On average, SCWD's production peaks in July and August at nearly twice the rate of February. Quarterly data summaries are sufficient for revealing seasonal and other trends in production (Figure 4-2).

SCWD's database contains monthly production totals for each well since October 1983.[17] Table 4-3 and Figures 4-3a and 4-3b present these data, summarized quarterly for each of the four SCWD service areas. The plots show various shifts in production among wells over time, including both increases and decreases in response to the 1987-1994 drought. Table 4-1b and Figure 4-3c present these data summarized annually. Figure 4-3d shows the average annual production for each District well during 1995-99 and 2000-03, and the estimated percent of time that each well operated.

[16] Because groundwater production peaks during summer, this report summarizes annual pumpage by calendar year rather than water year (October-September).

[17] The database excludes some wells which operated for only a short time after 1983 (e.g., the Hillcrest and Cliff wells). We obtained pumping records for the Hillcrest well dating back to 1966 from District files. Presumably, similar hard-copy records exist for other wells.

Quarterly production from the City of Santa Cruz Beltz wells has been highly variable, ranging from zero to 500 ac-ft/qtr (Figure 4-4).

In 2002-03, the approximate distribution of CWD pumping was 6 percent from its Cox Road wells and 94 percent from its Rob Roy Junction wells (Figure 4-4).

### 4.1.2 Radial Influence of Pumping

The influence of pumping on groundwater levels varies significantly as a function of aquifer conditions and hydraulic properties. The pattern of groundwater level drawdown surrounding a pumping well, or "cone of depression," is relatively deep and narrow when the aquifer transmissivity is low and the storage coefficient is high, and shallow and broad when the transmissivity is high and storage coefficient low. Because of the effect of the storage coefficient, a well's radius of influence is relatively large under confined conditions and much smaller under unconfined or leaky conditions.

Direct observation of a well's drawdown and radius of influence in the heavily developed Soquel-Aptos aquifers is difficult given the overlapping influence of other area wells and the lack of static, baseline conditions. Fortunately, the rigorous estimation of aquifer properties provided in Section 3 allows us to make reasonable distance-drawdown estimates using standard well-hydraulics equations. We use these estimates in Section 4.2 to help interpret historical hydrographs. Section 4.2 identifies several instances where the observed hydrographs appear to be consistent with the estimated radii of influence. Note that although the amount of drawdown at a particular distance is directly influenced by a well's pumping rate, the maximum distance of influence is determined solely by aquifer transmissivity and storativity, and the length of time since pumping began (e.g., Heath, 1983).

Figure 4-5 presents distance-drawdown curves representative of the various Soquel-Aptos aquifer conditions (Table 3-13) for pumping rates equivalent to 100 days of pumping, 18 hours per day, at typical well capacitates. This amount of pumping is approximately equivalent to historical maximum quarterly pumping rates (Table 4-3). These estimates apply to the pieziometric surface of the aquifer being pumped; drawdown would be less in any overlying or underlying unit.

For the general range of Purisima aquifer A transmissivities estimated in Section 3 (2,000 to 5,000 $ft^2$/day), a well pumping 700 gpm 18 hrs/day for 100 days results in about 10 to 20 ft of average daily drawdown at a distance of 5,000 ft under confined conditions, and about 1 to 5 ft of average daily drawdown at 500 ft under leaky conditions.

Drawdown is greatest and most far reaching for zone BC under confined conditions. After 100 days of pumping 300 gpm 18 hrs/day, the estimated average daily drawdown is about 75 ft at a distance of 1,000 ft, nearly 40 ft at 1 mile, and about 20 ft at 2 miles. For the same aquifer and pumping rate under leaky conditions, average daily drawdown is only about 10 ft at a distance of 500 ft.

Asymmetrical cones of depression are likely where the aquifer transitions between leaky and confined conditions. For each Purisima aquifer, drawdown probably extends further toward the east–the direction of increasing confinement.

Estimated drawdown is least in both magnitude and areal extent in the Aromas area. Under leaky conditions, average daily drawdown of about 1 ft occurs at a distance of 250 ft after pumping 750 gpm, 18 hrs/day for 100 days. Assuming confined conditions, as may occur in the underlying Purisima-F aquifer, an estimated 5 ft of average daily drawdown occurs at a distance of 5,000 ft. Drawdown of an intermediate nature occurs assuming unconfined conditions.

Figure 4-6 shows the distances between wells in the study area. SCWD production wells are generally at least 2,000 to 4,000 ft apart, but in some cases within 500 to 1,000 ft of each other.

Cones of depression probably overlap, especially where aquifer conditions are relatively confined, creating a pumping "trough." Thus, the pumping history of several nearby wells, and the aquifers from which they draw, must be considered when interpreting water level fluctuations. Water level fluctuations related to individual wells under variable use are moderated by these large radii of influence and the fairly constant overall rate of production for each service area.

LSCE (1984a) stated that the largest radius of influence for typical Purisima wells is 1,500 to 2,000 ft. The estimates presented here range much larger. Furthermore, our estimates are derived from equations that assume ideal aquifer conditions (e.g., infinite areal extent, constant saturated thickness). Actual drawdown is greater where cones of depression overlap or intersect low-flow boundaries. Such boundaries include decreases in aquifer permeability and thickness, faults, and deeply buried zones receiving minimal deep recharge.

### 4.1.3 Effect of Pumping Cycles

Production wells are turned on and off both daily and seasonally in response to varying water demand. This affects data measurements and the shape of the residual pumping depression.[18] Figure 4-7 is a set of calculated time-drawdown hydrographs illustrating the magnitude of diurnal water level fluctuations and net long-term drawdown and recovery. These estimates are for pumping 18 hours per day for 100 days, and for various aquifer conditions and distances from the pumping well.

For simulations representative of Purisima aquifer BC under confined conditions, water levels fluctuate more than 200 ft daily in a well pumping 300 gpm (Figures 4-7a, left side). After 100 days of pumping, the minimum and maximum daily drawdown is about 75 and 285 ft, respectively. If pumping stops at the end of 100 days, a slow water-level recovery begins such that 8 ft of residual drawdown remain after another 100 days. Under these conditions, a "static" water level measurement varies greatly depending on how the well was operated and how long it was off prior to measurement. Similarly, measurements in a monitoring well 30 ft from a production well can vary by plus or minus (±) 50 ft depending on when the measurements are taken during the daily pumping cycle. At a distance of 1,000 ft, the diurnal fluctuation becomes ±5 ft. At 2,000 ft, the diurnal fluctuation is minimal but (a) net drawdown is still about 60 ft after 100 days and (b) the recovery curve is essentially the same as at the pumping well.

As shown in Figure 4-7c, the residual pumping depression from cyclic pumping resembles the shape of a pan more rather than a cone. For the BC aquifer under confined conditions, this depression has a depth of several tens of feet within a radius of many thousands of feet. The same effect occurs in other aquifer zones, but to a lesser degree where transmissivities, storage coefficients, and/or aquitard leakage are greater. In the case of multiple pumping wells, these depressions may overlap and create broad areas of similar residual drawdown.

For conditions assumed representative of aquifer BC under leaky conditions, water levels fluctuate more than 150 ft/day in the pumping well (Figure 4-7a, right side). At the well, the daily maximum level stabilizes after 10 days at about 30 ft below the initial level, and full recovery occurs after only 10 days once the well is left off. Water levels fluctuate about ±25 ft at a distance of 30 ft, and about ±10 ft at a distance of 100 ft.

Figure 4-7b presents a similar set of drawdown hydrographs for conditions assumed representative of Purisima aquifer A (for a well pumping 700 gpm) and Purisima aquifer DEF (for a well pumping 350

[18] "Residual" refers to the drawdown remaining after a period of incomplete water-level recovery.

gpm). The magnitude of drawdown is roughly half of that estimated for aquifer BC, however the same general observations apply.

Although pumping cycles have an immediate effect on groundwater levels, long-term changes may be moderated by the influence of pumping-induced gradients on recharge and leakage. The hydraulic gradients caused by pumping induce additional recharge and leakage that may limit total drawdown and enhance recovery. When pumping is reduced, less recharge and/or leakage are induced.

### 4.1.4 Influence of Climatic Variation on Recharge

As discussed in greater detail in Section 5, groundwater recharge occurs from the deep percolation of precipitation and excess applied water. Applied-water recharge is fairly constant year to year whereas precipitation recharge varies with the climatic cycle (i.e., droughts versus wet periods). Figure 4-1 compares the Santa Cruz precipitation record, both as a bar chart and plot of cumulative departure from average, to the SCWD pumping record. Figure 4-8 identifies the major drought and wet periods of the past century. The last 30 years have included two significant droughts and two significant wet periods.

The climatic cycle potentially affects groundwater levels in a variety of ways. One potentially significant effect is increased groundwater use during droughts in response to depleted surface water supplies and increased irrigation needs. Although SCWD has not relied on surface water, others that do may resort to increased groundwater use during droughts, including use of the Beltz wells by the City of Santa Cruz. Groundwater recharge varies with precipitation, but the effect may be muted in the relatively deep aquifer zones from which the District draws. Substantial lag times are likely for recharge to travel to, or impact pressures within, relatively deep coastal aquifers. Low vertical hydraulic conductivity may limit flow to deep aquifers and cause a significant proportion of wet-period recharge to drain to streams. The effect of recharge on groundwater levels is generally minor relative to the influence of pumping.

## 4.2 Groundwater Level Hydrographs

This section reviews the available water-level data in sufficient detail to interpret the groundwater system and evaluate cause-and-effect relations between water levels, pumping, and aquifer and climatic conditions. SCWD monitors groundwater levels in 13 active and one or more inactive production wells, and 57 dedicated monitoring wells distributed among 17 installations of one to five wells each. Each monitoring well targets a relatively discrete zone of the Purisima Formation or Aromas Sands. The District's database includes the complete water-level record for its dedicated monitoring wells (i.e., since 1985) and for its production wells since 1990. We entered earlier production-well water levels from data sheets on file with the District dating back to 1973.[19] Additionally, the USGS monitored groundwater levels in several area production wells from 1965 to 1990, and these data were obtained through its web site. The City of Santa Cruz records groundwater levels in its Beltz production wells and a recently expanded system of dedicated monitoring wells (J. Hyman/City of Santa Cruz Water Department, written communication, June 1, 2004). Water level records are also available for CWD production wells (C. Wales/CWD, written communication, February 12, 2004).

Production-well water levels are recorded when the well is both on and off, referred to as pumping and static levels. Both types of measurements are influenced by the preceding length of time that the

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[19] See Figure 4-6 for the approximate location of inactive and destroyed wells. Active-well locations are shown in both Figures 1-2 and 4-6.

well was on and/or off. SCWD staff use the following protocol for monitoring pumping-well water levels (A. White/SCWD, written communication, November 25, 2003):

> Each production well is visited as many as four times over a four day period prior to the 15th and 30th of each month. On the first visit, a pumping or static level is taken depending on whether the pump is found on or off. In either case, there is no record of how long the pump was either on or off, a period that could range from minutes to days. During the next three days, the operator will try to sound the well during the reverse condition. If unsuccessful by the last day, the operator will either shut off the pump, wait 15 minutes, and take a static reading or turn the well on, wait 15 minutes, and measure a pumping water level.

Under these conditions, the collected data are inevitably "noisy" given that water levels are constantly adjusting to either pumping or recovery (as discussed in Section 4.1.3). The same is true for monitoring wells relatively close to pumping wells. Sudden water-level changes also may reflect equipment problems (e.g., leaky airlines), inconsistent or modified procedures,[20] or other measurement and recording errors. We refer to these collectively as "measurement artifacts" and identify them with question marks where suspected on the data plots. The production-well hydrographs presented in this section omit certain data spikes that obfuscate the distinction between static and production water levels.

Past studies pointed out uncertainties associated with "static" water level data and suggested waiting up to 24 hours after turning a well off before taking a measurement (e.g., Thorup, 1981; LSCE, 1981). This report's analysis (e.g., Figures 4-6 and 4-7) suggests that the ideal time for a static reading is immediately prior to the beginning of a daily pumping cycle. Alternatively, it is reasonable to accept that static conditions do not exist given that wells go on and off for various reasons, and because water levels may require days to months to fully recover. The long-term hydrographs presented in this section suggest that the District's procedures have been reasonably consistent over time.

Tidal fluctuations provide an additional source of water-level noise for coastal monitoring wells. Using a transducer and data logger in its new Soquel Point monitoring well, the City of Santa Cruz observed several feet of daily tidal response (C. Hopkins/Hopkins Groundwater Consultants, personal communication, June 24, 2004). Thus, an "error bar" of several feet should be considered for most coastal water level data.

Shallow groundwater-level data are available for monitoring wells installed at various remediation sites (e.g., gas stations). We reviewed reports on file with the Santa Cruz County Health Services Agency and obtained water-level records for several area sites.

### 4.2.1 USGS Records

Available SCWD groundwater level records begin about mid-way through the steep increase in District production that occurred between 1965 and 1985. To assess water-level changes throughout this period, Figure 4-9 presents hydrographs pairing USGS data dating back to 1965 with District records for four Purisima production wells. Declining trends during 1965-75 appear evident for the Monterey and Maplethorpe wells. A trend is less apparent for the Opal/Garnet wells. Water levels in the Aptos Creek well were already nearly –40 ft msl in 1965, indicating that a decline of about 50 ft or more had already occurred. Based on these few early data and the lack of significant trends after 1975, it appears that a large groundwater-level response to developed aquifer conditions occurred

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[20] Procedures may have been modified per consultant recommendations in the early 1980s (e.g., LSCE, 1981, 1984).

fairly quickly. This created conditions sufficiently conducive to leakage to offset further net declines.

### 4.2.2 Beltz and SCWD Service Area I Hydrographs

This and the following sections present hydrographs constructed from the monitoring records of SCWD, the City of Santa Cruz, and CWD. Their order of presentation is generally from west to east, starting with the Beltz wells and ending with the Aromas-area wells. Each figure includes plots of nearby pumping (where "nearby" is based on the variable radii of influence estimated in Section 4.1.2) and the cumulative departure of precipitation from average during the hydrograph period.

***Beltz Wells*** (Figure 4-10) – The Beltz wells produce from Purisima aquifer A (and AA in the case of Beltz 7). Figure 4-10a presents static and pumping water-level hydrographs for Beltz wells 2,[21] 4, 6, and 7 for varying periods ranging between 1979 to present. Other than Beltz 7, these wells are no longer operational. Static water levels generally have varied between 10 and –10 ft msl. Pumping levels have ranged from –10 to –70 ft msl, with the exception of Beltz 7 for which they have been as low as –120 ft msl.

Figure 4-10b presents hydrographs for Beltz wells 8 and 9, which have operated since the late 1990s, and the City's monitoring wells. Static levels are generally above sea level in Beltz 8 and as low as –30 ft msl in Beltz 9.

The Pleasure Point monitoring-well cluster is about 2,500 ft east and southeast of the Beltz production wells (Figure 4-6a). Its three piezometers monitor the A and AA aquifers. Water levels were below sea level when monitoring began in the late 1980s, corresponding to a peak Beltz pumping period. Water levels then recovered, eventually to nearly 20 ft msl, in response to reduced pumping and the end of the drought.

***SC-1, Opal, and Garnet Wells*** (Figure 4-11) – Monitoring-well cluster SC-1 is about 900 to 1,000 ft toward the coast from the Garnet well and inactive and former Opal wells. The Opal and Garnet wells have produced an average of 300 to 400 ac-ft/yr from Purisima aquifer A, resulting in 30 to 60 ft of drawdown, pumping levels as low as –60 ft msl, and, at SC-1, a 10-ft downward vertical gradient from the B to the A zone. Because of lower well efficiencies (LSCE, 1981), pumping levels in Opal 2 and 3 fell below –90 ft msl.

Water levels in SC-1A closely track static levels in the Opal 1 and Garnet wells, dipping below sea level during periods of sustained production. Reduced pumping from Opal 1 during 1989-1993 resulted in 10 ft of water level recovery in the A zone and the near loss of any vertical gradient. A steady decline in SC-1A levels was associated with a steady increase in Opal and Garnet production during 1993-2003. Little or no relation is apparent between SC-1 water levels and pumping from the Beltz wells about 4,000 ft to the southwest. Water levels at SC-1 are not significantly influenced by the drought cycle.

***SC-13A, Opal, and Garnet Wells*** (Figure 4-12) – Deep monitoring well SC-13A is near the Garnet and former Opal wells, although its screened interval corresponds to a zone deeper than Purisima A. While SC-13A water levels have been similar to Opal 1, Garnet, and SC-1 since the mid-1990s, records indicate that they were as much as 40 ft higher prior to 1989. Although this drop coincided with the start of the Main Street well 7,200 ft away, it is probably unrelated and instead reflects some sort of measurement artifact. Furthermore, water levels in SC-13A do not correlate to pumping by the Rosedale well, which is closer (5,400 ft) and also has a screened interval below the A aquifer.

[21] Sometimes referred to as "Beltz 1 & 2."

***Main Street, SC-18, and SC-10 Wells*** (Figure 4-13) – Average production of nearly 900 ac-ft/yr from the Main Street well results in pumping levels as low as –150 ft msl and an 80-ft difference between static levels and pumping levels. The average rate of production increased from about 700 ac-ft/yr in 1994-96 to 1,000 ac-ft/yr in 2000-02, resulting in an additional 11-ft decline in average static water levels. About 40 ft away, water levels in the Tu zone (SC-18AA) closely track the Main Street static levels. There is a downward vertical gradient of as much as 30 ft between the AA (SC-18A) and Tu (SC-18AA) zones. Levels recovered with reduced pumping in 2003.

Water levels fluctuate in response to seasonal groundwater production in SC-10AA, about 6,800 ft north of the Main Street well. The production wells responsible for this response probably include nearby private wells but also may include the Main Street well as indicated during the 1991 aquifer test (Section 3.2). SC-10AA levels have declined nearly 10 ft in 20 years, reducing the upward vertical gradient between SC-10AA and SC-10A. The nearly flat SC-10A hydrograph is probably controlled by groundwater discharge to nearby Soquel Creek. Neither SC-10A nor SC-10AA appear significantly influenced by the climatic cycle.

***Rosedale and Monterey Wells*** (Figure 4-14) – The Rosedale well produced as much as 1,000 ac-ft/yr during its initial years of operation in the mid-1980s, and has since produced an average of more than 500 ac-ft/yr from the Purisima A and AA aquifers. Static water levels fluctuate 10 to 40 ft/yr, are trending downward at more than 1 ft/yr, and are generally below sea level. Pumping water levels range from –70 to –130 ft msl, about 80 to 115 ft below static levels, and have been trending downward at more than 2 ft/yr since falling below the top of the well screens in 1994 (i.e., saturated thickness, and thus transmissivity, are declining). These downward trends are consistent with the fact that Rosedale pumps a relatively high proportion of the time (Figure 4-3d) and also may reflect increased production by the Main Street well through 2002, located about 2,400 ft to the northwest.

The Monterey well's production from the Purisima-A aquifer has averaged 200 ac-ft/yr during recent years. Production was twice as much during the mid-1980s. Static water levels declined 15 to 20 ft–falling below sea level–when Rosedale began operating about 2,300 ft to the northwest. Water levels partially recovered as production from the Main Street well, and then the Garnet well, lessened demands on the Monterey, Maplethorpe, and Tannery wells. The 1993-97 drop in Monterey water levels appears uncorrelated to pumping and probably represents measurement artifacts. Pumping levels are 20 to 30 ft below static levels.

***Maplethorpe and Tannery Wells*** (Figure 4-15) – Separated by a distance of approximately 560 ft, the Maplethorpe and Tannery wells are two of the District's closest production wells. Through 1999, their combined production from the Purisima-A aquifer averaged about 600 ac-ft/yr, with Tannery producing about 70 percent of the total. Maplethorpe's production became sporadic after 1995 and is now offline. A Tannery replacement well began operating during 2001-02.

Prior to 2000, Maplethorpe's static levels were 10 to 20 ft above pumping levels, fluctuated about 10 to 30 ft/yr, and were almost always below sea level. Seasonal-low static levels declined about 15 ft when the Estates well began operation in 1987. The Estates well produces from the Purisima-A and -BC aquifers in Service Area II, more than 5,000 ft to the east. The apparently greater influence of the Estates well than the closer Rosedale well on Maplethorpe's water levels reflects the increasing confinement and decreasing transmissivity of the A aquifer as it dips to the east. Maplethorpe's static levels rose about 10 ft in 1998 for an uncertain combination of reasons, then rose another 10 ft while the Tannery well was out of service. Since being offline, Maplethorpe's annual water-level fluctuations have continued as before, indicating the strong influence of the nearby Tannery well and other more distant District wells. Its nearly 30-year hydrograph exhibits minimal response to the hydrologic cycle.

Tannery pumping levels were 20 to 30 ft below static levels through the early 1980s, then declined to 50 to 60 ft below static once the Estates well began operation. Both static and pumping levels fluctuate about 15 to 25 ft annually and are nearly always below sea level. Static levels rose about 15 ft when both it and Maplethorpe were not operating. Initial production from the new Tannery II well is about 500 ac-ft/yr, with pumping levels about 10 ft lower than before.

***SC-3 Monitoring-Well Cluster*** (Figure 4-16) – Located at the coast, monitoring-well cluster SC-3 is 2,200 to 4,500 ft from the nearest District production wells (Opal 1 and Garnet to the southwest, Main and Rosedale to the northwest, and Monterey and Tannery to the northeast). Its hydrographs indicate a 30-ft downward gradient from Purisima zones C to B, and again from zones B to A. These strong vertical gradients are indicative of the B-aquitard's low permeability.

Zone-A water levels are near sea level and fluctuate about 10 to 15 ft/yr. The period of record began with declining levels in the A and B zones in response to Purisima production increases through the 1970s and early 1980s. Water levels stabilized and then partially recovered during 1989-93, as total production slightly decreased and peak production partially shifted from Rosedale to the more distant Main Street well. Zone B levels recovered less, but then recovered a few feet more in the late 1990s in response to decreased production from aquifer BC in Service Area II (Figure 4-3a). Water levels in the shallowest, C-zone monitoring well are relatively flat.

### 4.2.3 SCWD Service Area II Hydrographs

Consistent with radius-of-influence estimates (Section 4.1.2), hydrographs within Service Area II are compared to pumping over a wide area.

***SC-16 and Estates Well*** (Figure 4-17) – The Estates well currently produces somewhat less than 500 ac-ft/yr from the Purisima-A and -BC aquifers. Static levels average about –5 to –15 ft msl and fluctuate down to –70 ft msl. Although initially stable at about –80 ft msl, average pumping levels began declining more than 4 ft/yr when Service Area II production increased by several hundred acre-feet during the mid-1990s. Pumping levels now fluctuate near –130 ft msl, despite a decline in overall production. This suggests that either the Estates well is losing efficiency or the pumping depression has encountered one or more low-flow boundaries in the BC aquifer and/or deeply buried A aquifer. The deepest pumping levels have come within 15 ft of the uppermost well screens.

Monitoring-well cluster SC-16 is about 10 ft from the Estates well. Water levels fluctuated as much as 80 ft prior to 1990 when the Estates well was producing about 900 ac-ft/yr. Recently there is a 10 to 15 ft downward gradient from the C/D zones to the A/B zones.

***SC-14 and Madeline Well*** (Figure 4-18) – The District's Madeline well currently produces an average of 100 ac-ft/yr from the Purisima-BC aquifer. Pumping levels were declining about 16 ft/yr during 1982-86 until the nearby Estates well took over a large share of Madeline's production. Static levels declined roughly 20 to 30 ft when Service Area II production increased during the mid-1990s. Static levels currently average about –60 ft msl and fluctuate up to 70 ft/yr, and pumping levels are as deep as–240 ft msl, nearly 50 ft above the uppermost well screens. These levels are consistent with those predicted for the BC aquifer in Section 4.1.3 (Figure 4-7a).

Monitoring-well cluster SC-14 is about 40 ft from the Madeline well. The B- and C-zone water levels are nearly identical and similar to the Madeline's static levels. A-zone water levels are just below sea level and indicate an upward gradient to the BC zone.

***SC-5 Monitoring-Well Cluster*** (Figure 4-19) – Monitoring-well cluster SC-5 is located at the coast about midway between District Service Areas I and II.[22] The nearest District production wells are 3,000 to 4,000 ft away (Figure 4-6a). The cluster's five individual monitoring wells are completed in Purisima zones A through E. There is a 50-ft downward gradient from the water table (SC-5E) to zones D and C, then a 15 to 25-ft downward gradient from zone C to zone B, and again from zone B to zone A. These strong vertical gradients reflect the low permeability of the B and D aquitards. In zone A, water levels fluctuate 10 to 20 ft annually and range from about 10 to –20 ft msl. Annual fluctuations are generally about 5 ft in the shallower zones.

Production of up to 800 ac-ft/yr from Purisima aquifers A and BC by the Estates well beginning in the late 1980s resulted in a 15-ft decline in zone-A water levels and a lesser and more gradual decline in zone B levels. Zone A water levels have partially recovered as production from the Estates well has gradually decreased to less than 500 ac-ft/yr. Zones B through D water levels have followed a similar trend. The apparent response to the climatic cycle is probably most related to higher Service Area II pumping during the mid-1990s. The cause for the late 1990s recovery of zone D water levels is uncertain.

***SC-17 and Ledyard Well*** (Figure 4-20) – The District's Ledyard well produced about 250 ac-ft/yr from the Purisima-BC aquifer in the latter half of the 1980s. Since then, the well's production and frequency of use have declined such that pumping now averages about 30 ac-ft/yr. When producing about 200 ac-ft/yr in the early 1990s, static water levels were as low as –180 ft msl and pumping levels were nearly –300 ft msl, roughly consistent with the levels predicted in Section 4.1.3 (Figure 4-7a). Pumping levels have remained 150 ft above the uppermost well screens. Static levels rose when pumping decreased starting in 1994, but remain below sea level despite minimal production in recent years, indicating the wide range of influence of other area wells.

Monitoring-well cluster SC-17 is about 10 ft from the Ledyard well. During pumping periods, vertical gradients are respectively upward and downward from the A and D zones toward the BC aquifer, and levels in the uppermost D zone are generally just below sea level.

The approximate +40 ft msl water level in SC-17A is somewhat anomalous compared to much lower A-zone levels elsewhere, e.g., about –10 ft msl in SC-14A to northwest and –15 ft msl in SC-8A and SC-9A at the coast. This may suggest either a source of recharge from upland areas to the north or a hydraulic discontinuity within aquifer A that separates SC-17A from these other wells.

***Hillcrest and Seacliff 4 Wells*** (Figure 4-21) – The former Hillcrest and Seacliff wells were relatively shallow and near the coast, producing from the Purisima DEF aquifer until the mid-1980s. Hillcrest's production of 100 to 300 ac-ft/yr during its final years of operation resulted in static levels below –30 ft msl. At the coast, nearly 900 ft to the south, D- and E-zone water levels at SC-9 mimicked the Hillcrest hydrograph such that water levels were mostly below sea level and attained seasonal lows of –20 ft msl. As discussed in Section 6, these low levels correspond with chloride-concentration spikes in both Hillcrest and SC-9E.

Static and pumping levels in the Seacliff 4 well dipped to –30 and –90 ft msl, respectively, during its final full year of production in 1984, with an apparent chloride response in SC-8F (see Section 6). Construction and use of the Estates well allowed both Seacliff 4 and Hillcrest to cease production.

[22] Figure 4-6 is based on coordinates provided by SCWD. However, some maps place SC-5 nearly 5,000 ft to the west (e.g., LSCE, 2003).

***SC-9 Monitoring-Well Cluster*** (Figure 4-22) – Coastal monitoring-well cluster SC-9 is roughly equidistant (3,700 to 4,600 ft) from the current Service Area II production wells (Figure 4-6a). Its individual monitoring wells are completed in Purisima zones A through E. Water levels in the deeper zones were above sea level in the early 1980s, then declined 20 to 30 ft to below sea level in response to pumping by the Estates well. A high degree of confinement is suggested by the initially artesian levels in SC-9B[23]. Under peak pumping conditions, there is about a 15-ft upward gradient from the A zone to the C zone. Water levels fluctuate 10 to 20 ft annually in the A, B, and C zones.

As discussed above, the District's Hillcrest well operated about 900 ft inland from SC-9 until 1987. Production of up to 270 ac-ft/yr from the DEF aquifer by the Hillcrest well resulted in SC-9D water levels about –20 ft msl. The cessation of Hillcrest pumping in 1987 allowed shallow water levels to recover to +10 ft msl or higher, with a slight upward gradient from zone D to zone E (as well as a downward gradient from zone D to Zone C).

***Aptos Creek and T. Hopkins Wells*** (Figure 4-23) – The District's Aptos Creek and T. Hopkins production wells are 950 ft apart and produce similar amounts totaling nearly 500 ac-ft/yr, on average. The Aptos Creek well is screened in both the BC and DEF aquifers, whereas T. Hopkins is screened only in the latter. Static levels in both wells generally remain below sea level, fluctuate 40 to 80 ft/yr, and range to below –100 ft msl. Pumping levels are as low as –220 ft msl, and are generally below the uppermost well screens of the T. Hopkins well. Static levels recover to near sea level during periods of reduced pumping. Water levels in both wells respond clearly and predictably to their respective pumping.

***SC-8 Monitoring-Well Cluster*** (Figure 4-24) – The SC-8 monitoring-well cluster is on the coast toward the southeastern end of Service Area II. The nearest active production wells are Aptos Creek and T. Hopkins, 2,400 to 3,200 ft inland. The water level trends are generally similar to SC-9, with some recovery in shallow zones and sustained declines in lower zones in response to increased Service Area II pumping from deep wells. Similar to SC-9B, the initially artesian levels in SC-8B indicate a high degree of confinement. The marked decline in deep-zone water levels during 1985-89 corresponds to the start of production from the Ledyard well and then the Estates well. Since then, vertical gradients are usually toward the BC aquifer from both above and below.[24]

Although SC-8 is further away from Purisima A-aquifer production wells than SC-9, levels in SC-8A are slightly below those in SC-9A. This suggests the following: (1) groundwater flow into the deeply buried A aquifer is being intercepted by production wells up-dip to the west; (2) potential leakage into aquifer A is being intercepted by production wells that draw from overlying aquifers; (3) there may be a barrier to the north that separates SC-8A from high groundwater pressures evident in SC-17A; and (4) little inflow to aquifer A occurs to the east or offshore to the south, which is reasonable given its depth at –800 to –1,000 ft msl in this area (Figure 2-11).

Historic pumping from the DEF aquifer by the Aptos Creek well and older, relatively shallow District wells (mainly Seacliff 4) resulted in depressed shallow-zone levels in the mid-1980s, similar to what occurred at SC-9. As discussed in Section 6, this may help explain high chloride concentrations in SC-8F.

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[23] Artesian is used here in the classic sense of above-ground water levels. The term "flowing well" seems inappropriate for a monitoring well sealed in a subsurface vault.

[24] SC-8F water levels appear anomalous relative to SC-8E and SC-8D, and suggest the need to verifiy how these data are labeled.

### 4.2.4 SCWD Service Area III and IV, CWD, and PVWMA Hydrographs

Water-level changes in the Aromas area are generally subtle but appear to correlate with pumping across wide distances, suggesting fairly confined conditions at depth within the Purisima-F aquifer. On the other hand, coastal water levels are generally so near sea level that they cannot fall any further given the Aromas Sands hydraulic continuity with the ocean. Some of the water-level variability is likely tidal. Considering the additional density head of saltwater, the effective gradient appears to be flat or landward under current conditions. As discussed further in Section 6, a saltwater wedge extends onshore in the Aromas area, as shallow as –200 ft msl at La Selva Beach.

***Aptos Jr. High School Well*** (Figure 4-25) – The Aptos Jr. High School well is about 6,000 ft northeast of the coast, the most northern and furthest inland of the District's Aromas-area wells. However, as discussed in Section 3, it produces primarily from the Purisima Formation. Inactive since 1987, it has static water level data through 1990. While producing 100 to 200 ac-ft/yr, static water levels fluctuated between 20 and 40 ft msl and pumping levels ranged from 0 to –40 ft msl. Static levels rose about 15 ft when production stopped, fluctuating only a few feet per year near 50 ft msl.

***SC-A1, Country Club, and Cliff Wells*** (Figure 4-26) – The Country Club well is the District's most northern active production well in Service Area III. It is more than 1.5 miles southeast of the Aptos Creek well and about 2,600 ft inland from coastal monitoring-well cluster SC-A1. As with all of the District's active Service Area III and IV production wells, it draws from the lower Aromas and Purisima-F aquifers. Production currently averages just over 200 ac-ft/yr. Static levels are relatively steady at just above sea level and pumping levels are between –10 and –20 ft msl. Static levels appear insensitive to the climatic cycle and declined only one or two feet when average pumping rates increased by about 100 ac-ft/yr in the mid-1990s.

The Aromas Sands have only a nominal thickness at SC-A1 such that all three of the nested monitoring wells are screened in the Purisima-F aquifer (Figure 2-11). Water levels are generally 3 to 10 ft msl. The minor vertical gradients are toward the middle producing zones. Water levels declined abruptly by one to two feet in 1992, perhaps in response to pumping by nearby, non-District wells.

The District's former Cliff well was approximately 600 ft inland from SC-A1. It produced less than 100 ac-ft/yr until 1985. It had static levels from 2 to –10 ft msl and pumping levels below –50 ft msl. Its relatively high drawdown was probably related to well inefficiencies, but also may have reflected a relatively low transmissivity within the local Purisima aquifer.

***Bonita and San Andreas Wells*** (Figure 4-27) – The Bonita well is 2,800 ft inland from the Country Club well and has produced nearly 500 ac-ft/yr in recent years. Groundwater levels rose about 10 ft when production was reduced by about 100 ac-ft/yr after its first few years of operation. Through the 1990s, static and pumping levels were relatively steady averaging +15 and –15 ft msl, respectively, while fluctuating about 10 ft/yr.

Production from the Bonita well was reduced by another 200 ac-ft/yr when the San Andreas well began pumping about 400 ac-ft/yr in 1992. At the Bonita well, these changes in production caused little change in water levels, appearing to essentially offset each other. Since 2002, a 75 percent increase in San Andreas production has coincided with a 10 ft decline in Bonita water levels. Given that the Bonita well is about one-half mile from the San Andreas well, these responses demonstrate an apparent radius of influence at the high end of the range predicted for the Aromas area in Section 4.1.2.

The San Andreas well is about 2,600 ft from both the Bonita well to the north-northwest and Seascape well to the south-southwest. San Andreas water levels responded little, if at all, to recent production increases from <500 to as much as 800 ac-ft/yr. Static levels are fairly steady at just under 10 ft msl and pumping levels average about –20 ft msl.

***SC-A5 and Seascape Well*** (Figure 4-28) – Annual production from the Seascape well has fluctuated significantly from 200 to more than 700 ac-ft/yr. Static water levels dipped below sea level toward the end of a period of peak production from 1987 to 1990. Since then, static levels and levels in nearby monitoring-well cluster SC-A5 have been relatively stable at 1 to 10 ft msl despite a recent production increase. Pumping levels range from –20 to –40 msl. The sudden shift in static and pumping levels in 1986 may reflect a change in equipment or procedures. As discussed in Section 6, the upward trend in SC-A5A and SC-A5B chloride concentrations that began around 1995 does not correlate with any significant change or trend in water levels. This suggests the ongoing movement of saline water under past and existing conditions.

***SC-A2 Monitoring-Well Cluster*** (Figure 4-29) – Coastal monitoring-well cluster SC-A2 is about 2,200 ft southwest of the Seascape well and about 4,500 ft northwest of the Altivo and Sells wells. Water levels range between 0 and 10 ft msl, with a generally slight downward gradient. Water levels declined as much as 0.7 ft/yr from 1992 to 2002 and have since recovered several feet. These trends appear unrelated to pumping by the Seascape well, but could correlate with production from the Altivo and Sells wells. Furthermore, according to LSCE (2004): "Three private wells exist in the Seascape area in the vicinity of SC-A2. The annual pumpage and well construction details for these three wells are not known; however, these wells provide water for domestic use and landscape and agricultural irrigation and have been in existence for decades" (p. 3). Pumping from shallow zones by one or more of these wells could account for the upward gradient from SC-A2B to SC-A2C prior to 1987.

As discussed further in Section 6, there has been a significant rising trend in SC-A2 chloride concentrations since monitoring began. Based on the Ghyben-Herzberg relationship,[25] the depth to the freshwater-saltwater interface is equal to approximately 40 times the freshwater head above sea level under static-equilibrium conditions. This suggests that a water level of 9 ft msl or more would be needed to prevent the saltwater interface from reaching the lowermost screens of SC-A2A (–353 ft msl). Such levels have not occurred since the early 1990s. Lesser heads could be capable of repelling the interface under a dynamic equilibrium involving groundwater outflow to the ocean. Nevertheless, the rising chloride concentrations of SC-A2A and SC-A2B indicate landward movement of the interface.

***Altivo, Sells, and La Selva Beach Wells*** (Figure 4-30) – The Altivo and Sells wells are nearly 600 ft apart at the southeastern edge of SCWD Service Area IV. Prior to the summer of 2001, their combined production exceeded 300 ac-ft/yr. Static water levels were 2 to 11 ft above sea level and varied little, while pumping levels were generally 0 to –12 ft msl. The relatively small seasonal fluctuations and differences between static and pumping levels are consistent with the high aquifer transmissivities estimated for this area in Section 3. Due to water quality concerns (Todd Engineers, 2002), the combined production of the Altivo and Sells wells has been reduced to slightly more than 100 ac-ft/yr, resulting in up to 5 to 10 ft of water-level rise.

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[25] Original references in Dutch and German from 1899 and 1901, as cited in most hydrogeology textbooks (e.g., Domenico and Schwartz, 1990).

Static and pumping levels declined gradually by several feet during the 1987 to 1994 drought, coinciding with a cumulative production increase of 80 ac-ft/yr. The water level decline preceded the pumping increase, however, suggesting that reduced precipitation recharge or increased pumping by other wells were contributing factors. Additionally, increased pumping and/or reduced recharge across the Pajaro Valley during the drought altered the regional groundwater gradient from coastward to southward into the valley (LSCE, 1996). Water levels gradually rose after 1994, despite increased production from the Altivo and Sells wells, further supporting a direct or indirect correlation with the climatic cycle.

Pumping levels in the Sells well experienced increasingly deep downward spikes between 1990 and 1996, coinciding with the end of the drought, while the upgradient Altivo well did not. The two wells are screened at different depths and there may be differences in the way they intercept groundwater flow and leakage. The occurrence of high chloride concentrations in SC-A3B after 1994 may be correlated to the downward progression of Altivo pumping-level spikes.

Pumping levels were as deep as –100 ft msl in the District's former La Selva Beach wells, perhaps because of well inefficiencies. These two wells had only 10 ft of perforations per well.

***SC-A3 and SC-A4*** (Figure 4-31) – Coastal monitoring-well cluster SC-A3 is 2,400 to 3,000 ft southwest of the Altivo and Sells wells. Water levels have been trending downward by about 0.25 ft/yr, such that levels in the shallow zones now average +2 to +3 ft msl and levels in the deepest zone are just below sea level. Shallow-zone levels experienced a slight rise (~1 to 2 ft) related to the 2002-03 decrease in Altivo and Sells production.

There is an apparent slight downward gradient toward the zone monitored by SC-A3A, which has a chloride concentration about equal to seawater (~18,000 mg/L). The Altivo and Sells wells produce from similar and greater depths, but farther inland, resulting in the downward gradient at SC-A3 and the probably onshore movement of the freshwater-saltwater interface.

Based on the Ghyben-Herzberg relationship, a water level of approximately +4.5 ft msl correlates with an interface depth between the screens of SC-A3A and SC-A3B (about –180 ft msl). Actual heads are near sea level, however, and the Sells and Altivo wells intercept much of the upgradient groundwater flow. Thus, there is a significant potential for progressive saltwater intrusion in this area. Furthermore, the average water levels of the Sells and Altivo wells are too low to prevent saltwater from reaching these wells.

Monitoring well cluster SC-A4 lies about 6,500 ft south-southeast of SC-A3, Altivo, and Sells. Water levels abruptly declined by as much as 15 ft in the late 1980s, after which shallow levels trended slightly above sea level and levels in the deepest zone continued to decline by about 0.3 ft/yr, until partially recovering in 2002. These trends appear at least partially attributable to pumping by the Altivo and Sells wells, indicating a confined response in at least the deeper zones. The influence of pumping and water levels across Pajaro Valley to the east and south is also likely. As discussed in Section 6, the downward trend in deep-zone water levels corresponds to a rising trend in deep-zone chloride concentrations. Freshwater heads are below +9 ft msl, the level indicated by the Ghyben-Herzberg relationship for maintaining the interface near the depth of SC-A4A (~ –350 ft msl).

***Central Water District*** (Figure 4-32) – CWD currently operates three wells at Rob Roy Junction (the intersection of State Route 1 and Freedom Boulevard). This wellfield is inland from SCWD's Country Club well and about equidistant from the Bonita and Aptos Jr. High School wells to the south and north, respectively (Figure 4-6b). Presumably, these wells draw from both the Aromas and Purisima formations, as do most of SCWD's wells in the area. Since the 1980s, production has increased from roughly 400 to 600 ac-ft/yr.

CWD produces about 20 to 40 ac-ft/yr from its two Cox Road wells nearly 2 miles further inland to the north-northwest. These wells are near the northwestern edge of the Aromas Sands and most likely produce from the Purisima Formation.

Static water levels in the Rob Roy wellfield fluctuate less than 10 ft/yr and have varied between 10 and 24 ft msl since 1993. CWD-12 currently accounts for more than 60 percent of the wellfield's total production and has pumping levels trending slightly downward at about 2 ft/yr to as low as –25 ft msl. Pumping levels in the other two wells increased from slightly below to mostly just above sea level when CWD-12 came online in 1999. The relatively small amounts of water-level drawdown and annual fluctuation suggest essentially unconfined conditions.

At the Cox wellfield, static and pumping levels are offset by 40 to 80 ft, and fluctuate up to 20 ft/yr. Water levels have been trending upwards since 1993, with a distinct rise and reduction in annual fluctuations after 1998. This may have been a response to recharge during the series of wet years following the 1987-1992, 1994 drought, especially the extremely wet 1998 water year. Production changes by these and other nearby wells may also be a factor. The reason for the sudden drop in CWD-5 pumping levels in 2001 is unclear and may be a measurement artifact. Of all the hydrographs presented in Section 4, the Cox wells appear to exhibit the greatest response to the climatic cycle.

***Coastal Monitoring by PVWMA*** – The Pajaro Valley Water Management Agency (PVWMA) monitors groundwater conditions with a network of both coastal and inland monitoring-well clusters to the southeast of La Selva Beach. Monitoring-well cluster PV-1 is located on the coast a little more than 2 miles southeast of SC-A4. Groundwater levels are relatively stable at –1 to +5 ft msl, with a slight, apparent downward gradient. As stated by PVWMA (2001), "this relative stability results partly from the constant pressure provided by the ocean, which tends to even out the effects of climatic variations…This area is experiencing seawater intrusion even with water tables at or near sea level much of the time. Seawater is more dense than freshwater. Therefore, even if the freshwater table elevation is just at sea level, seawater can still migrate inland because of the difference in density" (pp. 4-6 to 4-7).

### 4.2.5 Remediation Sites

Figure 4-33 shows the monitoring-well hydrographs for five remediation sites located in the western study area (Figure 4-6a). Other sites with multiple-year records were unavailable elsewhere in the study area. Four of the sites are within the Soquel Creek alluvial plain and one is on the coastal terrace inland of Opal Cliffs. The monitored water levels are essentially representative of water table conditions. Depths to water are lower near Soquel Creek than on the terrace, and generally diminish from north to south toward the coast. Levels range between 5 and 40 ft msl, fluctuate up to 10 ft/yr, and exhibit subtle, if any, upward or downward trends. Although lacking strong multi-year trends related to the climatic cycle, annual high and low levels generally do correlate with whether a year was particularly wet or dry. In general, this shallow water-table zone represents a consistent source of groundwater for potential leakage to underlying zones.

## 4.3 Groundwater Surface Maps and Profiles

Previously prepared contour maps of groundwater-surface elevations are listed in the following table. The map prepared by Bloyd (1981) encompassed inland areas as well as the coastal terrace. The inland water-table contours predictably mimicked the topography, indicating groundwater flow toward streams and downgradient toward the ocean. Along the coastal terrace, pieziometric surface closed contours revealed several sub-sea level cones of depression surrounding major pumping wells, some of which intersected the coastline. No distinction was made between aquifer zones.

| Water-Level Period | Hydrostratigraphic Zone | Author |
|---|---|---|
| -Entire Soquel-Aptos area | | |
| April 1981 | composite of water table and productions zones | Bloyd, 1981 |
| ~1974 | individual maps for Purisima units A/AA, B, C, and DEF, and upper and lower Aromas | Montgomery Watson et al., 1998 |
| -Service Areas I & II coastal terrace | | |
| 1984 | composite of production zones | LSCE, 1985a |
| 1984 | individual maps for Purisima units A through D | LSCE, 1985a |
| Autumn 1993 | composite of Purisima A and AA | LSCE, 1994, 1996 |
| Spring 1994 | composite of Purisima A and AA | LSCE, 1996 |
| Spring 1999 | Purisima A | LSCE, 1999, 2000a |
| Autumn 1999 | Purisima A | LSCE, 2000c |
| Spring 2002 | composite of Purisima A and AA | LSCE, 2003 |
| Autumn 2002 | composite of Purisima A and AA | LSCE, 2003 |
| -Service Areas III & IV coastal zone | | |
| 1984 | composite of Aromas and Purisima F | LSCE, 1985a |
| Spring 1987 | composite of Aromas and Purisima F | LSCE, 1987b |
| Spring 1989 | composite of Aromas and Purisima F | LSCE, 1990, 1994 |
| Spring 1989 | Aromas "depth-zone B" | LSCE, 1996 |
| Autumn 1991 | Aromas "depth-zone B" | LSCE, 1996 |
| Spring 1999 | Aromas "zone B" | LSCE, 1999, 2000a |
| Autumn 1999 | Aromas "zone B" | LSCE, 2000c |
| Spring 2002 | Aromas "zone B" | LSCE, 2003 |
| Autumn 2002 | Aromas "zone B" | LSCE, 2003 |

The initial set of coastal terrace water-level maps prepared by LSCE (1985a) showed a positive gradient toward the ocean and no pumping depressions. Subsequent maps by LSCE portrayed the pieziometric surfaces of the Purisima A/AA zone and Aromas "zone B," and exhibited pumping depressions and landward gradients. LSCE's contours of the A/AA zone reflect the pieziometric surface of the western production zone, but do not represent the deeper levels that occur in the shallower BC and DEF production zones further east. Thus, these maps under represent landward gradients with the potential to induce saltwater intrusion in SCWD Service Area II. The definition of Aromas "zone B" is unclear given that the B-designation does not correlate with the hydrostratigraphy (Figure 2-4).

In a map showing autumn 1993 conditions for Purisima zone A/AA (LSCE, 1996), the onshore area of sub-sea level groundwater elevations encompassed approximately 5.5 square miles and intersected more than 3 miles of coastline. Levels were as deep as –16 ft msl along the coast. Employing a somewhat different interpretive style for an autumn 1999 map (LSCE, 2000c), the sub-sea level groundwater surface encompassed almost 3 square miles and intersected nearly 3 miles of coastline. And, for a map of autumn 2002 conditions, this area included approximately 3.8 square miles and 3.5 miles of coastline.

Maps of 1987 and 1989 groundwater elevations in the Aromas area depicted spring conditions (LSCE, 1987b, 1990, 1996). Groundwater elevation contours generally paralleled the coast, and the lowest elevation contour just inland from the coast was 2 to 4 ft msl. A map of autumn 1991 conditions showed a southeastward shift in gradient south of the Seascape well. Because of drought-lowered groundwater levels, LSCE (1996) explained, the gradient shifted away from the coast and toward the central Pajaro Valley. Nevertheless, levels were shown to be greater than 2 ft msl everywhere within the District. The gradient shifted back toward the coast in maps of autumn 1999 and 2002 conditions (LSCE, 2000c, 2003). The 1999 map, however, showed an onshore sea-level contour (i.e., 0 ft msl) at the southern end of the District.

Groundwater level maps prepared by Montgomery Watson et al. (1998) were used as rough initial conditions for setting up the 1982-1993 calibration period. The contours reflected some questionable data (e.g., anomalous "bulls eyes") which the model was expected to smooth out in a pre-calibration simulation for 1974-1981.

***Map View of Minimum Levels*** – For the current study, we have not attempted a new set of groundwater-level maps. Such maps are difficult to construct accurately given (1) the uncertainties associated with noisy "static" readings and (2) the difficulty of differentiating among the multiple pieziometric surfaces. The insight obtained from a calibrated groundwater model would greatly assist in the construction of such maps. For this report, we present both maps and cross sections of minimum measured groundwater levels in order to highlight the potential for saltwater intrusion.

Figure 4-34 presents maps of recent groundwater elevations (2003 or 2002). Posted below each monitoring well cluster are (1) the minimum groundwater elevation recorded among all zones and (2) the maximum elevation recorded within zones above the minimum-level zone. Posted above each production well are its minimum static and pumping groundwater elevations. Also shown are the water-table elevations at five remediation sites.[26]

Monitoring well minimum levels and production well static levels were all below sea level in Service Areas I and II at some time during 2002-03 (Figure 4-34a). Because aquifer conditions change significantly across this area, these data are difficult to contour accurately without the aid of a calibrated groundwater model. However, the map shows a reasonable 0-ft msl envelope that encompasses approximately 5 square miles onshore and intersects 4 miles of coastline.

Among the coastal monitoring wells (including Pleasure Point), maximum groundwater elevations within shallow zones ranged from +5 to +50 ft msl. This suggests that downward leakage into producing zones includes fresh groundwater originating from onshore. However, seawater leakage into these zones can occur where sub-sea level cones of depression extend farther offshore than the shallow freshwater zones. This is especially true where producing zones dip upward toward the seafloor; i.e., shallow freshwater zones do not exist where the producing zones outcrop on the seafloor. Furthermore, past conditions include times when shallow-zone heads fell below sea level along the coast, allowing seawater leakage directly into aquifer exposures at the shoreline (e.g., at SC-8, SC-9, and Pleasure Point during the 1980s).

As shown in Figure 4-34b, a 0-ft msl envelope was onshore along the District's entire Aromas coast at times during 2002-03. None of the production-well static levels or maximum monitoring-well levels was above the 8-ft msl level recently recommended for preventing saltwater intrusion (LSCE, 2004).

***Profile View of Minimum Levels*** – Figures 4-35 and 4-36 present profile views of the water-level data posted in Figure 4-34. Cross section X-X" follows the coastline from Pleasure Point to La Selva Beach (Figure 4-35). The deepest minimum levels occur locally in Purisima aquifer zones buried many hundreds of feet below sea level. Because the seafloor descends to only about –100 ft msl

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[26] Although water-table contour maps have been prepared for these and a number of other remediation sites, they cannot be reasonably pieced together into a larger map because of the variablility of relatively subtle local gradients as a function of topography, artificial drains, etc.

within 2 miles of shore, these aquifer zones are also deep beneath the seafloor where they extend perpendicular to the coast. However, these same units dip upwards to the west until outcropping as shown in Figure 2-10. Extended offshore to the southwest, these depressurized zones may outcrop on the seafloor and induce seawater leakage. The protection provided by overlying zones with positive freshwater heads does not extend to such offshore outcrops.

In the Aromas area, coastal water levels are near sea level. Given the contribution of saltwater density to total head, the freshwater heads along the coast are insufficient to prevent the landward movement of saltwater through the Aromas toward pumping wells.

Cross section Y-Y" follows the general line of production wells 1,000 to 5,000 ft inland from the coast (Figure 4-36). The static and pumping water levels are everywhere near or below sea level.

### 4.4 Groundwater Quality Indicators

Spatial and temporal patterns and trends in groundwater quality provide useful indicators of groundwater occurrence and movement. Tables 4-5 through 4-8 summarize the following available general mineral water quality data:

- Table 4-5a: nearly 700 samples dating back to 1942 from 25 SCWD and former production wells; summarized by well and by SCWD service area.
- Table 4-5b: more than 200 samples since the 1970s from six former and existing Beltz production wells.
- Table 4-6: 250 general mineral samples collected between 1995 and 2003 from 38 SCWD monitoring wells.
- Table 4-7: SCWD monitoring well data summarized by aquifer zone; the bottom of the table provides the typical composition of seawater (Hem, 1989).
- Table 4-8: 150 samples from Soquel and Aptos creeks collected by the USGS during 1952-1977, summarized by streamflow magnitude; also, two 1981 Soquel Creek samples analyzed for SCWD (Brown and Caldwell, 1981).

As summarized in Table 4-9 and the trilinear diagram presented in Figure 4-37, water from the various stratigraphic zones, study subareas, and streams is broadly distinguishable by average differences in water quality. The averaging of monitoring well data for the individual Purisima units masks considerable variability among individual wells, as indicated by the range of values provided in Table 4-6 and the trilinear diagrams of individual analyses presented in Section 6. Nevertheless, the differences among averages are representative and informative of the overall hydrogeology.

Observations based on general water quality differences include:

- Groundwater produced by SCWD Service Area I wells tends to be more mineralized and of a somewhat different type than monitoring-well samples collected solely from the Purisima-A aquifer. This supports the interpretation that pumping induces leakage into the A aquifer from adjoining units.
- The distinction of Purisima units B and D as primarily aquitard zones is supported by their average water quality compared to units A, C, and E.
- The Beltz wells and SCWD's Service Area I wells produce water of generally similar mineral content and type.

- Although the Main Street well is screened in the deep "Tu" and Purisima-AA zones, its total dissolved mineral concentration is lower than other Purisima wells. This may reflect a good connection to recharge where these units dip upward closer to the land surface (Figure 2-10) or a lower mineral loading related to the formation geochemistry.
- The low mineral content of water sampled at monitoring well SC-10AA suggests a connection to induced recharge (consistent with slowly declining water levels; Figure 4-13) or a lower mineral loading due to the formation geochemistry.
- The relatively high mineral content of shallow monitoring well SC-8F has similarities to seawater and intruded zones in the Aromas area (Figure 4-37), indicating seawater leakage or incursion into this area. General mineral analyses are unavailable for well SC-9E at the time it experienced low water levels and elevated chlorides in the mid-1980s.
- The relatively high mineral content of SC-5C plots similarly to groundwater influenced by intrusion in the Aromas area (Figure 4-37). However, this water quality may result from minerals leaching out of marine clays given that groundwater levels are consistently >30 ft msl.
- The old Seacliff and Hillcrest wells, which produced from the shallow Purisima E and F zones, had relatively high proportions of magnesium similar to Aromas-area wells producing from the Purisima F aquifer.
- An inverted U-shaped curve on the trilinear plot (Figure 4-37) connecting fresh, transitional, and saline Aromas groundwater with seawater is consistent with the interpretation of saltwater intrusion presented in Section 6.
- The trilinear-plot distribution of water types is generally consistent with water-type groups identified for Pajaro Valley (Figure 4-38).

## 4.5 Groundwater Storage

Groundwater is always flowing from points of recharge toward points of discharge. However, because of its slow velocity, groundwater is thought of as stored water. The total volume of groundwater storage has limited significance given that it is typically infeasible and/or undesirable to remove it by a significant percentage. The magnitude of usable groundwater storage is defined in part by its potential for replenishment during representative climatic cycles of wet and dry years.

There are three general components of groundwater storage in the Soquel-Aptos area:

- Confined and semi-confined aquifer storage – Groundwater storage fluctuates in a confined and semi-confined aquifer as a function of hydraulic pressure due to the compressibility of water and the aquifer matrix. Since by definition there is no change in saturated aquifer thickness, the usable storage capacity is small, i.e., typically less than one tenth of one percent of the aquifer volume. Trends in Soquel-Aptos groundwater levels suggest little net change in confined and semi-confined aquifer storage during the past 30 years.
- Unconfined aquifer storage – The fluctuating water table of an unconfined aquifer represents changes in groundwater storage as a function of the aquifer's varying saturated thickness and its specific yield (equal to slightly less than the aquifer porosity). In this case, the usable storage capacity is relatively large but mostly unmonitored, and thus unknown, across the study area. Whereas this storage readily leaks out as groundwater discharge to streams, it is not readily accessible to most wells because of the limited leakage rates to deep aquifers.

- Movement of the freshwater-saltwater interface may be thought of as a gain or loss of fresh groundwater storage equal to the volume of the aquifer affected (confined or unconfined) times the aquifer porosity. The potential change in storage from movement of the interface is relatively large. This storage is readily available for extraction until the interface is drawn too near to coastal wells. Saltwater dispersion from the interface into a leading transition zone may result in the recovery of brackish water. Wells may extract this storage much more quickly than the rate at which it can be replenished by natural groundwater flow. This is because the landward pumping gradient is typically larger than the seaward natural gradient, and because the groundwater flow pushing the interface seaward is mostly lost as discharge to the ocean. Groundwater levels do not trend downward as this storage is depleted because the pumped water is replaced with saltwater behind the interface, which in turn is replenished by the ocean. SCWD's production wells, especially those nearest the coast, have been drawing on this type of storage for many years. Alternatively, this source of water may be considered an inflow (i.e., saltwater intrusion) in the water balance equation, instead of a change in storage (as discussed in Section 5). Without knowing the location of the interface, the remaining volume of offshore fresh groundwater storage is uncertain.

### 4.6 Summary and Conclusions

***General Aquifer Conditions*** – Under the generally semi-confined to confined conditions of the Purisima aquifers in the vicinity of SCWD wells, groundwater levels and the direction of groundwater flow are primarily influenced by changes in pieziometric pressure related to pumping. Where conditions are most confined, pumping-induced drawdown of the pieziometric surface is significant and widespread, extending radially many thousands of feet. Drawdown accumulates from repeated pumping cycles, is exacerbated by overlapping cones of depression and various boundary effects, and may require many months to recover if and when pumping is reduced.

The response of groundwater levels to pumping in the Aromas area reflects a combined range of aquifer conditions. Relatively minor drawdown and flat hydrographs reflect unconfined to leaky conditions and hydraulic connection with the ocean, whereas distant responses to changes in pumping suggest confined conditions at depth.

***Groundwater-Level Trends*** – Prior to 1975, groundwater levels declined by as much as several tens of feet in response to the initial stages of groundwater development (Figure 4-9). During the last 30 years, static levels have fluctuated in response to pumping cycles, but have not trended significantly up or down despite large increases in production, lowered pumping levels, and major wet and drought periods.[27] For the Purisima area, possible explanations for the absence of water level trends include:

- Pumping-induced vertical gradients have induced leakage from shallow zones, which in turn has induced recharge from near-surface sources. Shallow zones supplying this leakage occur across the developed coastal terrace and probably across most of the basin.
- Pumping depressions have intercepted groundwater that formerly flowed to the ocean. This effect may be relatively minor given that estimates of pre-development ocean outflow are relatively small (about 1,000 ac-ft/yr [Essaid, 1992]; see Section 5).
- Cyclic pumping and generally confined conditions have created a broad, relatively flat trough of residual drawdown rather than a "pin cushion" of deepening drawdown cones.

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[27] The lack of water level response to variations in precipitation has been noted previously (e.g., LSCE, 1989).

- Managed groundwater production has distributed pumping to minimize excessive local drawdown.

In the Aromas area, groundwater levels have remained fairly stable near sea level as a function of relatively high aquifer permeability, shallow unconfined conditions, and good hydraulic connection with the ocean.

Water-level trends are a poor indicator of potential groundwater overdraft because of the influence of head-dependent boundaries (i.e., aquitard leakage, streams, the ocean, and the freshwater-saltwater interface). For wells pumping near the coast, once water levels fall to near or below sea level, continued or increased pumping is offset by onshore flow (i.e., intrusion) with only minimal additional drawdown.

***Groundwater Storage and Enhanced Recharge*** – There is little evidence for significant changes in onshore groundwater storage during recent years. The confined and leaky zones remain essentially "full" given that their fluctuating water levels represent changes in pressure rather than saturated thickness. Groundwater storage may fluctuate more significantly in the relatively unconfined Aromas Sands, especially in inland areas, as demonstrated by the hydrographs for CWD's Cox wells (Figure 4-32). Fresh groundwater stored in aquifers extending offshore is being depleted as the freshwater-saltwater interface is drawn toward shore.

The general lack of a water-level response to differences in wet- and dry-period recharge is consistent with our interpretation of leaky and confined conditions at the depth of most production wells, as well as hydraulic connection with the ocean. Leakage is controlled by the pumping levels in zones below confining layers more than by the relatively small changes in water-table height above confining layers. As such, increasing recharge to shallow zones has only a limited effect on deep water levels and is an ineffective means for preventing saltwater intrusion. Increased recharge may add to shallow groundwater storage, but this storage is difficult to manipulate with most existing wells.

***Saltwater Intrusion*** – The preceding analyses of aquifer structure and groundwater occurrence indicate three potential pathways for saltwater encroachment into the Soquel-Aptos aquifers:

- For shallow aquifers, cones of depression may reach out to the shoreline and induce seawater flow directly into a well's capture zone. Such conditions apparently occurred during the past operation of shallow coastal wells (e.g., the former Hillcrest well).
- For relatively deep aquifers, pumping depressions may extend far offshore until reaching the aquifer's seafloor exposure. Seawater pathways to these zones also may include faults, fractures, incised paleochannels, and leakage through overlying layers.
- Reductions in the seaward hydraulic gradient may cause the landward migration of the freshwater-saltwater interface (as appears to be occurring in the Aromas area).

The first two pathways capture seawater from above, whereas the third represents a saltwater wedge migrating along the aquifer base. The mechanisms, evidence, and potential for saltwater intrusion are discussed further in Section 6.

***Groundwater-Level Management*** – Documented relationships between groundwater pumping and groundwater levels are needed to evaluate measures for mitigating the potential impacts of pumping (e.g., saltwater intrusion). Unfortunately, several factors impede the development of such relationships, including:

- Measurement artifacts, data noise, unique local conditions, and cause-and-effect inconsistencies impart a degree of randomness, variability, and uncertainty into the data and our ability to interpret them. As such, apparent correlations between water levels and pumping may be more or less coincidental and/or locally unique and difficult to generalize.
- Data are sparse for 1965-83 when the greatest changes in pumping occurred. Thus, the data record does not reflect the full range of stresses needed to reveal these relationships.
- Groundwater levels are influenced by the cumulative effects of both near and distant wells, and both recent and past pumping, such that the effect of changing one well's pumping may be difficult to evaluate.
- Groundwater levels are strongly influenced by head-dependent boundaries (e.g., aquitard leakage and the ocean), and thus change relatively little when pumping increases or decreases. The multiple-regression approach used previously (LSCE, 1988) for relating pumping and water levels does not account for such boundary effects.

A calibrated groundwater model compensates for the latter two factors, and thus provides a valuable tool for answering "what if" questions relating to the effects of increased or decreased pumping.

# 5 Groundwater Budget

The preceding sections have described the hydrogeologic framework and hydraulic properties and gradients of the Soquel-Aptos groundwater system. This section addresses the balance of groundwater inflows and outflows that sustains these gradients and drives groundwater flow through the system. It begins by describing the various relevant components of the Soquel-Aptos hydrologic cycle, then assesses previous water-budget estimates, and concludes with this study's independent estimate of groundwater recharge and the groundwater budget.

## 5.1 Conceptual Water Budget

Figure 5-1 illustrates groundwater aspects of the Soquel-Aptos hydrologic cycle and Figure 5-2 is a flow chart of the conceptual water budget. The individual components represent common water-budget concepts that may be estimated from available data and/or conventional assumptions. They are described below in the context of the Soquel-Aptos groundwater flow system. For the convenience of defining these terms we implicitly assume:

- Average annual conditions
- No net change in groundwater storage (i.e., inflows equal outflows)

In this case, an average annual rate of saltwater intrusion is essentially a component of groundwater inflow rather than a change in fresh groundwater storage.

### 5.1.1 Groundwater Recharge

Percolating soil moisture that reaches the water table constitutes groundwater recharge. In the following discussion we distinguish between two sources of recharge, precipitation and applied water, and partition total recharge into its groundwater components, mainly baseflow and "deep recharge." As necessary, we define various other terms needed to define and estimate recharge.

***Precipitation Recharge*** – Precipitation within the study area boundary is the primary source of fresh groundwater in the Soquel-Aptos basin. The portion of precipitation that becomes groundwater recharge is expressed by the following relation:

Precipitation Recharge = Precipitation – Stormflow – Evapotranspiration (non-phreatophyte)

***Stormflow –*** Considered here to be synonymous with "runoff," stormflow is defined as the non-baseflow portion of total streamflow:

Stormflow = Total Streamflow – Baseflow

***Total streamflow*** is measured at various gaging stations. Streamflow contributions from surface return flows (e.g., wastewater outfalls, irrigation runoff) are minor in the study area.

***Streamflow percolation*** along losing streams represents a local loss of total streamflow and a local gain in groundwater recharge. When this occurs upstream of a gaging station it may be lumped with precipitation recharge and not independently estimated.

***Baseflow*** is the portion of total streamflow that originates from groundwater. It derives from both precipitation recharge and applied water recharge. Springflow is relatively minor in the study area and we include it with baseflow.

***Applied-water recharge*** is the portion of water used by people that for various reasons percolates to the water table. This includes water from leaky pipes, excess irrigation, and septic tanks. Its sources may include water produced from within the basin and water imported into the basin. Applied-water recharge from groundwater pumped within the basin is referred to as ***groundwater return flow***.

***Evapotranspiration*** (ET) (other than phreatophyte ET) is the portion of precipitation that neither enters a stream nor reaches the water table. This includes evaporation of standing water, the drying of wet soil and vegetation, and the transpiration of soil moisture extracted by plants. The study area lacks evaporation from major surface-water bodies. In developed and irrigated areas, potential evapotranspiration may be partially satisfied by applied water.

***Phreatophyte ET*** is the transpiration of groundwater by vegetation with roots that extend to the water table.

***Total recharge*** is the sum of precipitation recharge and applied-water recharge:[28]

Total Recharge = Precipitation Recharge + Applied-Water Recharge

The fate of total recharge may be summarized as follows:

Total Recharge = Baseflow + Phreatophyte ET + Deep Recharge

***Deep Recharge*** – Total recharge either (a) discharges from the ground as baseflow or phreatophyte ET, or (b) becomes "deep recharge." Deep recharge (together with any subsurface inflow) is the source of groundwater that flows through the aquifer-aquitard system until discharging from wells, discharging to the ocean, or leaving the basin as subsurface outflow (e.g., to Pajaro Valley). Thus:

Deep Recharge + Subsurface Inflow = Well Discharge + Discharge to Ocean + Subsurface Outflow

The term "deep" indicates a relative separation from stream-aquifer interactions, and is not meant as a strict separation between shallow and deep aquifers and wells. Also, the partitioning of total recharge between baseflow and deep recharge can be altered by groundwater pumping. Nevertheless, this conceptualization is useful and generally applicable in the context of the overall basin and SCWD groundwater production.

By combining and rearranging the above relations, deep recharge equals the following:

Deep Recharge = Precipitation Recharge + Applied-Water Recharge – Baseflow – Phreatophyte ET
= (Precipitation – Stormflow – ET) + Applied-Water Recharge – Baseflow – Phreatophyte ET
= Precipitation + Applied-Water Recharge – Total Streamflow – Total ET

### 5.1.2 Additional Budget Concepts

***Subsurface Inflow –*** Groundwater may enter the basin as subsurface inflow. The study area boundaries were selected to minimize the potential for subsurface inflow from upgradient and adjacent watershed areas. Whether or not there is any subsurface inflow across the northern study area boundary is sufficiently uncertain that an appropriate conservative assumption is to assume there is none. Subsurface inflow also includes the landward movement of groundwater, either fresh or salty, from the offshore portions of the Purisima and Aromas aquifers. Over the long term, net average subsurface inflow from offshore becomes ***saltwater intrusion***.

***Groundwater Discharge –*** Groundwater discharges from the Soquel-Aptos basin as springflow and stream baseflow, pumpage from wells, groundwater seepage into Monterey Bay, and phreatophyte

[28] See assumption stated above regarding the inclusion of streamflow percolation with precipitation recharge.

transpiration. "***Native***" groundwater discharge to streams and the ocean refers to conditions prior to the influence of pumping and applied-water recharge.

***Subsurface Outflow*** – Groundwater also has the potential to leave the basin as subsurface outflow into the adjoining Pajaro Valley. This is because the groundwater divide between the Soquel-Aptos and Pajaro basins is poorly defined and transient. A northwestward shift in the divide reportedly occurred during the 1987-94 drought, allowing groundwater from the Soquel-Aptos Aromas area to flow southeast into Pajaro Valley (LSCE, 1996). Because it seems unlikely that the divide ever shifts significantly outward from the study area boundary, there is probably a long-term net average outflow of groundwater to Pajaro Valley.

***Consumptive Groundwater Use –*** Consumptive groundwater use is the portion of groundwater pumped from the study area that discharges to the ocean as wastewater, is lost to evaporation and landscape evapotranspiration, and/or becomes exported from the basin in some other way. Non-consumptive groundwater use becomes return-flow recharge. One way to account for return-flow recharge in the water budget is to substitute consumptive groundwater use for total groundwater pumpage. However, the spatial distribution of water usage may vary considerably from where the water is pumped, and the return-flow recharge may enter a zone much shallower than the zone from which the water was extracted. Thus, a groundwater model should simulate pumping and return flows separately.

***Imported Water*** – Not all of the water used in the study area derives from local groundwater. In addition to using the Beltz wells, the City of Santa Cruz supplies the Live Oak area with water "imported" from its San Lorenzo River and north county stream diversions. A portion of this imported water use contributes to applied-water recharge.

***Induced and Rejected Recharge –*** Pumping wells create hydraulic gradients that induce groundwater flow into producing aquifer zones. This in turn may induce additional "deep recharge," i.e., the downward leakage of shallow groundwater and streamflow. At other times, some of the available shallow groundwater and streamflow may be "rejected" because of limited leakage capacities.

***Change in Groundwater Storage*** – In the Soquel-Aptos basin, most of the production-well and monitoring-well hydrographs do not represent significant changes in onshore groundwater storage. This is because (1) they mostly reflect changes in hydraulic pressure within confined and semi-confined aquifers, (2) they display little long-term trend, and (3) the wells are drawing partially on groundwater stored offshore, which has little affect on the hydrograph. Available contaminant-site hydrographs of the coastal terrace water table also lack significant multi-year trends (e.g., Figure 4-33). The water table across the interior uplands, however, is expected to more significantly rise and fall in response to wet and dry periods (e.g., CWD's Cox wells hydrographs; Figure 4-32). Because inland areas are mostly unmonitored, changes in basinwide groundwater storage are difficult to estimate. One indicator of changing groundwater storage is the gradual decline in baseflows during the dry season and drought periods. Changes in shallow groundwater storage associated with wet and dry periods mostly affect baseflows. This is because leakage rates limit recharge to relatively deep production aquifers. Because the location and rate of movement of the freshwater-saltwater interface are unknown, it is difficult to estimate changes in offshore groundwater storage.

### 5.1.3 Groundwater Mass Balance

A water mass balance is typically expressed as follows:

$$\text{Inflows} - \text{Change in Storage} = \text{Outflows}$$

The following relation summarizes this balance as described above for the Soquel-Aptos basin:

$$\text{Total Recharge} + \text{Subsurface Inflow} - \text{Change in Storage}$$
$$= \text{Baseflow} + \text{Pumping} + \text{Ocean Discharge} + \text{Subsurface Outflow} + \text{Phreatophyte ET}$$

Saltwater intrusion can be considered as either a component of subsurface inflow or a loss of offshore fresh groundwater storage.

The groundwater mass balance provides the ultimate limit on groundwater "yield," i.e., groundwater cannot be discharged indefinitely at a rate greater than its average rate of replenishment. However, this simple mass-balance approach does not account accurately for head-dependent flows. Groundwater yield is not an absolute and fixed quantity given that groundwater pumping may influence the rate of replenishment. Moreover, potential negative consequences are associated with groundwater pumping (e.g., saltwater intrusion, baseflow depletion). Consideration of these consequences constrain the combined optimal yield of all wells to an amount less than the rate of groundwater replenishment.

## 5.2 Previous Estimates of Groundwater Recharge and Yield

Tables 5-1 and 5-2 summarize previous estimates of average groundwater recharge and yield in the Soquel-Aptos area. Several non-mutually exclusive definitions of groundwater yield have been used, as listed below. Other than the last term, these assume average conditions with no net change in groundwater storage.

- ***Total Throughflow*** – Total groundwater flow through the system, which is equivalent to either (1) total recharge plus any subsurface groundwater inflow or (2) the sum of all outflows.
- ***Onshore Discharge*** – Groundwater discharge to streams and wells, which is equivalent to total throughflow minus subsurface outflow to the ocean (i.e., offshore discharge).
- ***Groundwater Production*** – Groundwater yield demonstrated by established rates of total groundwater pumping.
- ***Groundwater Consumptive Use*** – Established groundwater production minus the groundwater return flows that contribute to groundwater recharge.
- ***Optimal Yield*** – The amount of groundwater that can be beneficially used without causing undesired consequences (e.g., excessively deep groundwater levels, unacceptably depleted baseflows, and progressive saltwater intrusion). Other terms used in a generally synonymous manner by previous studies include safe yield, perennial yield, sustainable yield, potential yield, and practical developable yield. Optimal yield may vary depending on such factors as the spatial and temporal distribution of pumping, seasonal and climatic cycles, and the opportunity for exercising the capacity for groundwater storage. Pumping in excess of this amount is referred to as overdraft.[29]

Previous estimates of total throughflow range from 10,000 to more than 20,000 ac-ft/yr. Of this, groundwater outflow to the ocean has been estimated at 400 to 9,500 ac-ft/yr from the Purisima area, and as much as 12,000 ac-ft/yr from the Aromas area. Previous estimates of groundwater recharge and yield are discussed individually below.

***Hickey (1968)*** – Hickey estimated natural groundwater discharge from the primary aquifer zones of the Purisima Formation to be 10,000 ac-ft/yr. He estimated that this required an average rate of areal recharge of 4 in/yr, suggesting a recharge area of 46 square miles. Of this, he estimated wells

[29] Overdraft is sometimes more narrowly defined as pumping in excess of total inflow.

extracted 3,300 ac-ft/yr as of 1966. He explained that although the total amount of groundwater in storage is large relative to recharge, "little, if any, of the water in storage along the coast can be removed for water supply needs and only [a portion of] the perennial supply of water discharging past the coastline can be safely developed" (p. 37). This assessment of the limited potential use of coastal groundwater storage has been reiterated by others, e.g., LSCE (1985a).

***M. Johnson (1980)*** – Table 5-3 summarizes estimates from a 1980 USGS study of average annual groundwater recharge within the Soquel, Aptos, and Corralitos creek watersheds north of the Zayante fault. The amount of precipitation that becomes recharge was estimated to range from 4 to 7 in/yr and average as follows:

$$\begin{array}{ccccccccc} \text{Recharge} & = & \text{Precipitation} & - & \text{Runoff} & - & \text{Evapotranspiration} & & \\ 5.6 & = & 41.5 & - & 12.9 & - & 23.1 & & \text{(in/yr)} \end{array}$$

"Runoff" may be assumed to be synonymous with stormflow, and thus exclude baseflows derived from groundwater discharge.

***Muir (1980)*** – A 1980 USGS study by Muir estimated "potential yields" for both the Purisima and Aromas aquifers used by SCWD. He based his estimates on pumping conditions that resulted in no long-term change in groundwater storage during a period with average precipitation. His estimated potential yields were 4,100 to 4,400 ac-ft/yr for the Purisima area and 1,500 ac-ft/yr for the Aromas area. His estimates of production during the mid to late 1970s suggested that pumping exceeded potential yield by approximately 1,000 ac-ft/yr in the Purisima area and 100 ac-ft/yr in the Aromas area.

***Thorup (1981)*** – Based on the following relation, Thorup estimated total groundwater throughflow of approximately 12,700 ac-ft/yr from a 51-square mile Soquel-Aptos recharge area:

$$\begin{array}{ccccccccc} \text{Recharge} & = & \text{Precipitation} & - & \text{Runoff} & - & \text{Evapotranspiration} & & \\ 4.6 & = & 36 & - & 11.2 & - & 20.2 & & \text{(in/yr)} \end{array}$$

Of this amount, he estimated that 1,200 to 2,400 ac-ft/yr of groundwater outflow to the ocean was adequate to prevent saltwater intrusion. Of the remaining amount, he did not distinguish between the amount needed to sustain baseflows and the amount available for pumping. However, he concluded that the "safe yield" was sufficiently large to allow groundwater development in excess of the potential yield estimated by Muir (1980).

***LSCE (1984a, 1987b, 1989, 1990, 1994, 1995b, 1996, 2004)*** – LSCE defined the perennial yield of the Purisima Formation as the amount of groundwater, including current pumpage, that flows through the various subunits toward the ocean in excess of the amount needed to maintain a positive seaward gradient (1984a, p. 29; 1985, p. III-6). SCWD pumping was then 3,000 to nearly 3,500 ac-ft/yr and pumping by others was estimated to be less than 1,000 ac-ft/yr (1984a, p. 49). LSCE estimated that groundwater outflow from the Purisima Formation to the ocean was 9,500 ac-ft/yr based on the seaward gradient along the coast between Opal Cliffs and Rio Del Mar. Based on these estimates, their estimate of the Purisima Formation's perennial groundwater yield was 12,000 to 13,000 ac-ft/yr. Estimates of the following were unspecified: 1) the amount of groundwater flow needed to maintain a positive seaward gradient, 2) groundwater contributions to stream baseflow, and 3) total groundwater throughflow and/or total groundwater recharge.

LSCE (1989) recommended that SCWD develop a supplemental surface water supply within 5 to 10 years to offset Purisima pumpage and meet increasing demand. Subsequently, LSCE (1994, 1996) accepted an independent estimate of total municipal and private groundwater production of 11,400 ac-ft/yr (Faler, 1992; see separate discussion below), and concluded that this approximately equaled the sustainable groundwater yield. Furthermore, LSCE stated that groundwater pumpage exceeded sustainable yield locally within some aquifer zones inasmuch as the water-level goal of >0 ft msl could not be maintained.

In the Aromas area, LSCE (1987b, 1990) estimated groundwater flow to the ocean of 12,000 ac-ft/yr based on estimated transmissivities and gradients. The recharge rate and recharge area sustaining this flow were unspecified. LSCE concluded that the Aromas area could sustain additional groundwater development for use in the Purisima area.

Noting evidence of the possible landward movement of the Aromas saltwater interface after 1993, LSCE (1994, 1995b) retracted its recommendation that SCWD consider developing additional Aromas groundwater. Then, with the end of the 1987-1994 drought, LSCE resumed its suggestion that additional groundwater could be developed in selected portions of the Aromas area (LSCE, 1996). Recently, LSCE (2004) supported a maximum SCWD pumping rate of 1,800 ac-ft/yr (SCWD, 1998; see below) to prevent further saltwater intrusion in the Aromas area (up to 400 ac-ft/yr below recent annual production) and suggested that coastal water levels be maintained at +8 ft msl.

***UCSC Graduate Student Model (Handel et al., 1985)*** – A numerical groundwater flow model developed by UCSC graduate students under the direction of a visiting USGS lecturer simulated 10,500 ac-ft/yr of throughflow and 500 ac-ft/yr of groundwater outflow to the ocean. Native groundwater discharge to baseflow was estimated to be nearly 10,000 ac-ft/yr, of which about 3,100 to 3,600 ac-ft/yr were pumped from wells in their developed-aquifer scenarios.

***Essaid (1992)*** – As part of a conceptual model to support a numerical groundwater flow model of the Soquel-Aptos area, a USGS researcher used two approaches to estimate total groundwater throughflow (Table 5-4). The first method estimated recharge from the amount of precipitation remaining after accounting for runoff and evapotranspiration. While providing unit rates of precipitation, runoff, and evapotranspiration, her annual recharge estimates were reported volumetrically, and the effective recharge areas implied by these volumetric rates are questionable (Table 5-4). Furthermore, the assumed runoff rates are derived from total gaged flows, and thus include baseflows, a component of the recharge being estimated. By this method, total groundwater throughflow ranges from 7,700 to nearly 17,000 ac-ft/yr.

The second method equated total groundwater throughflow with estimated stream baseflow. Baseflow was estimated using a simple straight-line hydrograph separation for four gaged streams. Average total baseflow of 6,100 ac-ft/yr was estimated for the portion of gaged watersheds within the model area. Thus, this estimate did not reflect baseflow gains downstream of the gages or the baseflows of ungaged watersheds also within the model area (i.e., Arana, Rodeo, Porter, and Valencia creeks). Furthermore, this groundwater yield estimate did not include existing groundwater pumping or outflow to the ocean.

The results of the USGS numerical model are summarized in Figure 5-3 and its inset table. Under native conditions, the model simulated 13,000 ac-ft/yr of total groundwater throughflow consisting of 1,000 ac-ft/yr of outflow to the ocean and 12,000 ac-ft/yr of stream baseflow. The corresponding unit rate of recharge cannot be inferred because the active model area was unspecified. As noted in Figure 5-3, there are a number of other uncertainties associated with the simulated water budget as it was presented, including an unexplained imbalance of 4 to 18 percent and a 1930-65 decline in recharge. While the model simulates a 30 percent decline in Soquel Creek baseflow during 1950-

1984, such a decline is not apparent in the gaged and estimated baseflow records,[30] unless the loss is mostly hidden during wet-weather periods. For assumed 1984 conditions, the model simulated pumping of 3,600 ac-ft/yr, ocean outflow of about 400 ac-ft/yr, and more than 10,000 ac-ft/yr of baseflow and outflow to the Aromas formation.

***SCWD (1998)*** – SCWD coordinated preparation of the 1998, *Statement on the Status and Estimated Practical Developable Groundwater Yield of the Soquel-Aptos Area*. It concluded that (1) SCWD required a supplemental supply of no less than 1,000 ac-ft/yr in the Purisima area and (2) SCWD's practical developable yield from its existing Aromas wells was 1,800 ac-ft/yr.

***Montgomery Watson et al. (1998, 1999a, 1999b)*** – The integrated groundwater-surface water model (IGSM) developed for SCWD encompasses about 112 onshore square miles, nearly 48 of which are within or tributary to the Pajaro Valley outside the Soquel-Aptos study area. Tables 5-5 and 5-6 summarize the recharge rates and simulated water budget of the approximate model area representing Soquel-Aptos (summarized succinctly in Tables 5-1 and 5-2).

The model assumes recharge rates independently for agricultural, urban, and undeveloped lands. As indicated in Table 5-5, there are some discrepancies between the reported unit and volumetric rates. Total streamflow, rather than only stormflow, seems to be used to estimate recharge as a portion of precipitation and applied water. Overall, the provided model results suggest an average recharge rate of 6 to 8 inches per year within the Soquel-Aptos area.

The average water budget simulated for 1982-93 conditions (Table 5-6) suggests groundwater recharge of about 20,000 ac-ft/yr within the Soquel-Aptos area and 2,600 ac-ft/yr of subsurface flow across its northern boundary. Simulated pumping was nearly 18,000 ac-ft/yr, ocean outflow was 1,700 ac-ft/yr, and outflow to Pajaro Valley was about 900 ac-ft/yr (Montgomery Watson, 1998).

Subsequent simulations were used to estimate a sustainable yield for the Purisima aquifer relative to the threat of saltwater intrusion (Montgomery Watson, 1999a). Given some pumping adjustments among existing wells, a sustainable yield of approximately 6,230 ac-ft/yr was estimated based on the need to achieve specified groundwater levels, maintain positive ocean outflow, and prevent a decline in groundwater storage. Of this sustainable yield, 3,070 ac-ft/yr represented SCWD's Purisima production and the remainder was pumping by others. Compared to average 1996-1997 conditions, this suggested that SCWD was pumping about 610 ac-ft/yr in excess of its portion of the Purisima area's estimated sustainable yield.

Combining this estimate of SCWD's sustainable yield from the Purisima area (3,070 ac-ft/yr) with an assumed Aromas area SCWD yield of 1,800 ac-ft/yr (SCWD, 1998) gives a total SCWD groundwater yield of 4,870 ac-ft/yr. SCWD has been using this estimate of its sustainable groundwater supply for planning purposes (e.g., Montgomery Watson, 1999b).

***Faler (1992), Pingree (1997), and Wolcott (1999)*** – Recognizing that other groundwater producers pump a substantial amount of groundwater throughout the Soquel-Aptos area, SCWD initiated an inventory of private wells and an estimation of their consumptive groundwater use. This work was concluded by staff at the Santa Cruz County Health Services Agency and addressed only the Purisima area (Figure 5-4). We reviewed this work and completed the analysis for the Aromas area, as presented in Table 5-7 and summarized in Table 5-2.

[30] e.g., see ahead to Figures 5-8 and 5-11.

Use of Soquel-Aptos groundwater by SCWD, CWD, the City of Santa Cruz, small water systems, and private parcels is estimated at approximately 6,700 ac-ft/yr for the Purisima area and 3,600 ac-ft/yr for the Aromas area.[31] Assuming approximate indoor and outdoor consumptive use factors, the estimated consumptive use of groundwater in the Purisima and Aromas areas is about 5,700 and 2,800 ac-ft/yr, respectively. This study assumes that these are currently the best available estimates of groundwater usage in the study area. As noted by Wolcott (1999), however, the estimated water use may include some stream diversions. Also, potential return flows from distribution leaks are unaccounted for.

The initial assessment by Faler (1992) assumed considerably higher water-use factors, resulting in an estimated 11,400 ac-ft/yr of total groundwater use in the combined Purisima and Aromas areas.

## 5.3 Estimated Groundwater Recharge

Consistent with the conceptual water budget presented in Section 5.1, this section presents our estimate of Soquel-Aptos groundwater recharge. This estimate requires associated estimates of precipitation, streamflow, and evapotranspiration. We provide guidance for developing spatial and temporal distributions of recharge for groundwater modeling. Additionally, our estimated record of stream baseflows is applicable to the transient calibration of a basinwide model. For the purposes of this report, we present an estimate of basinwide average annual recharge suitable for an overall balance of total inflows and outflows.

***Precipitation*** – Figure 5-5 shows the Soquel-Aptos portion of an isohyetal map of the Santa Cruz Mountains region constructed from the records of 120 precipitation gages adjusted to reflect long-term average (Geomatrix, 1999). Based on these contours, Figure 5-6 shows estimates of average annual precipitation for 32 USGS-gaged watersheds in the region (Geomatrix, 1999). The study-area watersheds have the following averages:

- Branciforte Creek at Santa Cruz: 41 in/yr (less for the study-area portion)
- Soquel Creek at Soquel: 41 in/yr
- Soquel Creek near Soquel: 43 in/yr
- West Branch Soquel Creek: 44 in/yr
- Aptos Creek at/near Aptos: 38 in/yr

***Total Streamflow*** – Figure 5-7 is a map of the gaged watersheds in the Soquel-Aptos study area. Table 5-8 presents the gaged annual flows of Branciforte, Soquel, and Aptos Creeks. Table 5-9 provides the average annual flows of these watersheds, adjusted to a 51-year average corresponding to the USGS gaged record for Soquel Creek at Soquel. Dividing the watershed area into the average annual flows gives values of unit discharge, expressed in inches per year (Table 5-9). The study area gaged watersheds have unit discharges ranging from 10 to 17 in/yr.

The inset graph in Figure 5-6 plots the correlation between average annual watershed precipitation and mean annual unit discharge for USGS-gaged streams in the Santa Cruz Mountains region (Geomatrix, 1999). This relation is useful for estimating the unit streamflow of ungaged portions of the study area.

***Baseflow*** – Figure 5-8 illustrates the method used by this study to separate the gaged streamflow hydrograph into separate stormflow and baseflow components. Using a log scale to plot discharge,

[31] These estimates are based on maximum annual groundwater production by SCWD, CWD, and the City of Santa Cruz's Beltz wells.

each year's baseflow recession is fit with a straight line, i.e., an exponential function. The backward extension of this curve helps distinguish between baseflow and stormflow toward the end of the wet season.

The rate of baseflow is assumed to correlate to shallow groundwater levels, i.e., baseflows are greatest when shallow groundwater levels peak toward the end of the wet season, typically about April. The wet season is defined by plots of monthly precipitation (e.g., Figure 5-8) and water-table hydrographs (e.g., Figure 4-33). Baseflows are assumed to increase at a linear rate during a typical wet season until intersecting the baseflow recession curve at a time approximating the occurrence of peak groundwater levels. During significant breaks in wet-season precipitation we infer that baseflows level off until precipitation resumes or the wet season ends (e.g., water year [WY][32] 1953, Figure 5-9).

As shown in Figures 5-9, 5-10, and 5-11, and summarized in Table 5-10, this technique was used to estimate annual baseflows for the study area's gaged watersheds. Figure 5-12 illustrates the relationship between total gaged flow and estimated baseflow for the gaged record of Soquel Creek at Soquel. Table 5-9 gives average unit baseflows, in inches per year, calculated from the hydrograph separations and adjusted to the 51-year base period. Unit baseflow estimates for the gaged watershed areas range from 1.4 to 3.5 in/yr.

Few data are available for estimating the average annual baseflows of streams not gaged by the USGS. Late dry season baseflows of <0.2 cubic feet per second (cfs) were measured in Arana Gulch during 1999 (Balance Hydrologics, 2002). Baseflows ranging from 0.5 to 1.8 cfs were measured in lower Valencia Creek between December and April 2002, with the observation of a steeper baseflow recession than Aptos Creek upstream of Valencia Creek (Coastal Watershed Council and Swanson Hydrology & Geomorphology, 2003; Swanson Hydrology & Geomorphology, 2003). We assume somewhat nominal values of unit baseflow for the Aromas area given the lack of streamflow data, the area's low precipitation, and the potential for the water table to lie below streambed elevations in portions of the included watersheds. Estimated average unit baseflows for the entire Purisima and Aromas areas are about 2.2 and 0.9 in/yr, respectively (Table 5-11).

Baseflows represent releases from groundwater storage as well as responses to annual recharge. A linear regression between annual precipitation and estimated annual baseflows for Soquel Creek during WYs 1953-2002 results in a correlation coefficient (i.e., $r^2$) of 0.64. Including the estimated baseflow for the preceding year in a multiple linear regression increases the correlation coefficient significantly to 0.81. However, adding a second preceding year to the regression increases the correlation coefficient to only 0.82. Thus, the study-area uplands are most effective at storing groundwater recharged during the current year and immediately preceding year.

***Stormflow*** – Subtracting the estimated baseflows from the total gaged flows provides an estimate of average watershed stormflow. As presented in Table 5-11, unit stormflow estimates range from 8 to 15 in/yr for the gaged watersheds.

***Evapotranspiration*** – Evapotranspiration is a function of several factors including precipitation, temperature, solar radiation, vegetation, and soil type. The California Irrigation Management Information System (CIMIS) provides estimates of monthly "reference evapotranspiration" (ETo), which represents the unrestricted water consumption of irrigated pasture grass. Annual values of ETo for the Soquel-Aptos study area range from 39 to 46 in/yr (Figure 5-13).

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[32] For example, WY 2004 extends from October 1, 2003 to September 30, 2004.

An applicable range of native (i.e., non-irrigated) evapotranspiration rates cited in the literature include the following:

| Setting | | Ppt (in/yr) | ET (in/yr) | Source |
|---|---|---|---|---|
| Pacific Douglas fir-redwood | | | 30 | Lull, 1964 |
| Western mixed conifer | | | 22 | |
| California woodland-grass | | | 18 | |
| Pajaro basin | Forest | 32 | 24 | SWRB, 1953 |
| | | 40 | 28 | |
| | | 48 | 32 | |
| | Dry-farm orchard | | 17 | |
| | Chaparral | 32 | 20 | |
| | Valley floor (phreatophytes?) | | 50+ | |
| Scotts Valley Santa Margarita Sandstone | | 45 | 19 | Johnson, 2001a, 2002 |

As reviewed in Section 5.2, previously assumed rates of average evapotranspiration for the Soquel-Aptos basin have ranged from 20 to 26 in/yr. Evapotranspiration is relatively low in the Aromas study area because (1) precipitation decreases toward the Pajaro Valley and (2) the Aromas soils have high percolation rates and retain relatively little water for plant use during the dry season.

Table 5-11 provides evapotranspiration estimates for the study area watersheds. Values range from 27 in/yr for the upper Soquel Creek tributaries to 19 in/yr where the Aromas Sands are exposed in the Harkins Slough watershed and adjoining areas.

A rough estimate of phreatophyte evapotranspiration suggests a value of about 0.3 in/yr averaged across the entire study area. This estimate considers more than 50 miles of riparian corridor and assumes phreatophytes use an additional 24 in/yr. Because this amount is relatively small, it is not explicitly accounted for in our basinwide recharge estimates.

***Deep Recharge from Precipitation*** – Based on the preceding estimates, deep recharge from precipitation is estimated in Table 5-11 as follows:

Deep Recharge from Precipitation = Precipitation – Total Streamflow – Total ET

Estimates range from nearly 2 to more than 5 in/yr for various portions of the study area. Averages for the Purisima and Aromas areas are 2.2 and 3.8 in/yr, respectively.

***Precipitation Recharge*** – Precipitation recharge is the sum of baseflows and deep precipitation recharge. Estimates range from 2.5 to more than 6 in/yr for the various portions of the study area. In the Purisima area this tends to be split almost equally between baseflows and other discharge, whereas in the Aromas area baseflows comprise about one-fifth of estimated precipitation recharge. The estimated unit rate of precipitation recharge averages 4.4 in/yr for the Purisima area and 4.7 in/yr for the Aromas area.

***Applied-Water Recharge –*** The assumptions used to estimate consumptive use (Table 5-7) also provide the basis for estimating applied-water recharge. Among SCWD customers, total water use is split between 30 percent for indoor use and 70 percent for outdoor use (ESA, 2004). The County assumed a 50:50 split between indoor and outdoor water use (Wolcott, 1999). We assume the SCWD split applies to urban areas and the County split applies to rural areas. Adopting the consumptive-use factors assumed by County staff (Wolcott, 1999; Table 5-7), 80 percent of outdoor use becomes evapotranspiration. Thus, 6 percent of urban outdoor use has the potential to become groundwater recharge. Dividing 6 percent of SWCD's annual use by its total service area (approximately 14 square miles) gives an estimated unit rate of applied-water recharge of 0.5 in/yr within District boundaries. Consideration of distribution system leaks, and return flows from other groundwater producers, would increase this estimate by roughly one to a few tenths of an inch per year.

Within the non-sewered portions of the study area, on-site wastewater discharge is an additional component of applied-water recharge (i.e., septic tanks). County staff assume 75 percent of indoor use becomes such recharge (Wolcott, 1999; Table 5-7). Combined with the above assumptions for outdoor use, applied-water recharge is approximately 47 percent of total water use in non-sewered areas, which is less than 0.5 in/yr averaged areally. Little or none of this return flow occurs within the Forest of Nisene Marks State Park, which encompasses large portions of the Aptos and Soquel creek watersheds (Figure 5-4).

***Areal Distribution of Recharge*** – Factors affecting the areal distribution of recharge across the study area include spatial variations in climate (e.g., Figure 5-5), vegetation, soils, geologic outcrop (Figure 2-10), and development (Figure 5-4). For a model focusing on aquifers along the coastal terrace, uniform recharge rates could be applied across large portions of the upper watersheds. This assumes that most recharge has the opportunity to leak downward to producing aquifer zones.

In the Aromas area, the location of the groundwater divide with Pajaro Valley is uncertain. However, we assume that groundwater recharged in the upper Harkins Slough watershed generally flows under the drainage divide and toward the coast. A recharge area roughly this size is needed to account for the yield of Aromas wells between Aptos and La Selva Beach.

***Temporal Variation of Recharge*** – Recharge varies with time as a function of the variability and timing of precipitation. A recharge time series is needed for a transient groundwater model (e.g., one that can be calibrated to the estimated baseflow record). Figure 5-14 and its inset table present a hypothetical relation between annual precipitation, stormflow, evapotranspiration, and recharge for the central Purisima area for WYs 1974-2000. The stormflow relation is based on the hydrograph separations for Soquel Creek (Figure 5-9 and Table 5-10). These relations are not necessarily the same as relations based on differences in average precipitation (Table 5-11). Furthermore, these relations are imprecisely known and would probably be adjusted within reasonable limits to achieve model calibration. Based on these rough assumptions, no recharge occurs during about 15 percent of all years, recharge of 16 in/yr occurs during the wettest year, and recharge averages about 5 in/yr. Because water levels along the coastal terrace fluctuate relatively little in response to the climatic cycle, simulating annual variations in recharge may not be critical for modeling the production aquifers. However, recharge variations would be needed to simulate baseflow variability.

## 5.4 Estimated Groundwater Mass Balance

We conclude this section with a simple mass balance of net average groundwater inflows and outflows. This simplification is justified considering that the mass-balance approach provides poor estimates of head-dependent budget terms (e.g., stream-aquifer interactions, leakage between depth zones, and groundwater inflows and outflows along the ocean boundary). Furthermore, we assume no net change in onshore groundwater storage given little evidence to the contrary during the past 30 years. Although there may be an ongoing storage decline in unmonitored areas, there is little basis for an estimate. The ongoing loss of offshore fresh groundwater storage is accounted for as a subsurface inflow of intruding saltwater.

While providing a rough estimate of basin yield, the mass balance approach is not suited for answering "what if" questions relating to the effects of increased or decreased pumping and/or recharge. Numerical modeling is able to more accurately estimate a groundwater budget by solving the mass balance simultaneously with head-dependent hydraulics and considering spatial and temporal variability. This report provides the information and assumptions needed to support such an effort.

Generalizing the detailed estimates from Table 5-11, Table 5-12 presents estimated average unit and volumetric rates of groundwater recharge for the study subareas. The reported estimates are sufficiently detailed to avoid major roundoff errors when inserted into the water balance equations. However, this detail is not intended to convey accuracy. At a minimum, estimates should be rounded to the nearest 1,000 ac-ft/yr when used for planning purposes.

In the Purisima area, average annual precipitation recharge is estimated at 12,200 ac-ft/yr, divided about evenly between baseflow and deep precipitation recharge. Precipitation recharge of 3,600 ac-ft/yr is estimated for the Aromas area, of which 2,900 ac-ft/yr is assumed to be deep recharge. There is significant uncertainty in these estimates considering that a 1 in/yr increase in estimated evapotranspiration (4 to 5 percent) reduces the recharge estimates by nearly 25 percent. Additionally, the assumed recharge areas are uncertain (e.g., whether or not to include areas north of the Zayante fault; where to draw the effective recharge boundary between the Purisima and Aromas areas).

Our estimate of precipitation recharge for the Purisima area roughly equals three previous estimates (Hickey, 1968; Thorup, 1981; Essaid, 1992) (Table 5-1). It also roughly equals LSCE's (1984a) estimate of the Purisima Formation's perennial yield; however, our estimate of precipitation recharge contributes about 6,000 ac-ft/yr to stream baseflow whereas the former perennial yield estimate does not. For the Purisima and Aromas areas combined, our estimate of precipitation recharge equals about 80 percent of the amount modeled by Montgomery Watson (1998).

From Table 5-7, the estimated consumptive use of groundwater is approximately 5,700 ac-ft/yr for the Purisima area and 2,800 ac-ft/yr for the Aromas area. These consumptive-use estimates compensate for potential applied-water recharge, except for an increment of additional recharge associated with imported water use in the Live Oak area. Consumptive use is a convenient term to use in this simple mass balance, given its stated limitations. However, applied-water recharge should be accounted for explicitly in a groundwater model for the reasons stated above.

***Purisima Area*** – Assuming no change in onshore groundwater storage and no net boundary inflows or outflows other than with the ocean, a simple inflows-equal-outflows mass balance for the Purisima area is as follows:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Deep Precipitation Recharge | + | Saltwater Intrusion | = | Consumptive Use | + | Groundwater Discharge to Ocean | |
| 6,100 | + | ? | = | 5,700 | + | ? | (ac-ft/yr) |

Simplified further:

| | | | | | |
|---|---|---|---|---|---|
| Deep Precipitation Recharge | = | Consumptive Use | + | *Net* Groundwater Discharge to Ocean | |
| 6,100 | = | 5,700 | + | 400 | (ac-ft/yr) |

In this case, 400 ac-ft/yr of net groundwater discharge to the ocean is estimated as a residual of independent estimates of deep precipitation recharge and consumptive use. This estimate should be considered highly approximate given the associated assumptions and uncertainties. It is less than 5 percent of the offshore discharge estimated by LSCE (1984a), similar to the offshore discharge modeled by Essaid (1992), and half or less of the offshore discharge Thorup (1981) estimated necessary to prevent saltwater intrusion (Tables 5-1 and 5-2). Such discharge occurs mostly from shallow zones with water levels above sea level. Deeper zones with groundwater levels at or below sea level are receiving leakage and subsurface inflow that potentially involves saltwater intrusion. Thus, despite a net outflow to the ocean, intrusion may be occurring at some depths and locations, and an average consumptive use of 5,700 ac-ft/yr may exceed the sustainable yield. Stable water levels, some outflow to the ocean, and possibly minimal reductions in onshore storage do not necessarily indicate the absence of overdraft.

***Aromas Area*** – We assume no change in onshore storage for a simple inflows-equal-outflows groundwater mass balance of the Aromas area. A rough estimate of groundwater outflow to Pajaro Valley during drought years may be derived using the following form of Darcy's law:

$$Q = T \times W \times i$$

where $Q$ is the volumetric rate of groundwater flow, $T$ is aquifer transmissivity, $W$ is the width of flow perpendicular to the gradient, and $i$ is the lateral hydraulic gradient. An autumn 1991 groundwater contour map representative of drought conditions (LSCE, 1996) shows a gradient of about 0.0003 from SCWD's Aromas area southeast into Pajaro Valley. Assuming a transmissivity of 10,000 $ft^2$/day (Table 3-13) and a flow width of 20,000 ft gives a flow of about 500 ac-ft/yr. Assuming that such gradients occur an average of one year out of five, groundwater outflow to Pajaro Valley averages about 100 ac-ft/yr.

In the following mass balance equation, average annual saltwater intrusion and groundwater discharge to the ocean remain unestimated.

| Deep Precip. Recharge | | Saltwater Intrusion | | Consumptive Use | | Subsurface Outflow to Pajaro Valley | | Groundwater Discharge to Ocean | |
|---|---|---|---|---|---|---|---|---|---|
| 2,900 | + | ? | = | 2,800 | + | 100 | + | ? | (ac-ft/yr) |

Groundwater is discharging to the ocean along the northern Aromas area coastline, while progressive saltwater intrusion is evident along the southern coastline. Some saltwater intrusion is needed to balance the water budget given the estimates of recharge, consumptive use, and outflow to Pajaro Valley, and the knowledge that some groundwater is discharging to the ocean. Thus, without quantifying the unknown terms, the mass balance indicates a significant groundwater deficit.

## 5.5 Summary and Conclusions

The following table summarizes our mass-balance estimates of key groundwater budget parameters, expressed in both unit and volumetric rates for average annual conditions. These estimates are highly approximate given the limitations of the mass-balance approach and the associated assumptions and uncertainties. The estimates are sufficiently detailed to avoid confusing roundoff errors in the balance of terms. However, this detail is not intended to convey accuracy. Estimates should be rounded to the nearest 1,000 ac-ft/yr when used for planning purposes.

| | Purisima Area (in/yr) | Aromas Area (in/yr) | Purisima Area (ac-ft/yr) | Aromas Area (ac-ft/yr) |
|---|---|---|---|---|
| Precipitation Recharge | 4.4 | 4.7 | 12,200 | 3,600 |
| Baseflow | 2.2 | 0.9 | 6,100 | 700 |
| "Deep" Precipitation Recharge | 2.2 | 3.8 | 6,100 | 2,900 |
| Groundwater Production | 2.4 | 4.7 | 6,700 | 3,600 |
| Consumptive Use | 2.1 | 3.7* | 5,700 | 2,800 |
| Applied-Water Recharge** | 0.4 | 1.0* | 1,000 | 800 |
| Discharge to Ocean | 0.1 | > 0 | 400 | > 0 |
| Subsurface Flow to Pajaro Valley | n/a | ~0.1 | n/a | ~100 |
| Saltwater Intrusion | ? | > 0 | ? | > 0 |

Notes: "> 0" means unknown but larger than zero.
Values reflect small roundoff errors.
n/a = non-applicable.
*Higher mainly due to smaller area.
**Not including imported water contribution.

The following caveats are associated with the mass-balance approach:

- It does not account accurately for head-dependent flows (e.g., aquitard leakage, aquifer-stream and aquifer-ocean interactions, subsurface flows into Pajaro Valley).
- Groundwater recharge and its distribution among various discharges are neither absolute nor fixed given potential changes in the system dynamics (e.g., changes in pumping).
- With little basis for estimating long-term changes in groundwater storage, we assume no change in onshore storage for a simple inflows-equal-outflows mass balance.
- Potential negative consequences associated with groundwater pumping (e.g., saltwater intrusion, baseflow depletion) constrain groundwater production to amounts less than the estimated rate of groundwater replenishment. Stable groundwater levels, some outflow to the ocean, and potentially minimal reductions in onshore groundwater storage do not necessarily indicate the absence of overdraft.
- The mass balance of net inflows and outflows obscures important aspects of the flow system. For example, saltwater intrusion may be occurring in offshore portions of the Purisima aquifer despite a positive estimate of net groundwater discharge to the ocean.
- A calibrated numerical model provides a better tool for answering questions related to the effects of increased or decreased pumping and/or recharge. It more accurately estimates a groundwater budget by (1) solving the mass balance simultaneously with head-dependent hydraulics and (2) considering spatial and temporal variability. This report provides the information and assumptions needed to support such a modeling effort (e.g., updating the existing IGSM model).

Our groundwater mass balance of current average conditions assumes no net change in onshore groundwater storage, no subsurface inflows other than saltwater intrusion, and no boundary outflows other than discharge to the ocean and subsurface outflow to Pajaro Valley. Given these assumptions and the caveats discussed above, the findings of the groundwater mass balance are summarized as follows:

- Precipitation recharge averages about 4.4 in/yr for the Purisima area and 4.7 in/yr for the Aromas area. Lower precipitation in the Aromas area is offset by lower estimates of evapotranspiration.

The estimated volumetric rates of precipitation recharge are 12,200 and 3,600 ac-ft/yr for the Purisima and Aromas areas, respectively.

- Our estimate of precipitation recharge for the Purisima area is roughly the same as three previous estimates (Table 5-1). Our estimate of precipitation recharge for the Purisima and Aromas areas combined is about 80 percent of the amount modeled by Montgomery Watson (1998).
- The recharge estimates are highly sensitive to the assumed values of evapotranspiration. A one inch per year increase in estimated evapotranspiration (4 to 5 percent) reduces the recharge estimates by nearly 25 percent.
- The assumed recharge areas are uncertain (e.g., whether or not to include areas north of the Zayante fault; where to draw the effective recharge boundary between the Purisima and Aromas areas).
- Purisima area baseflows account for about 50 percent of the estimated precipitation recharge. There is little data upon which to estimate baseflows for the Aromas area. Thus, the estimate that Aromas area baseflows equal about one-fifth of precipitation recharge is highly approximate. Additional stream surveys and baseflow measurements are warranted for the study area's ungaged streams.
- Deep precipitation recharge contributes to pumping wells, discharge to the ocean, and subsurface outflow to Pajaro Valley ("deep" indicates a relative separation from stream-aquifer interactions). It is estimated to be 6,100 ac-ft/yr (2.2 in/yr) in the Purisima area and 2,900 ac-ft/yr (3.8 in/yr) in the Aromas area. The Aromas area has a higher unit rate mostly because of its lower estimate of unit baseflow.
- Changes in groundwater storage across the interior uplands (where most inland storage change occurs) are difficult to estimate from available data. We assume that fluctuations in shallow groundwater storage resulting from wet and dry periods affect mostly baseflow. The effect of water-table fluctuations on recharge to relatively deep production aquifers is constrained by aquifer-aquitard leakage rates.
- Total groundwater production in the Purisima and Aromas areas is estimated at 6,700 and 3,600 ac-ft/yr, respectively, about 75 to 85 percent of which becomes consumptive use.
- The estimated unit rate of applied-water recharge is about 0.5 in/yr averaged over both developed and over undeveloped (i.e., non-sewered) areas. Averaged separately over the entire Purisima and Aromas areas, the estimated unit rates are 0.4 and 1.0 in/yr, respectively.
- Net groundwater discharge to the ocean from the Purisima area is estimated at 400 ac-ft/yr as a residual of deep precipitation recharge and consumptive use. This discharge occurs mostly from shallow zones with water levels above sea level. Deeper zones with groundwater levels at or below sea level are receiving leakage and subsurface inflow with the potential to be saltwater intrusion. Thus, the estimated average consumptive use of 5,700 ac-ft/yr may exceed the sustainable yield
- For the Aromas area, we estimate that precipitation recharge and consumptive use both equal nearly 3,000 ac-ft/yr, and groundwater outflow to Pajaro Valley averages roughly 100 ac-ft/yr. Our simple mass balance approach is unable to quantify either groundwater discharge to the ocean or saltwater intrusion. However, from our analyses in Sections 4 and 6, we recognize that groundwater is discharging to the ocean along the northern Aromas coastline while saltwater intrusion is actively occurring along the southern coastline. Based on this understanding, some

saltwater intrusion is needed to balance the groundwater budget, indicating a significant groundwater deficit.

# 6 Saltwater Intrusion

Historic and persistent low groundwater elevations caused by pumping in the Soquel-Aptos area have contributed to long-standing concerns that saltwater intrusion may threaten the area's groundwater resources.[33] This section evaluates the occurrence and potential of saltwater intrusion along the Soquel-Aptos coast by (1) introducing saltwater intrusion concepts, mechanisms, and indicators (2) reviewing previous assessments, (3) analyzing historic water-quality data for indications of saltwater intrusion, and (4) assessing intrusion pathways and conditions in the study area.

## 6.1 General Concepts

The term saltwater intrusion broadly applies to the occurrence of saline water in coastal aquifers. Given that saltwater can occur naturally at depth along the coast, the term "saltwater encroachment" has been used to describe the movement of saltwater into zones previously occupied by freshwater (Heath, 1983). In the following discussion we distinguish between the migration of the freshwater-saltwater interface, upconing of the saltwater interface, and seawater leakage into aquifers through near-shore outcrops. We also review the various water-quality indicators of saltwater intrusion.

### 6.1.1 Migration of the Saltwater-Freshwater Interface

Groundwater in coastal basins flows from recharge areas toward streams, wells, and the coast. In undeveloped coastal basins there is a net outflow of fresh groundwater to the ocean. If the outflow of fresh groundwater decreases, the subsurface saltwater-freshwater interface shifts landward until achieving a new equilibrium. If onshore groundwater levels are drawn down below the density-equivalent of sea level, the interface may migrate progressively inland.

***Single Aquifer without Pumping*** – In the simple case of a thick, homogeneous unconfined aquifer extending offshore, saltwater extends landward along the aquifer base as a wedge beneath fresh groundwater flowing to the ocean (Figure 6-1a). The wedge shape of the freshwater-saltwater interface reflects the greater density of saltwater, i.e., freshwater essentially floats over the saltwater. The deepest portion of a stationary wedge (i.e., its "toe") may extend beneath the land surface even when there is ample freshwater discharge, little or no pumping, and the interface "tip" remains offshore. Common use of the term "intrusion" applies to this relatively natural, static condition, as well as progressive landward movement of the interface caused by pumping.

***Multiple Aquifers without Pumping*** – In multi-layered groundwater systems, the location of the saltwater-freshwater interface may vary among the different aquifer zones (Figure 6-1b). The rate of groundwater outflow particular to each zone results in a unique location for each interface. In such cases, the overall configuration of the saltwater-freshwater interface is a complex function of the distribution of hydraulic pressures within each aquifer, the hydraulic conductivity of each aquifer, and the vertical conductivity of the bounding aquitards (or "confining units", as labeled in Figure 6-1b).

The saltwater interface in deep confined aquifers is often located farther offshore than in shallow unconfined aquifers (Figure 6-1b). The freshwater in an unconfined aquifer can discharge readily to the ocean, allowing the saltwater interface to exist near shore. Freshwater in confined aquifers seeps out slowly through the overlying aquitards. The slow seepage rates, combined with relatively high heads driving groundwater flow from distant recharge areas, allow the freshwater to maintain

[33] In this report, saltwater refers to saline groundwater in aquifers beneath the seafloor and coastal areas, as distinguished from seawater in the open ocean.

positive pressure beneath the sea floor, pushing the saltwater interface away from the coastline. Although the interface of each aquifer is wedge shaped, the composite profile of the interface for multiple aquifers may not be.

***Multiple Aquifers with Pumping*** – The freshwater-saltwater interface shifts shoreward in response to a reduction in fresh groundwater outflow and hydraulic gradient, as occurs from groundwater pumping or drought (Figure 6-2a). With sufficient remaining outflow, the interface stabilizes at a new equilibrium position. If the outflow becomes too diminished, the interface will migrate progressivley toward the depressed freshwater heads within the pumping trough. As the interface moves farther onshore, groundwater produced from coastal wells becomes impacted.

The extent of interface migration depends on the amount of water pumped from a particular aquifer and the amount of leakage from overlying and underlying units. Water extracted from the lower aquifers is replaced by some combination of (a) groundwater flow fed by inland recharge, (b) freshwater and/or saltwater migrating shoreward through the aquifer, and (c) freshwater and/or saltwater leaking from overlying and underlying units.

The initial location of a freshwater-saltwater interface is critical to evaluating its migration. An interface initially far from shore may migrate landward for a considerable time before reaching monitoring or production wells. Furthermore, the farther the interface is from the pumping well, the greater the potential that freshwater leakage from overlying zones will replenish the producing aquifer. This leakage may slow or effectively halt the interface migration in the pumped aquifer. However, this leakage could exacerbate seawater intrusion in the overlying aquifer and result in the eventual downward leakage of saltwater.

The impacts of saltwater intrusion are often persistent even as measures are taken to mitigate its cause. This is because the landward gradient created by a deep pumping trough is steeper than the seaward gradient resulting from reduced or no pumping. Reduced pumping may neutralize the onshore gradient, but have a relatively small and delayed effect on pushing the interface back. With the resumpition of groundwater outflow, the removal of saltwater ions from the aquifer is delayed by the slow reversal of cation-exchange processes (Hem, 1989).

***Interface Hydraulics*** – The depth to the freshwater-saltwater interface is approximated by the Ghyben-Herzberg relation (Figure 6-3). According to this relation, the depth to the interface is equal to 40 times the freshwater head above mean sea level, assuming a homogeneous and isotropic aquifer under static equilibrium conditions and a saltwater density equal to seawater (i.e., 2.5 percent greater than freshwater). Thus, for a 1-ft decline in the groundwater surface, the interface moves inland until it is 40 ft closer to sea level.

Figure 6-4 presents the Glover (1964) solution for the freshwater-saltwater interface, which more accurately accounts for groundwater discharge to the ocean along a seafloor seepage face. As shown, the length of the interface toe protruding onshore is inversely proportional to the seaward flow of freshwater (or simply the hydraulic gradient) and directly proportional to the aquifer thickness. The Glover solution also assumes homogeneous and isotropic aquifer conditions.

Because of diffusion, dispersion, and the surging action of tides and coastal pumping, freshwater and saltwater mix along the interface within a transition zone (Figure 6-1a). Mixed saltwater advects seaward with the outflowing groundwater, creating a small landward current of saltwater even when the interface is stationary.

### 6.1.2 Upconing

Upconing refers to the effect of a pumping well on the shape of the freshwater-saltwater interface (Figure 6-5). Consistent with the Ghyben-Herzberg relation, a pumping well's cone of depression produces an inverted cone in the interface. This cone rises 40 times higher than the depth of drawdown, assuming homogeneous and isotropic conditions. Where hydraulic conductivity is less vertically than horizontally, as is nearly always the case, the amount of upconing is smaller. At some critical height, the cone becomes unstable and saltwater flows upward to the well. When pumping stops, the impacts of upconing are relatively reversible compared to the onshore movement of an entire saltwater wedge. Thus, the water quality impacts of upconing may be more variable than those of a migrating saltwater interface.

### 6.1.3 Seawater Leakage through Offshore Outcrops

Pumping depressions may induce saltwater intrusion without encountering the saltwater interface. In the case of an unconfined or semi-confined aquifer, seawater may be captured by a pumping depression that reaches the shoreline, as illustrated in Figure 6-6. In a confined aquifer, pumping depressions may extend relatively far offshore and induce saltwater leakage directly from the ocean and overlying or underlying intruded zones. Potential leakage pathways include aquifer outcrops on the seafloor, fractures, and paleochannels that cut into the confining layer (Figure 6-2b). Although such pumping depressions also may cause the interface to move landward, seawater leakage may present a more immediate threat if the interface is initially far offshore.

### 6.1.4 Indicators of Saltwater Intrusion

Saltwater intrusion is generally identified through the chemical analysis of groundwater. Whereas diminished groundwater outflow and groundwater levels at or near sea level indicate the potential for intrusion, actual saltwater intrusion is indicated by various geochemical changes in groundwater quality. A simple mixture of freshwater and seawater is unexpected because of the cation exchange and sulfate reduction that occur when seawater first enters a freshwater aquifer. No single analysis provides a definitive indicator of the early stages of saltwater intrusion. However, results from a combination of analyses allow us to interpret instances where saltwater has mixed with freshwater.

It is often difficult to identify incipient saltwater intrusion at low chloride concentrations. This is because natural variations in freshwater chloride concentration often mask the early effects of freshwater-saltwater mixing. Mixing trends between groundwater and saltwater are more easily defined when and where chloride concentrations exceed 1,000 milligrams per liter (mg/L) (Richter and Kreitler, 1993).

Common geochemical indicators of saltwater intrusion include the following:

- ***Increasing Chloride Concentrations*** – Whereas the dominant anion in groundwater is typically bicarbonate or sulfate (generally <300 mg/L in the study area), seawater is chloride rich (i.e., 19,000 mg/L). A steady increase in chloride concentration is the best indicator of saltwater intrusion. For example, a contour representing groundwater with 500 mg/L chloride is used to delineate the advance of saltwater intrusion in Salinas Valley, where background concentrations generally vary between 100 and 200 mg/L.
- ***Sodium:Chloride Ratios*** – Along the advancing saltwater front, sodium often replaces calcium on the aquifer matrix through ion exchange. Therefore, the groundwater ratio of sodium to chloride (Na:Cl) drops and may serve as an early indicator of saltwater intrusion. Na:Cl ratios also can be used to help differentiate between saltwater intrusion and other sources of mineralized water. Jones et al. (1999) suggested that an advancing saltwater front is indicated by

Na:Cl molar ratios below 0.86 (the value for seawater). Municipal wastewater, by contrast, typically has a Na:Cl molar ratio greater than 1.

- ***Trilinear Plots*** – Trilinear plots provide a convenient method of diplaying and comparing general mineral data from many water samples. As illustrated in Figure 6-7, the relative abundance of individual cations and anions is plotted in the left and right triangles, respectively, and their combined distribution is plotted in the central diamond. Waters from similar or related sources will generally plot together. The mixture of two waters will generally plot along a straight line between the two end-member types within the central diamond. The trend towards saltwater intrusion, however, often plots along a curved path as shown in Figure 6-7. Data from wells with known saltwater intrusion in Pajaro Valley are plotted on this figure. The arrow tracks the evolution of the water chemistry from freshwater to saltwater. Often only the first, upward leg of this curve is observed because production wells become too saline for use before reaching the downward leg, and sampling is discontinued.
- ***Chloride-Bicarbonate Ratios*** – The ratio of chloride to bicarbonate-plus-carbonate contrasts the relative abundance of the dominant seawater and freshwater anions (Revelle, 1941 as cited by Todd, 1980). As a ratio of concentrations expressed in mg/L, the value for seawater exceeds 100 and values for groundwater unaffected by saltwater are generally less than 0.3. For groundwater relatively low in total dissolved solids, this ratio provides little benefit over evaluating chloride concentrations alone.
- ***Other Indicators*** – Hem (1989) suggested several other indicators for saltwater intrusion, including the concentration ratio of calcium to magnesium (about 0.3 in seawater and greater in freshwater); the ionic proportion of sulfate (about 9 percent in seawater and larger in freshwater); and the concentrations of minor constituents such as iodide, bromide, boron, and barium.

## 6.2 Previous Assessments

During the past four decades, previous studies have both raised and dismissed concerns regarding the potential for saltwater intrusion in the Soquel-Aptos area. A brief review of this past work provides an important technical and historical context for this study's interpretation of past and current, actual and potential, saltwater intrusion. Previous assessments, including some for the adjoining Pajaro Valley coast, are described below.

***Hickey (1968)*** – Hickey acknowledged that a saltwater wedge existed somewhere offshore of the Soquel-Aptos area, possibly close. He noted a slight increase in the chloride concentration of groundwater produced from the Hillcrest and Opal 3 wells. He recommended establishing a network of coastal monitoring wells and shifting pumping inland. These recommendations were achieved in following years through SCWD's establishment of a coastal monitoring-well network and the discontinued use of several coastal wells (e.g., the Hillcrest and Seacliff wells).

***Muir (1980)*** – Muir identified two potential mechanisms of saltwater movement into the Soquel-Aptos coastal aquifers: (1) the horizontal migration of the saltwater wedge at depth and (2) the downward movement and subsequent lateral migration of seawater through shallow deposits adjacent to the coast. He noted that there were no vertical barriers to intrusion given that the aquifers are in contact with the ocean where they are exposed on the seafloor and along the sides of the Monterey submarine canyon.

He defined saltwater degradation as groundwater with chloride concentrations above or approaching 100 mg/L, compared to typical concentrations of 20 to 80 mg/L in Purisima groundwater and about 20 mg/L in Aromas-area groundwater. He believed that intrusion by the second of the mechanisms he listed had been occurring in the Capitola area since 1959, as evidenced by chloride concentrations in groundwater pumped from Opal 1, Hillcrest, and various private wells. He inferred that the freshwater-saltwater interface was probably advancing landward but was still some distance offshore or at depth.

***Thorup (1981)*** – In rebutting Muir, Thorup stated that the purported evidence for saltwater intrusion was inconclusive. He identified several wells in the vicinity of New Brighton Beach State Park that were less than 200 ft deep and had chloride concentrations of 100 to 150 mg/L. He described this as a localized perched zone containing native brackish water, given that water levels were +25 to +43 ft msl.

However, he noted the occurrence of sub-sea level pumping depressions around several SCWD production wells. If water levels remained below sea level after resting overnight, he recommended curtailing pumping by one third to one half to allow water levels to rise above sea level. He also suggested developing additional groundwater yield by constructing a new well in the Seascape area.

***LSCE (1981)*** – Similar to Thorup, LSCE stated that (1) water quality data did not provide conclusive evidence of saltwater degradation and (2) there is a shallow zone in the vicinity of New Brighton Beach with naturally high chlorides and groundwater levels above sea level.

***LSCE (1984a)*** – LSCE cited natural and/or unknown sources for high chlorides sampled from monitoring well cluster SC-5 near New Brighton Beach, perhaps related to the marine origin of the Purisima Formation.

LSCE also said that shallow, poor quality water might have been leaking into the deteriorating casings of the Opal and Hillcrest wells. Data collected from monitoring-well clusters SC-8 and SC-9 also indicated poor quality water in shallow zones above sea level. A one-time poor quality sample from SC-8E was described as an anomaly attributable to problems with sampling technique, sample preservation, and/or laboratory analysis.

Regarding the poor water quality detected in shallow zones at SC-8F and SC-9E, LSCE stated: "It is possible that these shallow wells, located on the beach and in their respective outcrop areas, are 'recharged' with poor quality water at the coastline while the majority of the formation is recharged with freshwater farther inland." As described, this is similar to the second of the intrusion mechanisms described by Muir (1980). LSCE continued, "In this case, the poor quality is only a localized concern; and the high water levels ensure no landward subsurface intrusion" (pp. 32-33).

Reporting on two SCWD wells constructed in 1983, LSCE described the detection of saline water below –390 ft msl in the Sells well test boring and no saline water in the Bonita well boring. Reviewing the electric logs of previously constructed wells in the Aromas area, LSCE noted that saline water also was encountered in 1979 when the Altivo well was drilled and in 1970 when the Seascape well was drilled (from –390 to –495 ft msl). LSCE drew a profile of the freshwater-saltwater interface based on this information. LSCE reasoned that the 1970 existence and location of the saltwater wedge was naturally occurring because saline water was encountered in the Seascape boring prior to significant, local groundwater development.

***LSCE (1985a)*** – LSCE contoured the top elevation of the saltwater wedge between Seascape and La Selva Beach. Near La Selva Beach it was at about –200 ft msl at the coast and –800 ft msl at Highway 1. Near Seascape it was –500 ft msl, and deepened further to the northwest.

In the Purisima area, LSCE noted the effect that pumping the Hillcrest well had on shallow coastal water levels monitored by SC-9D. However, there were no signs of water quality problems as a result.

***LSCE (1987b)*** – LSCE observed no change in the saltwater interface near Seascape during 1970-1986 although SCWD Aromas production had increased from 600 to 1,900 ac-ft/yr during that time. Reporting on the construction of four Aromas monitoring-well clusters, LSCE noted the detection of the saltwater interface at depth beneath each location except SC-A1. LSCE stated that upconing was not expected because the production well screens were sufficiently high above the interface considering the aquifer's high transmissivity. Furthermore, SCWD pumping had had no effect on groundwater levels at the coastline, and pumping had not caused any gradient reversal. LSCE recontoured the top of the saltwater wedge, which showed an inland inflection at La Selva Beach.

***Mann (1988)*** – Dr. John Mann (1988) was invited by PVWMA to review and comment on an assessment of saltwater intrusion in Pajaro Valley (LSCE, 1987a). He stated that intrusion probably began along the Pajaro Valley coast as early as 1947. Although generally concurring with the reviewed study, he noted, "What is not recognized generally is that the critical freshwater level must be maintained some distance above sea level to avoid any inland movement of seawater. This is in accordance with the Ghyben-Herzberg principal" (pp. 3-4). He estimated that levels should be maintained at or above +5 ft msl in the 200-ft deep alluvial aquifer and +15 ft msl in the 600-ft deep Aromas aquifer. Otherwise, "it must be presumed that seawater is wedging in toward the shoreline from the subsea outcrop" (p.4), although this may occur more slowly in the Aromas aquifer than the alluvial aquifer because of lower permeability, greater distance to the subsea outcrop, and some degree of confinement at depth.

***LSCE (1988b)*** – For PVWMA, LSCE contoured the top elevation of the freshwater-saltwater interface along the entire coast from Seascape to Springfield Terrace south of the Pajaro River.

***LSCE (1989)*** – LSCE noted that the relatively new and deep Rosedale and Estates wells were causing groundwater levels to decline below sea level at the coast for "lengthy periods to continuously." LSCE recommended that pumping be redistributed to new shallow wells and suggested that more groundwater could be developed from the Aromas area for use in the Purisima area.

***LSCE (1990)*** – LSCE stated that "pumping from the District's Aromas production wells had only a minimal effect on the groundwater basin" (p. 10).

***Essaid (1992)*** – Essaid described potential saltwater intrusion mechanisms for the Purisima aquifer similar to those of Muir (1980): saltwater may enter the freshwater aquifer by either (1) vertical leakage through the seafloor or (2) landward migration of the saltwater-freshwater interface. For simulated 1985 conditions, she concluded that leakage was not occurring and freshwater flowed offshore through all Purisima units. This simulation did not reflect pumpage from SCWD's Estates, Ledyard, T. Hopkins, or Main Street wells, or any private wells, but did include the Hillcrest and Seacliff wells.

In simulating the movement of the saltwater interface, she used initial locations for each Purisima unit estimated through steady-state simulation. However, she believed the interface to be much farther offshore as a result of non-equilibrium conditions following the end of the Pleistocene's low stand in sea level. Her conceptual model suggested lateral movement of the interface back and forth over geologic time between the coast and aquifer exposures along the walls of the Monterey submarine canyon.

For 1930 conditions, the toes of simulated interfaces for aquifers AA/A and BC just touched Pleasure Point. Then, for the 1985 simulation, these interface toes intersected the point. Simulating twice the 1985 pumpage (including the now destroyed Hillcrest and Seacliff wells) caused saltwater leakage into unit E. It appears that such leakage did occur during the late 1980s (see Section 6.4.1).

The increase from 1985 pumping rates to rates twice as high caused simulated coastal water levels to decline from 0 ft msl to –50 ft msl. This resulted in the cessation of groundwater outflow to the ocean in aquifers A and E. Groundwater levels now fall within this range (Figure 4-35).

She concluded that, "The most immediate potential cause for seawater intrusion is pumping in the shallow Purisima subunits near the coast that could induce downward leakage of seawater through ocean floor outcrops" (p. 29). This conclusion is significant given that all Purisima units are shallow somewhere along the coast between Live Oak and Aptos. She also noted that her model did not account for high-permeability pathways that occur at scales smaller than the layers she modeled. These pathways might respond more quickly to conditions conducive to saltwater intrusion.

***LSCE (1994)*** – LSCE stated an unmet goal of maintaining Purisima coastal groundwater levels above sea level, although actual target levels were unspecified. In the case of the Aromas area, coastal groundwater levels remained above sea level, but small declines had coincided with increases in chloride and total dissolved solids. Increased chloride in SC-A2B and SC-A3B indicated possible landward movement of the interface, which LSCE stated had not otherwise moved prior to 1993. LSCE attributed falling water levels in SC-A4 and SC-A5 to declining groundwater levels in Pajaro Valley. The groundwater gradient had shifted away from the coast and toward Pajaro Valley during 1991-1994. Based on these observations, LSCE withdrew its recommendation that additional groundwater could be developed in the Aromas area to help alleviate saltwater intrusion concerns in the Purisima area.

LSCE predicted water level responses to pumping using a multiple-regression model it had been developing since 1988. This model directed the redistribution of pumping needed to achieve water-level objectives and forecast the need for supplemental water to help meet future water demands through conjunctive use with groundwater.

***LSCE (1995b)*** – LSCE stated that a significant change in SC-A3 chloride concentrations–and a slight change at SC-A2–provided an "early warning" of saltwater intrusion in the Aromas area, consistent with the intended purpose of the monitoring system. They explained that once the saline water affected the B-monitoring wells it would be difficult to track further progression of the interface because the next shallower wells had screens much higher up and/or had multiple screens.

LSCE noted that chloride-bicarbonate ratios for the production wells were in the range of 0.12 to 0.3, which is typical of groundwater unaffected by saline intrusion. The Sells well had the highest potential for upconing because the interface was closest to its screens and had apparently moved further inland. LSCE acknowledged the possibility of "progressive degradation of coastal water quality as has occurred at PVWMA's coastal monitoring well PV-1 despite essentially constant water levels" at +2 to +4 ft msl (p. 7). PV-1 chloride concentrations had begun rising in 1988 and had reached 9,000 mg/L. LSCE concluded that the interface would not move any further inland as long as water levels did not decline further. Furthermore, "Conditions do not warrant [a] major change in operations at the current time, particularly since production water quality has not changed" (p. 7). LSCE again said to hold off on plans to develop more Aromas water for use in the Purisima area, and recommended moving some of the Altivo and Sells pumping to a more inland location.

***LSCE (1996)*** – LSCE expressed concern over low groundwater levels along the coast in the Purisima area between SC-5 and SC-8. The A-zone levels were at historic lows and continually below sea level. LSCE stated the need for supplemental water in both the Aromas and Purisima areas, but also resurrected the idea that more water could be developed from selected portions of the Aromas area for use in the Purisima area.

***LSCE (1999)*** –LSCE stated, "As measured at the water supply wells, there has been no evidence of seawater intrusion or other water quality degradation in the District's groundwater supply" (p. 4). This statement coincided with a stabilization and/or reversal of negative trends during a series of wet years following the 1987-1994 drought.

***PVWMA (2001)*** – In its *State of the Basin* report, PVWMA described conditions in the La Selva Beach area as follows: "The shallow wells at both [SC-A3 and SC-A4] show relatively low and stable chloride conditions. The medium wells…had stable conditions until late 1993, when chloride in SC-A3 started to increase rapidly, indicating that either seawater was migrating inland in this depth zone or water was moving upward from the lower zone of the Aromas Sands, where chloride concentrations are similar to those of seawater. The deep wells…show very high chloride levels, with SC-A3 at the concentration of seawater and SC-A4 increasing steadily since it was drilled [in 1986]" (p. 5-8).

***LSCE (2003)*** – LSCE observed that concentrations were steady or lower as a result of changes in pumping (e.g., reduced production from the Sells and Altivo wells due to elevated chromium).

***LSCE (2004)*** – LSCE recommended a reduction in Aromas pumping by adoption of a previous "practical developable yield" estimate of 1,800 ac-ft/yr for the SCWD wellfield (SCWD, 1998). Citing the conclusions of Mann (1988), LSCE recommended maintaining water levels at +8 ft msl in SC-A2B and installing two new monitoring wells in the Aromas area.

## 6.3 Assessment of Intrusion Indicators

Among the saltwater intrusion indicators introduced above, chloride concentrations provide the longest data records for both production and monitoring wells. For production wells, we reviewed these data together with electrical conductivity and concentrations of total dissolved solids (TDS). In addition, we computed sodium:chloride molar ratios to evaluate early indications of intrusion for both production and monitoring wells. Lastly, we constructed trilinear plots for various groups of production and monitoring wells to assess possible mixing of freshwater and saltwater. The other methods mentioned above provided limited additional insight or were limited by data availability. In Section 6.4 we interpret the causes and pathways for saltwater intrusion in the context of the assessed indicators.

Each indicator is discussed separately for the Purisima and Aromas areas. Within areas, wells are discussed from west to east.[34]

### 6.3.1 Chloride Concentrations

The District analyzes for chloride on at least a semi-annual basis, and as often as monthly for selected wells and periods. For the chloride chemographs presented below, concentration scales vary

[34] See Figure 4-6 for the approximate location of inactive and destroyed wells. Locations of active wells are shown in both Figures 1-2 and 4-6.

from plot to plot in order to highlight any incipient trends. Because of their longer periods of record, the production wells are presented first.

***Purisima Production Wells*** – Figure 6-8 presents plots of chloride concentration and electrical conductivity[35] for the Beltz wells. In Beltz well 2, electrical conductivities increased gradually from 500 to 1,200 µS/L between 1974 and 1995, while chloride concentrations increased abruptly after 1990 from about 75 to 180 mg/L. Beltz 7 has exhibited a slight increase in chloride from 35 to >50 mg/L since 1975.

Figures 6-9 and 6-10 present chloride and TDS plots for SCWD's Purisima wells. Chloride concentrations for the Opal wells trended upward throughout their period of use, beginning at <40 mg/L and reaching 100 mg/L in the 1980s. The Garnet well has exhibited a similar, but steeper, trend since its construction in 1995. Chloride concentration spikes of >100 mg/L have occurred in the Hillcrest, Maplethorpe, and Tannery wells.

Given their location near the coast, the records for the Beltz 2, Opal, Garnet, and Hillcrest wells may reflect the subtle influence from one or more forms of saltwater intrusion (of these, only the Garnet well remains active).

***Aromas Production Wells*** – Figures 6-11 and 6-12 provide choride and TDS plots for the Aromas production wells. Although chloride concentrations are low (<40 mg/L), each of the wells show a possible upward trend beginning about 1995, preceded in some cases by a subtle, long-term increase. As discussed below, these trends coincide with trends in Aromas monitoring wells exhibiting saltwater intrusion. Shallow and mid-depth monitoring wells also had initial chloride concentrations of <40 mg/L before increasing rapidly.

***Purisima Monitoring Wells*** – Figure 6-13 presents chloride chemographs for the five monitoring-well clusters along the Purisima area coast. The plots are positioned from west to east across the page and from shallow to deep from top to bottom. None of these records provides evidence of an encroaching saltwater interface. However, there are several indications of potential seawater leakage into near-shore cones of depression.

At SC-1, chloride concentrations in the shallow B-zone well have spiked near and over 100 mg/L. Groundwater levels in this well are consistently >9 ft msl. Purging at the time of sampling could draw water from as low as –8 ft msl at the bottom of the screened interval. The A-zone well experienced a rising chloride trend that coincided with water-level recovery in the Opal 1 production well, as discussed further in Section 6.4.

The two shallow wells at SC-3 show hints of increasing chloride concentration during the last year or two. However, groundwater levels in these wells are >20 ft msl, ruling out a seawater source. Elevated chlorides could result from leakage through strata containing marine clays, as induced by the strong downward gradients (Figure 4-16).

When monitoring began in 1983, shallow groundwater at SC-5 was found to be more mineralized than most other Purisima groundwater, having chloride concentrations as high as 700 mg/L. This and other local instances of poor quality groundwater (e.g., Muir, 1980) have been attributed to natural or other unknown causes, but not saltwater intrusion given that groundwater elevations are

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[35] Electrical conductivity provides an indication of total mineral content, expressed in micro-siemens per centimeter (µS/L), and equals roughly 60 percent of total dissolved solids in mg/L. Although usually normalized to 25°C and referred to as specific conductance, this was not evident in the Beltz data record.

>20 ft above sea level (Thorup, 1981; LSCE, 1981, 1984a). Chloride concentrations in SC-5D rose sharply to as high as 3,000 mg/L in the early 1990s. This may have reflected poor quality water in the zone-D aquitard concentrated further as a result of the 1987-1994 drought. Since then, SC-5D has not been monitored for chloride, and concentrations in the three deeper SC-5 wells have been fairly stable at <200 mg/L.

Occurrences of high chloride in shallow groundwater were documented at SC-9 and SC-8 during the late 1980s, with peak concentrations of about 400 mg/L and >5,000 mg/L, respectively. Concentrations in SC-9E have since declined to <50 mg/L, while concentrations in SC-8F have remained above 500 mg/L. These cases (discussed further in Section 6.4.1) appear attributable to seawater leakage and/or shallow interface advancement induced by now-destroyed near-shore production wells. The persistence of high chloride in SC-8F suggests that it might encounter the leading toe of a shallow saltwater interface near the bottom of its well screen along the base of Purisima unit F.

Among all of the Purisima monitoring well clusters, chloride concentrations are highest in the shallow wells and lowest in the deep wells, consistent with potential seawater leakage into near-shore aquifer exposures. However, recent small increases in the chloride concentrations of SC-9A and SC-8B could indicate deeper saltwater encroachment.

***Aromas Monitoring Wells*** – Figure 6-14 presents chloride chemographs for the Aromas monitoring wells. The plots are positioned from northwest to southeast across the page, and shallow to deep from top to bottom. Whereas chloride concentrations decrease with monitoring well depth for the Purisima monitoring wells, concentrations increase with well depth at three of the four Aromas clusters, indicative of the landward movement of the freshwater-saltwater interface.

At coastal monitoring well cluster SC-A1, concentraions are less than 40 mg/L among all depth zones and exhibit little trend (if anything, slightly downward). Based on these data, contours depicting the top of the interface have been drawn angling offshore to the northwest (LSCE, 1987b), consistent with the absence of an on-shore interface in the Purisima area.

At the other three Aromas monitoring clusters, the screens for the deepest two wells (i.e., those labeled A and B[36]) were originally placed just below and above the saltwater boundary. As such, the initial 1987 chloride concentraions of the deepest wells ranged from 3,000 to 15,000 mg/L while the shallower wells had typical initial concentrations of less than 50 mg/L.

In hindsight, we can now see that chloride concentrations in the deepest "A" wells were already following upward trends when the wells were installed in 1986. In other words, progressive saltwater intrusion in the form of an advancing freshwater-saltwater interface was already underway. The following sample results summarize these trends (rounded to nearest 100 mg/L):

| Well | Mid-Screen Elev. (ft msl) | 1987 | 1989 max | 1990 max | 1995 max | 2000 max | 2002 |
|---|---|---|---|---|---|---|---|
| SC-A2A | –343 | 7,200 | 8,300 | 8,500 | 9,300 | 12,000 | 13,000 |
| SC-A5A | –485 | 4,500 | 5,400 | 4,900 | 5,000 | 5,700 | 5,300 |
| SC-A3A | –197 | 15,000 | 16,600 | 18,400 | 18,000 | 18,900 | 20,400 |
| SC-A4A | –344 | 3,100 | 3,800 | 4,900 | 6,500 | 8,000 | 8,400 |

[36] Recall that the A, B, C, etc. labeling of the Aromas monitoring wells does not correlate to particular aquifer zones (Figure 2-4).

On the coast at La Selva Beach, chloride concentrations in SC-A3A reached that of seawater by 1990 and have stabilized at that level. The rate of increase in SC-A5A has been moderate, probably due to its inland location and upconing as a potential cause (see Section 6.4.3). Concentrations in coastal wells SC-A2A and SC-A4A have been following a fairly steady upward trend toward that of seawater, increasing by more than 5,000 mg/L since 1987.

Above the interface, three of the four "B" wells have experienced upward trends, as summarized below (mg/L):

| Well | Mid-Screen Elev. (ft msl) | 1987 | 1990 max | 1995 max | 2000 max | 2002 |
|---|---|---|---|---|---|---|
| SC-A2B | –303 | 29 | 48 | 94 | 185 | 280 |
| SC-A5B | –415 | 10 | 15 | 22 | 25 | 39 |
| SC-A3B | –147 | 8 | 11 | 1,540 | 2,700 | 2,300 |
| SC-A4B | –304 | 17 | 17 | 18 | 13 | 18 |

The smooth upward trend for SC-A2B suggests steady on-shore movement of the interface, whereas the sudden concentration increase and volatility of SC-A3B suggests upconing or passage into a poorly mixed transition zone. The upward trend of SC-A5B is clear despite concentrations that are still <50 mg/L. SC-A4B remains above the interface.

Among the "C" wells, only SC-A2C has experienced a consistent increase in chloride, although several spikes have occurred in SC-A3C. Representative values are as follows (mg/L; *spikes):

| Well | Mid-Screen Elev. (ft msl) | 1987 | 1992-93 | 1995 | 1997-99 | 2000-01[37] | 2002-03 |
|---|---|---|---|---|---|---|---|
| SC-A2C | –23 | 62 | 54 (4/93) | 156 (3/95) | 281 (3/97) | 401* (8/00) | 190 |
| SC-A3C | –32 | 83 | 45 (10/92) | 47 (9/95) | 108* (2/99) | 1,020* (10/01) | 44 |

Similar to SC-A3B, concentrations in SC-A2C experienced a sudden increase followed by a partial and somewhat erratic decline. This may reflect passage into a transition zone that later became diluted by increased groundwater flow. The shallow depth of these well screens just below sea level indicates that the trailing upper tip of an interface has arrived nearly onshore. The fact that concentrations exceeding 250 mg/L occurred in SC-A2C before occurring in deeper SC-A2B suggests that a separate, shallow interface exists in the upper Aromas. Alternatively, the near-sea-level elevation of SC-A2C may indicate seawater leakage into a cone of depression extending to the coast. Although SC-A2C water levels are 3 to 4 ft above sea level, corrections for seawater density and tidal fluctuations may negate this small positive elevation. Instances of elevated chloride and their relation to water levels and nearby pumping are discussed further in Section 6.4.2.

### 6.3.2 Sodium:Chloride Ratios

SCWD typically analyzes for major ions annually, although sampling frequency ranges from semi- to bi-annually. SCWD monitoring wells were not sampled for general minerals until 1995 or later, thus missing some high chloride events that occurred in the late 1980s, and the early encroachment of the Aromas saltwater interface. Nevertheless, the sodium:chloride ratio (Na:Cl) indicator appears to provide subtle clues of potential intrusion that might otherwise be missed from inspecting chloride data alone. The ion data, along with computed Na:Cl molar ratios, are summarized in Tables 4-5 through 4-7. Ratios cannot be calculated for the Beltz wells due to insufficient sodium data.

[37] These one-time spikes may represent measurement errors, e.g., cross contamination from more intruded zones.

***Purisima Production Wells –*** Among the Purisima production wells, only the Opal wells exhibited a clear downward trend in Na:Cl ratios, reaching a low of about 0.4 by 1982 (Figure 6-15). Na:Cl ratios remain between 0.6 and 0.8 for the Garnet well. This information is consistent with the chloride record (Figure 6-9a).

Minimum values of Na:Cl ratios for the Hillcrest and Seacliff wells range between 0.4 and 1.0, consistent with their relative close proximity to the coast and apparent past instances of seawater capture.

***Aromas Production Wells*** – Na:Cl ratios for the Aromas production wells are generally >1.0 and do not exhibit obvious trends (Figure 6-16).

***Purisima Monitoring Wells –*** Na:Cl ratios for SC-3C have trended downward to <0.8 (Figure 6-17), consistent with recent small increases in chloride concentration (Figure 6-13a). Because groundwater levels in this well are >50 ft msl, these results indicate that Na:Cl ratios can be affected by processes other than saltwater intrusion (e.g., leakage through marine clays).

Na:Cl ratios in the shallowest wells of clusters SC-9 and SC-8 have generally held steady between 0.3 and 1.0, consistent with the residual effect of apparent episodes of seawater leakage and/or interface advancement in the 1980s. Given that chloride concentrations in SC-9E returned to <50 mg/L by 1991, the ion exchange affecting Na:Cl ratios is slow to reverse itself, at least in the case of some monitoring wells (the greater circulation of groundwater associated with pumping wells appears to allow a more rapid reversal of ratio values, e.g., the records of Opal 1 and Hillcrest [now both destroyed], Figure 6-15). As such, the relatively low ratio values for SC-5C could suggest past seawater leakage.

The Na:Cl ratios of deeper wells SC-9A and SC-8B fell sharply during 1999-2000, coinciding with small increases in chloride (Figure 6-13b). Ratios for the other wells in these clusters have generally trended slightly downward.

***Aromas Monitoring Wells –*** Na:Cl ratios for the intruded, deepest wells of the Aromas monitoring clusters have held steady at values ≤1 since sampling for major ions began in the 1990s. Well SC-A3A, which has a chloride concentration equal to that of seawater, has a Na:Cl ratio about equal to seawater (0.85), whereas the ratios for partially intruded zones tend to be lower than seawater (e.g., SC-A2A and SC-A3B). Ratio values for the slightly impacted SC-A2B have decreased through time until converging with the stable values of SC-A2A. This provides some confidence in the "early warning" significance of declining Na:Cl ratios. Ratio trends suggest that chloride concentrations will rise in SC-A5B and SC-A4B. Low ratio values for shallow well SC-A5D suggest that this zone may have been impacted by saltwater at some time in the past despite chloride concentrations currently <50 mg/L.

### 6.3.3 Trilinear Plots

Trilinear plots for the production and monitoring wells are provided in Figure 6-18 and discussed below.

***Beltz Wells –*** The Beltz 2 well shows a definite trend indicative of saltwater intrusion (Figure 6-18a). This corroborates the interpretation of possible saltwater intrusion suggested by increasing chlorides during the time this well operated (Figure 6-8).

***SCWD Production Wells –*** SCWD production wells generally do not show a trend on trilinear diagrams indicative of saltwater intrusion. Water samples obtained from production wells completed in the Purisima Formation (Figures 6-18b and 6-18c) show considerably more variability in water type than do samples collected from production wells completed in the Aromas area (Figure 6-18d), however it is difficult to associate the Purisima variability with saltwater intrusion.

***Purisima Monitoring Wells –*** Water samples collected from monitoring wells completed in the AA, A, and B units of the Purisima formation show no definitive trends indicating saltwater intrusion (Figures 6-18e through 6-18f). Although samples from SC-1A appear to be trending toward seawater in the middle diamond of the trilinear plot, its chloride concentrations are not tracking toward seawater in the lower-right triangle.

A possible, although weak, trend is apparent in monitoring well SC-5C (Figure 6-18g). The data are not sufficient to definitively associate this trend with saltwater intrusion; furthermore, water levels are >30 ft msl such that any possible intrusion would have had to occur and end prior to the start of water-level monitoring in 1983.

The high chloride concentrations in well SC-8F (Figure 6-18h) cause this well's data to plot very close to seawater on the trilinear diagram. Major ion data are unavailable for the high chloride episode observed in SC-9E, however the resulting low sodium concentrations place the recent data in a distinctive position on the trilinear plot.

***Aromas Monitoring Wells –*** Trilinear diagrams of water quality data from the Aromas monitoring wells further support the interpretation of an advancing saltwater interface. Except for well SC-A1A, trilinear plots for the "A" wells show a trend definitive of saltwater intrusion (Figure 6-18i).

The trilinear plots show progressively less saltwater in each cluster's shallower wells. Among the "B" wells, the trilinear plot indicates intrusion most for well SC-A3B, and moderately so for wells SC-A2B and SC-A5B (Figure 6-18j). SC-A2C is the only "C" well to show pronounced saltwater intrusion (Figure 6-18k), and the data are inconclusive for the "D" wells (Figure 6-18l).

## 6.4 Assessment of Intrusion Mechanisms and Pathways

The above discussion suggests the following potential mechanisms and pathways for saltwater degradation of the Soquel-Aptos aquifers:

1. Direct leakage into near-shore shallow aquifers where drawdown cones reach the shoreline as a result of shallow, near-shore pumping (e.g., Hillcrest well).

2. Saltwater leakage through confining units, fractures, or offshore outcrops where sub-sea level pumping troughs extend relatively far offshore, beyond the protection of shallow zones with positive freshwater heads (e.g., Beltz and Opal wells; SC-9A and SC-8B).

3. Landward migration of the saltwater interface within one or more individual aquifer units extending offshore (e.g., the southern Aromas coast; possible signs in SC-8F).

4. Upconing of the saltwater interface below a pumping well (as possibly seen in SC-A5A adjacent to the Seascape well).

5. Pumping-induced leakage of saline water from sources not associated with seawater intrusion (e.g., SC-5C).

Specific instances of these are described below in the context of relevant water-level and pumping records and the local hydrogeology. As before, we begin with the Beltz wells on the west and end with the Aromas-area wells to the southeast.

### 6.4.1 Purisima Area

***Beltz 2 Well*** – Among the Beltz wells, several lines of evidence suggest that Beltz 2 experienced minor saltwater degradation prior to ending operation in 1999. This well was completed in the Purisima-A aquifer from about 50 to 100 ft below sea level and was located about 2,000 ft from where the aquifer outcrops offshore (Figure 2-10). Figure 6-19 compares the chloride, water-level, and pumping records for this well. Sub-sea level static and pumping groundwater levels (–6 and –60 ft msl, respectively) coincided with a period of peak Beltz production during 1987-92. The static and pumping levels of Beltz 4, 6, and 7 also were below sea level (Figure 4-10a), and levels in the coastal Pleasure Point monitoring well were +1 to –10 ft msl. In an apparent response to these low levels, Beltz 2 chloride concentrations more than doubled to 180 mg/L between 1990 and 1995, and the electrical conductivity increased to 1,200 μS/cm. Beltz 2 chloride concentrations did not become excessive, however its trilinear plot indicates an ionic balance influenced by saltwater (Figure 6-18a). Since the last drought, the overall use of the Beltz wells has decreased and chloride concentrations in the currently operating wells have been <70 mg/L.

The history of Beltz 2 suggests a potential pathway for seawater leakage into the Purisima-A aquifer in response to pumping depressions extending offshore. The nearest SCWD production well, Garnet, is more than 5,000 ft from the offshore outcrop of aquifer A (Figure 2-10), and could contribute several feet of drawdown at the outcrop assuming a confined response (Figure 4-5). Saltwater entering the aquifer as a result of Beltz pumping could eventually migrate down dip toward SCWD's production wells. Production from the Beltz wells probably would be impacted first, in which case curtailing Beltz production would probably prevent further saltwater movement through the Purisima-A aquifer. The recent installation of additional monitoring wells by the City of Santa Cruz allows for improved management of coastal groundwater levels and early detection of saltwater encroachment into the Purisima-A aquifer off Pleasure Point.

***Opal and Garnet Wells and SC-1 Cluster*** – Figure 6-20 compares water levels, chlorides, and pumping for the Opal and Garnet production wells and SC-1 monitoring wells. The chloride concentration of the Opal wells trended slowly upward for more than 40 years, reaching 100 mg/L in the early 1980s. Pumping was then reduced in the late 1980s and early 1990s. Interestingly, as water levels recovered, chloride concentrations 900 ft toward the coast in SC-1A increased slightly, following a trend similar to the water-level rise. This suggests a relatively small inflow or leakage of saltwater that is usually masked by the larger flow of fresh groundwater towards the pumping well. Although chloride concentrations have not become problematic, evidence of a saltwater pathway, rising chloride concentrations in the Garnet well, and SC-1A water levels near sea level indicate a vulnerability to saltwater leakage under current conditions and rates of production.

***SC-3 and SC-5 Well Clusters*** – Poor quality water in shallow zones monitored at SC-5, and hints of saltwater degradation at SC-3, do not represent active intrusion considering that their water levels range from 20 to 60 ft msl. Possible explanations include the following:

- Heavy nearby pumping lowered groundwater levels sufficient to induce saltwater intrusion prior to the start of monitoring in 1983. The residual saltwater degradation mixed with rising groundwater after nearby wells ceased pumping. Muir (1980) documented several private wells in the area near SC-5.
- The pumping-induced downward gradients seen at SC-3 and SC-5 have caused poor quality water to leak from marine clays, an infilled estuary, or some other source. Such connate water is typical of deeply buried marine deposits, not shallow zones flushed with recharge. However, a relatively small flux of poor quality water can significantly influence a monitoring well, considering the relatively low pumping rates used for sampling. Perhaps significantly, SC-3C

directly overlies the Purisima-B aquitard and SC-5D is screened within Purisima-D aquitard (Figure 2-11).

***Hillcrest Well and SC-9 Cluster*** – Figure 6-21 provides water-level, pumping, and chloride records related to the occurrence of elevated chlorides in SC-9E and the Hillcrest well. Chloride concentrations in the relatively shallow Hillcrest well began rising in the mid-1970s, peaking at over 100 mg/L. Static levels were mostly below sea level when it was pumped regularly during 1975-77 and 1984-86. During the latter period, groundwater levels 900 ft away in coastal monitoring wells SC-9D and SC-9E closely followed the Hillcrest hydrograph, reaching minimum elevations of –24 and –4 ft msl, respectively. Having been mostly >100 mg/L since 1983, chloride concentrations in SC-9E peaked at >400 mg/L in late 1987, while concentrations in the Hillcrest well reached 135 mg/L. With the startup of the Estates well, production from the Hillcrest well ended in 1987 and chloride concentrations in SC-9E steadily declined to <50 mg/L, where they remain. Chlorides in the deeper SC-9 wells followed a similar pattern, but with lower concentrations.

The water-level and chloride response to Hillcrest pumping appears to be a case of seawater capture by a drawdown cone in a shallow aquifer extending offshore (e.g., Figure 6-6). Muir (1980) claimed that this type of intrusion was occurring between Capitola and Aptos and Essaid (1992) warned that this type of intrusion had the most immediate potential. Fortunately, the water-quality impacts in this case were essentially reversible. Although SC-9E maintains a Na:Cl ratio similar to seawater (Figure 6-17), the high chlorides were flushed out by groundwater outflow. With the retirement of the Hillcrest and Seacliff wells, relatively shallow wells capable of causing this type of intrusion are no longer operated by SCWD.

***Seacliff 4 Well and SC-8 Cluster*** – Operation of the relatively shallow Seacliff 4 well through 1987 appears to be associated with minor saltwater intrusion in Purisima unit F. Figure 6-22 provides relevant water-level, pumping, and chloride records. The static levels of Seacliff 4 were –30 ft msl or lower during 1983-84. During this same time, chloride concentrations in coastal monitoring well SC-8F (1,700 ft away) rose to >4,500 mg/L. Coinciding, but lower, chloride peaks occurred in the deeper SC-8 wells (Figure 6-13b). Drawdown from the Aptos Creek well may have contributed to this response. Chloride concentrations in SC-8F remain >500 mg/L, and spike higher at times, but have not sustained concentrations >2,000 mg/L since operation of Seacliff 4 ended in 1985. Chloride concentrations in water produced from Seacliff 4 never exceeded 65 mg/L (Figure 6-9b).

While levels in the deeper SC-8 wells frequently dip below sea level, groundwater levels in SC-8F were generally >2 ft msl during operation of Seacliff 4. Because the screened interval of SC-8F extends to –189 ft msl, it may encounter the leading toe of a saltwater wedge at the base of unit F, consistent with the Ghyben-Herzberg relation (i.e., 189 ft ≈ 40 × 4.7 ft). In this case, operation of Seacliff 4, and perhaps other area wells, appears to have caused the landward advancement of a shallow freshwater-saltwater interface. Alternatively, seawater may have leaked into the coastal pumping trough, perhaps as a result of the extreme high tide and surf event that occurred during March 1983.

***SC-8B and SC-9A*** – Recent small increases in SC-8B and SC-9A chloride concentrations, along with sharp declines in their Na:Cl ratios, suggest possible saltwater leakage or interface migration into deep units of the Purisima Formation. As can be seen in Figure 6-23, this occurred when water levels recovered in response to reduced pumping such that A-zone water levels were low relative to overlying zones.

### 6.4.2 Aromas Formation

***Country Club Well and SC-A1 Cluster*** – Figure 6-24 shows the chloride, water-level, and pumping records for the Country Club well and SC-A1 monitoring well cluster. In the coastal monitoring wells, recent water levels generally have been 4 to 9 ft msl and chloride concentrations are <40 mg/L and steady. Chloride concentrations have experienced a gradual, slight increase in the Country Club well, with static water levels fluctuating between 0 and 4 ft msl in recent years. Although a saltwater interface is not evident at SC-A1, there is a 7,600-ft gap between it and SC-A2 to the southeast where an interface is encountered. Because the Country Club well lies between these monitoring wells, SC-A1 does not ensure the earliest possible warning of potential intrusion if the interface continues to move onshore from south to north.

***SC-A2 Well Cluster*** – Consistent with the Ghyben-Herzberg relation and the landward movement of the freshwater-saltwater interface, Figure 6-25 illustrates the correlation between falling water levels and rising chlorides at monitoring-well cluster SC-A2. Chloride concentrations have risen fairly steadily in the two lower monitoring wells, despite a post-1990 decrease in nearby groundwater production. According to the Ghyben-Herzberg relation, a water level of ≥9 ft msl would be needed to maintain the interface below the bottom-most screens at –353 ft msl. Such water levels have not occurred in SC-A2B since the early 1990s, and have never been observed in SC-A2A or SC-A2C. Elevated chloride concentrations in SC-A2C, the cluster's shallowest well, are consistent with its annual minimum heads of <1 ft msl. Interestingly, chloride concentrations in SC-A2C peaked at nearly 300 mg/L in 1997, a level only recently approached in the deeper SC-A3B well. This suggests that a separate, shallow interface may exist in the upper Aromas Sands. Additionally, upconing may be associated with three nearby private wells mentioned by LSCE (2004).

***Seascape Well and SC-A5 Cluster*** – Figure 6-26 presents chloride chemographs, groundwater level hydrographs, and quarterly pumping for the Seascape well and adjacent SC-A5 monitoring-well cluster. The deepest monitoring well, SC-A5A is encountering saltwater intrusion with levels rising to >5,000 mg/L. Although SC-A5B concentrations remain low, they also have been rising and may explain the recent volatility of chloride concentrations in the Seascape well, which is screened only 32 ft higher. Section 6.4.3 provides an analysis of upconing that may explain the rising chlorides at SC-5.

***SC-A3 and SC-A4 Well Clusters*** – Figure 6-27 presents chloride concentrations, hydrographs, and pumping records for the Sells and Altivo wells and SC-3 and SC-4 monitoring-well clusters. Chloride concentrations in SC-A3A are already that of seawater. Concentrations in SC-A3B rose suddenly in the mid-1990s as water levels gradually declined from about +3 ft msl to 0 ft msl. The steady increase in chloride in SC-A4A more than a mile southeast of SCWD's production wells suggests landward movement of the saltwater interface in response to other Pajaro Valley pumping. However, both water levels and chlorides in SC-A3 and SC-A4 appear to have responded to the recent decline in Sells and Altivo pumping.

***Altivo and Sells Wells*** – Chloride concentrations in the Altivo and Sells wells, although still <35 mg/L, appear to have increased slightly and become more volatile in recent years (Figure 6-28).

***PV-1 and PV-8 Monitoring Well Clusters*** – Figures 6-29 and 6-30 show the water-level and chloride records for coastal monitoring-well cluster PV-1 and cluster PV-8 located 1 mile inland; both clusters are a little more than 2 miles southeast of SC-A4. Similar to SC-2A and SC-4A, chloride levels in the two deepest PV-1 wells steadily increased from the late 1980s through the 1990s, reaching concentrations from 8,000 to 14,000 mg/L. The rising chloride concentrations were in response to a decline in PV-1 deep-zone water levels from about +4 ft msl in the late 1980s to as low as –1 ft msl by the mid-1990s.

While the saltwater interface was moving onshore at PV-1, chloride concentrations one mile inland were already >8,000 mg/L in the deep PV-8 well (screened below –570 ft msl). This suggests that a deep interface already extended far inland prior to 1980, after which the upper portion of the interface migrated landward, perhaps in a relatively separate overlying zone.

### 6.4.3 Estimation of Saltwater Interface and Upconing

We used the methods presented in Figures 6-3 through 6-5 to estimate the saltwater interface and potential for upconing along several profiles of the Aromas area coast. In doing so, we treated the combined Aromas and Purisima-F aquifers as a single, homogeneous, and isotropic aquifer. This disregards the formations' layering and relatively low vertical hydraulic conductivity (which are characteristic of most sedimentary deposits). Our selection of moderate pumping rates and relatively large aquifer thicknesses, combined with the Glover solution's tendency to overestimate the freshwater hydraulic gradient, helped to offset the assumed absence of anisotropy.

Key aspects of our assumptions include the following:

- For an assumed freshwater hydraulic gradient we used the average gradient between each coastal monitoring well and the shoreline, and extended this gradient inland. However, the water table typically becomes flatter inland of the coastal monitoring wells.
- The Glover solution calculates freshwater heads based on the estimated flow of groundwater to the ocean. Darcy's law is typically used to estimate this flow (Figure 6-4), but tends to grossly overestimate it. This is because the aquifer thickness transmitting the freshwater flow is non-uniform; the flow is three-dimensional; and anisotropy is not accounted for. We omitted the flow term by reducing the Glover equations as shown in Figure 6-4. In this case, the method's oversimplification becomes apparent because the input gradient does not match the calculated gradient.
- In each case, we assumed an aquifer thickness between 400 and 600 ft. This choice was somewhat arbitrary given the undefined bottom of the local Purisima aquifer and the changing thickness of freshwater flow as the interface is approached. Within these limits, and the constraints imposed by other variables, we selected a thickness that helped match the interface location with known instances of elevated chloride.
- The width of the offshore seepage face through which groundwater discharges to the ocean is significantly underestimated because of the assumed lack of aquifer anisotropy. As groundwater flows upward to this interface under actual conditions, a relatively large seepage face is required to compensate for low vertical hydraulic conductivity.
- In addition to the Glover interface solution, we compute and plot the Ghyben-Herzberg interface based on the observed gradient between the shoreline and coastal monitoring wells.
- To estimate the potential for upconing, we used each well's long-term average pumping rate applied to a 90-day pumping period (except for the Country Club and Bonita wells, as noted in Figure 6-32). The use of peak quarterly pumping rates caused unrealistic upconing or required the unrealistic adjustment of other variables. This is because the method does not account for anisotropy.
- For the upconing estimates, we used transmissivities and storage coefficients consistent with the analyses presented in Section 3.

***Seascape Well and SC-A3 and SC-A5 Clusters*** – Figure 6-31 shows the estimated freshwater-saltwater interface, with and without upconing, along a profile through the Seascape well and monitoring well clusters SC-A2 and SC-A5. These results are consistent with saltwater intrusion in SC-A2A and SC-A5A, elevated chlorides in SC-A2B and SC-A2C, and low but increasing chlorides in SC-A5B and possibly the Seascape well. Without upconing, it appears that the interface would not affect SC-A5A. However, including the effect of upconing beneath the Seascape well brings the interface up to the elevation of the lower SC-A5 wells. The detection of saltwater in the original Seascape test bore was near the extrapolated Ghyben-Herzberg interface but above the non-pumping interface estimated by the Glover solution.

LSCE (2004) mentioned the existence of three private wells near SC-A2. Representing these wells with a single well pumping 100 gpm 500 ft from SC-A2 creates upconing that raises the interface into the screened interval of SC-A2A.

Neither the Glover nor Ghyben-Herzberg interface estimates account for elevated chlorides in the shallow SC-A2C well. There may be a shallower saltwater interface migrating into the upper Aromas Sands. Alternatively, upconing by one of the nearby private wells may be more significant than shown.

Rising chloride concentrations in SC-A2 and SC-A5 during the past 15 years indicate that a saltwater interface has moved into its current position approximately as shown in Figure 6-31. As the interface continues to move inland, the Seacliff well will be at increased risk from upconing.

***Altivo and Sells Wells and SC-A3 Cluster*** – Figure 6-32 presents a similar interface estimate through SC-A3 and the Sells and Altivo wells. The Glover interface estimate passes through SC-A3A, accounting for its seawater-concentration of chloride. SC-A3B also has significantly elevated chlorides. Lying between the Glover and Ghyben-Herzberg estimated interfaces, the screened interval of SC-A3B may be within the transition zone of the freshwater-saltwater interface. A relatively broad transition zone may be attributable to the proximity of the two production wells and tidal affects. Estimates of upconing indicate potential risks to the Sells and Altivo wells, and may account for their slightly rising and volatile chloride concentrations. Reduced production from these two wells since 2002, because of water quality issues unrelated to intrusion, has lessened this risk.

***SC-A4 Cluster*** – Figure 6-33 is an estimated profile of the saltwater interface through monitoring-well cluster SC-A4 south of La Selva Beach. The estimated interface is consistent with a sharp boundary between significantly elevated chloride in SC-A4A and unimpacted freshwater in SC-A4B.

***PV-1 and PV-8 Monitoring Well Clusters*** – Figure 6-34 presents a rough approximation of the saltwater interface through PV-1 and PV-8, about two miles southeast of SC-A4. Apparent similarities to the other estimated interface profiles demonstrates the probably existence of a single, continuous interface along the Pajaro Valley coast.

***Country Club and Bonita Wells and SC-A1 Cluster*** – The estimated saltwater interface profile shown in Figure 6-35 passes through SC-A1 and the Country Club and Bonita wells. The estimated interface is consistent with the fact that none of these wells has been impacted by intrusion. However, with the interface moving onshore to the southeast at SC-A2 during the past 15 years, the potential exists for it to move further onshore at SC-A1. Additionally, this analysis illustrates the potential risk of upconing for wells as far inland (>1 mile) as the Bonita well. The slight rise in the chloride concentrations of these and other Aromas production wells might be attributable to the marginal effects of upconing.

***Summary*** – Figure 6-36 presents the five estimated interface profiles at the same scale on one page. As shown, the estimated interface is relatively deep to the northwest, becomes increasingly shallow toward La Selva Beach, and then deepens slightly but extends far inland southeast along the Pajaro Valley coast. These estimates do not reflect the influence of stratification and anisotropic permeability within the Aromas and Purisima formations. Nevertheless, they provide a rough picture of the composite interface and potential for upconing that is consistent with observed chloride concentrations and indicative of the potential threat to production wells. In reality, the interface and upconing profiles are probably controlled by aquifer layering. Although it is reasonable to consider the straightforward Glover solutions, more sophisticated methods are needed to simulate the interface profile and potential for upconing with greater confidence.

## 6.5 Summary and Conclusions

***Purisima Area*** – Production and monitoring wells in Purisima aquifers A, BC, and DEF exhibit no definitive signs of active saltwater intrusion. However, earlier intrusion into shallow zones is well documented and subtle indications exist of possible saltwater leakage into deeper zones.

Water quality indicators for the Beltz 2, Opal, and Garnet wells suggest the existence of saltwater pathways into the Purisima-A aquifer where it is exposed on the seafloor or not too far below it. The seafloor outcrop of the A aquifer extends off Pleasure Point and is closest to the Beltz wells (Figure 2-10). Saltwater entering these outcrops would be detected by City of Santa Cruz monitoring wells and would impact the Beltz wells before advancing down dip toward SCWD wells more than 5,000 ft from the offshore outcrop. Downward leakage provides a shorter pathway to the Garnet and former Opal wells (e.g., <100 ft to the A aquifer offshore of SC-1). As the stratigraphy dips to the east, leakage into the lower Purisima units becomes significantly constrained by the low vertical permeability of overlying layers (e.g., aquifer A begins at –800 ft msl offshore of SC-8).

Previous instances of saltwater intrusion occurred where Purisima units E and F are exposed at the coast. One instance was the apparent capture of seawater by the drawdown cone of the Hillcrest well during its last years of operation (as documented by SC-9E). In another instance, the toe of a shallow saltwater wedge appears to have been pulled inland by the Seacliff 4 well and perhaps other nearby wells (as documented by SC-8F). With the retirement of the Seacliff wells, this shallow wedge appears to have retreated.

The positions of the freshwater-saltwater interfaces within individual Purisima aquifers are unknown, with the exception of a possible shallow saltwater wedge in unit F offshore from Aptos. Interface locations probably begin at or just beyond each aquifer's seafloor outcrop (Figure 2-10), and extend further south and offshore where each aquifer dips below confining layers. Interface locations remain offshore but have probably moved landward in response to pumping. The potential for upconing is relatively low given the layered nature of the Purisma units.

Fresh groundwater stored between the coast and the interface is being "mined" given that coastal groundwater levels now persist near or below sea level except in the shallowest units (Figure 4-34). Replenishment of this offshore storage is hindered by the pumping trough's interception of deep groundwater flow and the limited leakage that may occur through overlying zones. Although there are subtle indications of possible saltwater encroachment at depth (e.g., SC-8B and SC-9A), it is possible that poor quality water is leaching from aquitards or other sources (e.g., SC-3C and SC-5D).

Where each aquifer zone is deeply buried, seawater leakage is limited by the cumulative thickness and low vertical permeability of overlying units. Paleo-stream channels incised into the seafloor and backfilled with permeable sediments may breach confining layers and create conduits for more rapid seawater leakage into deeper layers. Assuming the Purisima units dip 4 degrees to the east, a paleochannel 70 ft deep could cut through to a buried unit to an underlying aquifer 1,000 ft further east than its seafloor outcrop, and perhaps that much closer to a pumping depression.

The saltwater interface tends to be relatively close to shore where aquifer units are shallow and unconfined. Thus, these units are susceptible to rather immediate intrusion, as documented in the case of SCWD's former Hillcrest and Seacliff wells. Where coastal groundwater levels persist indefinitely at or below sea level in deeper, confined zones, saltwater intrusion may have further to travel from the nearest seafloor outcrop but nevertheless may be moving toward pumping wells. Although shallow zones along the coast typically contain fresh groundwater above sea level, low vertical permeability may limit the downward leakage necessary to prevent deep-aquifer cones of depression from reaching seafloor outcrops.

Groundwater levels must be managed to ensure that hydraulic gradients are adequate to prevent saltwater intrusion. It appears that this will require reduced production from some existing wells. If adequate outflow is maintained during most years, the saltwater interface can be maintained at a reasonable distance from production wells, providing at least a small storage buffer for drought periods. Because groundwater production has drawn on offshore storage for many years, and the location of the interface is unknown, the current size of this storage buffer may be small.

***Aromas Area*** – Although SCWD's Aromas production wells exhibit no definitive signs of saltwater intrusion, monitoring wells indicate that the freshwater-saltwater interface is actively moving inland and poses a significant threat to future groundwater production as this trend continues. Continued onshore movement of the interface seems likely under current conditions considering that relatively steady increases in monitoring well chloride concentrations have occurred over the past 10 to 15 years despite little change in water levels. The local encroachment of the saltwater interface appears to be part of a larger phenomenon encompassing the entire Pajaro Valley coast. As such, the causes are both local and regional.

Based on standard equations for predicting the saltwater interface and upconing profiles, upconing may present the most immediate threat of saltwater degradation to near-coast wells (e.g., Seascape, Sells, and Altivo). However, the effects of aquifer layering and anisotropy (not considered in these equations) probably reduce the potential for upconing, while amplifying the potential for horizontal interface movement.

Under current conditions, onshore movement may be expected to spread northward, but may not reach coastal monitoring well SC-A1 unless groundwater production increases northwest of the Seascape well.

Ongoing intrusion along the Aromas area's southern coast provides evidence that maintaining groundwater levels at or just above sea level provides inadequate protection against saltwater intrusion. The observed conditions appear generally consistent with the concept of the Ghyben-Herzberg relation.

A continuation of current conditions will likely result in saltwater contamination of SCWD's most southeastern wells. The interface is already onshore and within the depth interval of production well screens. Hydraulic gradients between production wells and the coast are insufficient to prevent further inland movement.

Although the problem is regional, the responses of water levels and chloride concentrations to changes in pumping indicate that further intrusion can be impeded locally by reductions in SCWD production and/or increased recharge. However, the efficacy of relatively modest measures may be limited due to the regional nature of the problem.

# 7 Stream-Aquifer Interactions

The potential impact of SCWD groundwater pumping on Soquel Creek baseflow has been deliberated for nearly 20 years, generating at least 12 reports by 8 authors that included 13 general methodologies and 29 individual analyses. In spite of this substantial effort, there remain differences of opinion among experts regarding the manner and extent to which baseflow may have changed, and the likely causes of such changes.

A critical review and synthesis of these previous investigations is warranted to support SCWD's current process of selecting a supplemental water supply. None of the considered supply alternatives would likely deplete baseflow. However, each alternative would operate in conjunction with SCWD's ongoing groundwater use. A significant and reasonable potential for groundwater pumping to induce streamflow depletion could affect the determination of available groundwater yield. Available groundwater yield, in turn, determines the amount of supplemental supply needed. The interchange of water between aquifers and streams also affects the feasibility of storing groundwater in the aquifer system without excessive loss to streams. Some alternatives rely on storing groundwater during wet years for use during subsequent droughts.

Given the hydrogeologic conditions along Soquel Creek and the principle of conservation of mass, it is not unreasonable to surmise that groundwater pumping would have some effect on baseflow. However, observed changes in baseflow have been small and the timing of those changes has not correlated well with changes in pumping.

The objective of this review is to develop an interpretation of stream-aquifer interaction that is consistent with this apparent discrepancy and as much of the data presented by prior investigations as possible. This section presents an interpretation of the Soquel Creek stream-aquifer system that (1) reconciles the apparent discrepancies among prior investigations and (2) serves as a basis for evaluating the stream-aquifer implications of water supply alternatives being considered by SCWD. Appendix A contains the detailed critique of the prior investigations.

## 7.1 Inventory of Factors that Potentially Affect Baseflow

Various characteristics of the stream-aquifer system along Soquel Creek can be deduced from hydrologic principles. These characteristics form a foundation for interpreting data, evaluating the methods and conclusions of prior investigators, and developing an interpretation of stream-aquifer interactions. Also, the timing and magnitude of significant changes among factors affecting baseflow constrain the timing and magnitude of possible impacts. For example, the amount of baseflow depletion caused by groundwater pumping could not exceed the amount of pumping, nor could a decrease in baseflow be caused by a well not yet operational at the time of the observed decrease. A brief tabulation of some of these *a priori* findings and constraints serves as a useful starting point for reviewing previous investigations and developing a revised stream-aquifer conceptual model.

Listed below are a number of these factors, along with a brief description of their expected potential impacts and constraints on the magnitude of such impacts. Section 7.1 concludes with a more detailed discussion of the potential influences of groundwater pumping by SCWD and private wells.

***Logging and Forest Fires*** – Balance Hydrologics (2003; Figure G-2) compiled a timeline of historical activities and natural events, including logging and forest fires, that likely affected Soquel Creek geomorphology. Although exact logging acreages are not available, large-scale harvest of old-growth timber was common until the 1940s. Three forest fires consuming 100-250 acres each occurred in 1934, 1936 and 1958. Since 1960, there have been no major fires and logging has consisted of smaller harvests of second-growth timber. Forest fires and clearcuts both tend to temporarily increase stream baseflow for a number of years as vegetation regrows. The diminished root zone thickness and canopy cover following these events allows a greater percentage of precipitation to percolate to groundwater. The expected baseflow impact would be an abrupt increase followed by a gradual return to previous levels over perhaps 10-20 years.

***Grazing* –** Intensive grazing tends to compact soils and decrease above-ground biomass, and these changes increase direct runoff and decrease deep percolation of precipitation. The effects on streamflow can be quite noticeable and include increased peak runoff during storms and decreased summer baseflow (Rhoades et al., 1964; Rauzi and Hanson, 1966; Wood and Blackburn, 1981; Gilgerd, personal communication, January 12, 1995). Soil compaction develops gradually and at different times among individual parcels in the watershed. Thus, any related baseflow impacts would be expected to increase gradually over a period of years to decades as forest is converted to rangeland or vice versa.

***Rural and Urban Development* –** Construction of roads and buildings can increase or decrease precipitation recharge over the surface of a watershed, depending on (1) the disposition of runoff from impervious surfaces, (2) the extent to which vegetation is irrigated, (3) the leak rate from water distribution pipelines, and (4) the presence or absence of septic systems. A systematic analysis of all of these factors would be necessary to reach any conclusions about net impacts on recharge and/or baseflow.

***Riparian Evapotranspiration* –** Many trees and shrubs along creek channels are phreatophytes with roots that draw water directly from the water table. Because of their proximity to the creek, evapotranspiration (ET) by these plants in summer draws fairly directly on baseflow. Diurnal flow fluctuations were documented in several of the previous investigations and were attributed to riparian ET. However, none of the previous investigations considered the area of riparian canopy that would be required to deplete flow by the observed amounts, which can be estimated by dividing the amplitude of the fluctuations by the ET rate. Observed ET-related fluctuations in flow at the Main Street gage were commonly on the order of 0.5-0.8 cfs in August 2001 (Balance Hydrologics, 2003). Assuming an average riparian canopy width of 400 ft (Balance Hydrologics, Figures G-9 and G-10), a corridor of vegetation 1.9 miles long would be needed to consume 0.8 cfs of water at an ET rate of 0.21 in/day, such as occurred on hot days in August 2001. Peak hourly ET is about four times average daily ET, and thus requires a reach of only 0.4 mile for a 0.8 cfs reduction. Vegetation farther upstream also depletes flow, and those depletions travel downstream to arrive at the gage. Because of delays caused by in-channel travel time, however, those fluctuations become out of phase with local ET fluctuations. For an average low-flow velocity of 0.5 ft/sec, ET fluctuations from vegetation 4.1 miles upstream of the gage would be exactly out-of-phase with fluctuations generated by vegetation at the gage. This self-canceling effect caused by phase lags is a major reason observed diurnal ET fluctuations are much smaller than total ET estimated for all upstream riparian vegetation.

***Streambed Aggradation and Degradation* –** Several previous investigators suggested that streambed aggradation or development of gravel bars near gaging locations could cause an apparent decrease in baseflow simply because a larger percentage of total flow would move as underflow through the gravels beneath the streambed. However, none of the investigators attempted to estimate the amount of water that could plausibly flow through the subsurface assuming reasonable estimates of gravel permeability, as we do here. Consider three possible flow paths: surface flow in the creek, underflow in coarse sands and gravels that comprise the streambed (hyporheic zone), and shallow groundwater flow through the alluvial deposits along the creek valley. Subsurface flow through the alluvium can be estimated using the Darcy equation assuming the alluvium is 2,000 ft wide, 50 ft thick, with a water-table slope equal to the valley-floor slope (33 ft/mi), and a hydraulic conductivity of 300 ft/day (sands). The resulting flow estimate is 2.17 cfs for the entire alluvial thickness. Aggrading the creekbed by 1 ft would raise the water table by approximately 1 ft, or 2 percent of the total flow thickness. Subsurface flow would therefore increase by 2 percent, to 2.21 cfs. This suggests that surface flow would decrease by only 0.04 cfs, which would be detectable only at very low flows. The sediments in the creekbed are on average coarser and more permeable than the alluvium, but have a much smaller cross-sectional area. The creekbed could conceivably consist of a 50-ft-wide swath of coarse, clean gravels 5 ft thick with a hydraulic conductivity of 2,000 ft/day. Even if the hydraulic gradient is locally steepened where water flows through a gravel bar to twice the average value, the subsurface flow through the channel deposits would be only 0.07 cfs. The high hydraulic conductivity and gradient relative to the overall alluvium are more than offset by the much smaller cross-sectional area of the channel deposits. A 1-ft increase in gravel thickness would increase flow through the channel deposits by 20 percent, or by 0.014 cfs, which would be difficult to detect. Thus, if the entire valley-floor alluvium is needed to convey a significant amount of flow via the subsurface, then minor changes in streambed elevation will have a negligible effect on observed surface flow.

The sediments in the creekbed are on average coarser and more permeable than the alluvium, but their cross-sectional area is much smaller. The creekbed could conceivably consist of a 50-ft-wide swath of coarse, clean gravels 5 ft thick with a hydraulic conductivity of 2,000 ft/day. Even if the hydraulic gradient is locally steepened to twice the average value where water flows through a gravel bar, the subsurface flow through the channel deposits is only 0.07 cfs. In other words, the high hydraulic conductivity and gradient relative to the overall alluvium are more than offset by the much smaller cross-sectional area of the channel deposits. A 1-ft increase in gravel thickness would increase flow through the channel deposits by 20 percent, or by 0.014 cfs, which would be difficult to detect. Two conclusions can be drawn from these calculations:

1. Aggradation of the creekbed will raise the water table by an equal amount, shunt only a tiny percentage of surface flow into the subsurface, and surface flow will remain essentially the same.
2. Flow gains and losses along the length of the creek associated with local variations in the permeability, width and depth of the alluvium could conceivably be as large as 2 cfs.

***Loma Prieta Earthquake*** – The October 1989 Loma Prieta earthquake significantly impacted the baseflows of Soquel Creek and other streams in the region at the start of the third water year of the 1987-1994 drought (Figure 7-1; Rojstaczer and Wolf, 1991). Baseflows at the Soquel gage increased by a factor of about 25, the recession from which lasted into the following summer. These increased flows were a release from groundwater storage. How the ensuing storage deficit may have impacted baseflows during the years after the earthquake is uncertain.

***Groundwater Pumping*** – The principle of conservation of mass and the Darcy equation governing groundwater flow make it inevitable that groundwater pumping near a stream that is hydraulically connected to the adjacent shallow aquifer will increase the rate of groundwater recharge from the stream and/or decrease the rate of groundwater discharge to the stream, either of which will result in decreased baseflow. The SCWD Public Advisory Committee (1998) recognized these principles when it reached the following conclusions:

- "It is also probable that lowering of groundwater levels below the streams is contributing to reduced base flows."
- "As a result of pumping groundwater, there has been an inducement of more recharge than occurred in the absence of pumping. This is a predictable result for any stream-aquifer system."

The question, then, is what is the magnitude of baseflow depletion. If the creekbed and near-surface geologic materials are fine-grained and much less permeable than other groundwater flow paths reaching the well, the rate of streamflow depletion will be a small percentage of the well pumping rate. If baseflow is strongly affected by other factors, the depletion might also be a small percentage of baseflow or a small percentage of the range of baseflow fluctuation.

Water pumped from a well is a combination of groundwater that otherwise would have discharged to a creek and groundwater and surface water that would have otherwise discharged directly to the ocean. At one extreme, if 100 percent of the pumped water would have flowed in and/or to the creek, the maximum amount of baseflow depletion would equal the pumping rate of the well or wells. The following table gives several subtotals of measured or estimated groundwater pumping that could potentially affect Soquel Creek baseflow. For SCWD, these are typical pumping rates for 1989-2002 and are expressed in cubic ft per second to facilitate a comparison with streamflow.

| Well or Wells | Annual Average (cfs) | Summer Average (cfs) |
|---|---|---|
| SCWD Pumping | | |
| Main Street well | 1.0 | 1.2 |
| A/AA wells east of creek | 2.0 | 2.5 |
| All A/AA wells | 3.0 | 4.0 |
| All Purisima wells | 4.6 | 5.9 |
| Estimate of private pumping upstream of Main Street (Pingree, 1997) | 0.4 | 0.8 |

These subtotals represent a range of potential stream impacts that may or may not be indicated by different hypotheses regarding the hydraulic connection between various aquifers and Soquel Creek. Streamflow depletion would correlate with the average annual pumping rate if drawdown were spread out over time and area and the associated downward vertical gradients propagated gradually up through the layered units. If vertical flow within the aquifer system is more rapid, streamflow depletion might track seasonal variations in pumping, such that summer baseflow depletion would correlate to summer pumping rates. The Main Street well could have a pronounced effect on measured baseflow because it is very close to the creek and the Main Street gage. If stream-aquifer interaction is highly controlled by layering within the Purisima Formation, the wells most likely to affect baseflow are wells located east of the creek that pump from the Purisima A and AA units. The creek flows across the area where these units intersect the land surface (Figure 2-10). If drawdown diffuses more readily between units and horizontally, then perhaps streamflow would correlate with pumping from all A/AA wells or from all Purisima wells. These subtotals indicate that if most of the water produced from SCWD wells derives from induced seepage from the creek, then observed baseflow depletion should be on the order of 1 to 6 cfs.

For comparison, estimated pumping from private residential and irrigation wells in the Soquel Creek watershed upstream of Main Street is also shown in the table. These amounts are subtotals of a comprehensive effort by SCWD to inventory private wells and estimate their production (Pingree 1997). The amounts shown here are subtotals for assessors parcel zones 99, 100, 102, 103 and 104, which correspond roughly to the Soquel Creek watershed above Main Street. The amounts are net pumping after accounting for return flows from septic systems and deep percolation of applied irrigation water. The maximum potential impact of these wells on baseflow is a depletion of 0.4 to 0.8 cfs, depending on how rapidly pumping affects baseflow. Local historians familiar with agricultural development in the Soquel area have pointed out that widespread conversion of nonirrigated orchards to heavily irrigated nursery crops during the 1960s and 1970s probably increased groundwater pumping during that period (R. Nutter and R. Tyler, personal communications, February 4 and 5, 2004). Subsequent displacement of nursery crops with urban or rural residential land uses essentially substituted one type of water use for another. Net consumptive use of groundwater could have increased or decreased somewhat in the process, depending on the fate of stormwater and wastewater.

The locations and depths of SCWD's wells are sufficient to conclude that the streamflow depletion they cause is less than their total amount of pumping. All of the wells except the Main Street well are located considerable distances downstream of the gage, and to obtain all of their water from creek seepage, the drawdown from each well would have to be oriented in a single direction. In general, drawdown extends radially from a well. Layering of units within the Purisima Formation would tend to increase the extent of drawdown parallel to bedding relative to across the bedding, but this is a planar orientation, not a single direction. Also, many of SCWD's Purisima wells are located as close or closer to the ocean than the creek, which tends to increase the percentage of well yield derived from intercepted ocean outflow. The Main Street well is very close to the creek and gage, but the deep strata tapped by the well intersect the land surface well to the west of the creek. Thus, based on this qualitative interpretation , the expected amount of streamflow depletion near Main Street caused by SCWD's wells is greater than zero but probably less than about 2 cfs.

A rough estimate that potentially constrains the interpretation of leaky-aquifer conditions near Main Street is the radius over which leakage would be needed to supply the full discharge of the well. The estimated area of the circle could be constrained at one end by plausible precipitation recharge rates and at the other end by the maximum plausible anisotropy in the layered aquifer system. None of the previous investigators tested this approach. The Darcy equation can be applied to vertical leakage flow as follows:

$$Q_p = K_z A \, dh/dz$$

where $Q_z$ is the discharge rate of the well (assuming 100 percent of the discharge is supplied by leakage), $K_z$ is the vertical hydraulic conductivity, $A$ is the area of the circle over which leakage occurs, and $dh/dz$ is the average vertical hydraulic gradient within area $A$. At the Main Street well, for example, annual-average pumping is about 300 million gallons, which is equivalent to a constant pumping rate of 570 gpm. The vertical gradient is the difference in water levels between monitoring well SW-1 and the Main Street well (49 ft in August 2002), divided by the vertical distance between the SW-1 perforated interval and the top of the Main Street well perforated interval (about 197 ft). The radius of the circle over which leakage occurs can be calculated for various assumed values of $K_{z.}$ At the leaky end of the spectrum, for example, a 10:1 ratio of horizontal to vertical hydraulic conductivity could be assumed throughout the aquifer system. Straight-line and log-log analyses of the 1991 aquifer test results indicate a horizontal hydraulic conductivity of 6.3 to 7.5 ft/day (Linsley, Kraeger Associates and Luhdorff & Scalmanini Consulting Engineers, 1991; also see Section 3), corresponding to a vertical hydraulic conductivity of about 0.7 ft/day. The radius of leakage in this case would be 447 ft, and the average one-dimensional leakage rate would be 764 in/yr. This leakage rate greatly exceeds estimated average annual precipitation recharge rates (see Section 5). Therefore, if the system were this leaky, the great majority of water pumped by the Main Street well would be derived from leakage from shallow aquifers hydraulically connected to the creek, and the associated induced seepage should be easily detectable in long-term stream gaging records.

At the opposite extreme, one can estimate the radius of leakage that would be large enough to collect the full flow of the well from precipitation recharge, assuming an average annual recharge rate of 5 in/yr. This calculation results in a circle with a radius of 4,300 ft (0.8 mile) and a ratio of horizontal to vertical hydraulic conductivity of 2,500:1. These values are both relatively high for typical groundwater basins. Thus, it seems likely that local hydrogeologic conditions fall somewhere between these extremes and that at least some of the well production derives from leakage and, hence, stream baseflow.

## 7.2 Review of Prior Stream-Aquifer Analyses

Each of the previous analyses provides useful information for understanding stream-aquifer interactions and past variations in baseflow. However, most of the analyses suffer from one or more of the following shortcomings:

- Interpreting a decreasing trend or shift in baseflow from historical fluctuations that could be reasonably interpreted as normal variations within a system that remains essentially unchanged.
- Not considering or analyzing the full range of factors that influence baseflow.
- Dwelling on factors at odds with the timing, location, and/or magnitude of purported effects or other physical evidence.

Our critique of previous analyses is summarized in Table 7.1 and provided in detail in Appendix A.

## 7.3 Additional Analyses

For this report, we conducted four additional analyses: two of changes in the frequency distribution of low flows over time, one of water-table elevations relative to Soquel Creek, and one of the correlation between annual baseflow and precipitation.

Evaluating the frequency distribution of low flows for different periods of time provides a more complete picture of the baseflow regime than average flows during those periods. The years selected for analysis can be stratified by climatic conditions (e.g. wet, normal, and dry years) to partially control for variability related to precipitation. Two methods can be used to evaluate frequency distributions. The first is to plot complete flow-duration curves, which involves ranking all the daily flows in each analysis period and plotting them against their percentile. The second is to select a small number of specific flow magnitudes (e.g., 0, 1, 2, 3 and 4 cfs) and plot the number of days in each analysis period that flows are less than or equal to those values. As with all evaluations of low-flow records at gaging stations, the data are vulnerable to significant errors in the stage-discharge rating curve caused by minor changes over time in channel vegetation and bed form.

***Analysis 1 –*** Daily flows in Soquel Creek at the Main Street gage were ranked and plotted as exceedance-frequency curves (also known as flow-duration curves) for each year in the period of record (WYs 1952-2002). Streamflow depletion by groundwater pumping tends to pull down the low-flow end of the frequency distribution. Pumping has steadily increased during the period of record, and if it has caused a gradual increase in baseflow depletion, the tail end of the curves for recent years would tend to plot below those for earlier years.

The curves were grouped into wet, normal and dry years to minimize the effect of variable climatic conditions. Within each group, eight to twelve years spanning the full period of record were plotted together to see whether trends were evident. The plotted years are shown in bold colors in Table 7.2 and were screened to ensure that annual precipitation and annual creek discharge both fell within the same hydrologic category. The resulting flow-duration curves for wet, normal and dry years are displayed in Figures 7-2, 7-3, and 7-4, respectively. To facilitate a visual assessment of trends, the low-flow end of each curve is labeled with the last two digits of the year. In all three year-type classifications, the lowest curves are for years during the 1987-1994 drought (the low-flow days during WY 1995 were actually in October 1994). However, there was no consistent trend in the relative positions of the curves prior to 1987, and the curves for subsequent years (1996-2002) returned to the typical pre-drought range.

The 1987-1994 period stands out as an unusual event but not a trend. Groundwater pumping could not have been the primary cause of low flows during that period because it would have similarly affected prior and subsequent years and would have caused a detectable trend in curve position over time.

***Analysis 2 –*** A bar graph of the number of days of zero flow each year was superimposed on a graph of the cumulative departure of annual precipitation, as shown in the lower graph in Figure 7-5. A pattern in the timing of zero-flow days suggests a plausible physical mechanism for their occurrence. Zero-flow days have consistently occurred toward the end of major droughts, as measured by the magnitude of the "valley" in the cumulative departure graph (that is, by cumulative precipitation deficit or, approximately, by the product of intensity and duration). The 1976-1977 and 1987-1994 droughts were the largest droughts that occurred during the 1951-2002 period of streamflow record, and were the only periods when zero-flow days occurred. Importantly, zero-flow days did not commence until the latter part of each drought, and in the case of the 1987-1994 drought lingered for 1-2 years after the return to normal and wet years. However, as noted above, the October 1989 earthquake had a significant impact on baseflows during the 1987-94 drought. A substantial increase in baseflow occurred immediately following the earthquake, the recession from which lasted into the following summer (Figure 7-1). This release from groundwater storage may have contributed to a subsequent decline in baseflow.

Other aspects of the graphs in Figure 7-5 worth noting are that the 1959-1966 drought was small in comparison to later droughts, and the occurrence of low-flow days does not appear to correlate with pumping at the Main Street well or other Purisima A/AA wells. A plausible mechanism to explain these patterns is that zero-flow days result from multi-year periods of significantly below-average precipitation recharge attenuated by shallow groundwater storage effects. Baseflow is supplied by gradual drainage of groundwater from the hills and ridges between the many tributary channels of Soquel Creek. This storage capacity is sufficiently large that multiple years of below-average recharge are required to deplete baseflow to zero, and conversely, several years of normal or above-average recharge are needed to replenish storage to the point that baseflow recovers. The storage capacity and water-table fluctuations that would be needed to generate the observed baseflow variations in Soquel Creek are geologically quite reasonable. For example, the volume of groundwater discharge needed to supply 2 cfs of baseflow for an entire year could be supplied by a 0.6-ft decline in average water-table elevation over the 40-square mile watershed above the gage (assuming a specific yield of 0.10). This range of fluctuation is miniscule compared to the plausible range of fluctuation for the rugged terrain present in the watershed. Thus, the conceptual model of a shallow stream-aquifer system that is strongly affected by variations in precipitation recharge, and that leaks water at a relatively small, constant rate to deep aquifers, completely explains the observed history of exceptionally low flows in Soquel Creek.

***Analysis 3 –*** The conclusion by prior investigators that Soquel Creek gains flow downstream of the Main Street Well was supported by a very small number of streamflow and groundwater measurements (LSCE, 1998c; LKA and LSCE, 2003; Balance Hydrologics, 2003). To supplement these observations, water-level measurements from shallow monitoring wells at groundwater contaminations sites near Soquel creek were compiled and compared with the creekbed elevation at the point closest to the well. The well locations are shown in Figure 4-6a and the water-level and creekbed elevations are shown in Figure 4-33. At the two sites on Soquel Drive, shallow groundwater levels are all still lower than the creekbed elevation. A half-mile farther downstream, however, shallow wells on Porter Street and Bay Avenue have water levels 10-16 ft higher than the creekbed. These wells are slightly downstream of SCWD's Nob Hill monitoring well, where groundwater levels have been consistently 2-3 ft higher than the creekbed. Collectively, all of these wells fit a consistent pattern: shallow groundwater levels near Soquel Creek increase downstream of the Main Street Well area, from below the creekbed elevation to above the creekbed elevation. This pattern of groundwater levels is consistent with a few baseflow measurements that indicated a transition from losing to gaining conditions along that reach.

***Analysis 4*** – To support the water-budget analysis, historical records of total flow in Soquel Creek at the gage in Soquel were partitioned into baseflow and stormflow components. The method and results are presented in Section 5.3 and Figures 5-7 through 5-10. The new baseflow information offered an opportunity to expand on a previous effort by Jackson (2001) to correlate baseflow with precipitation during prior months, specifically by testing correlations for all months, not just late-summer months. A linear regression between annual precipitation and estimated annual baseflows for Soquel Creek during WYs 1953-2003 resulted in a correlation coefficient ($r^2$) of 0.64. Including the estimated baseflow for the preceding year in a multiple linear regression increased the coefficient substantially, to 0.81. However, adding a second preceding year to the regression provided no further predictive benefit. These results are similar to Jackson's findings and are consistent with our interpretation, in which shallow groundwater storage buffers the effect of extreme wet or dry conditions on stream baseflow. It is the mechanism by which large droughts or extremely wet years can have a noticeable effect on baseflow for 1-2 years after the return to normal climatic conditions.

## 7.4 Interpretation of Stream-Aquifer System

Soquel Creek and other area streams flow across a layered sequence of units belonging to the Purisima Formation. These layers consist of extensive but discontinuous lenses of sandstone, siltstone, claystone, and mixtures thereof. Groundwater flows much more easily within coarse-grained layers than between layers. The layers dip a few degrees, which is important when projecting drawdown effects or flow paths over large horizontal distances. When evaluating drawdown and flow paths in the immediate vicinity of an individual well, however, the layering can be considered essentially horizontal, with high horizontal permeability and low vertical permeability. One consequence of the layering is that deep aquifers tapped by SCWD's supply wells are confined, which means storativity is small and water-level fluctuations caused by pumping are large. The shallowest aquifer contains a true water table, with high storativity (i.e., specific yield) and small water-level responses to recharge and pumping events. Each creek is hydraulically coupled to the shallowest aquifer, with no intervening unsaturated zone.

Another consequence of the layering is that streamflow is relatively responsive to processes near the land surface (such as precipitation recharge and shallow pumping) and sluggishly responsive to groundwater pumping at depth. As the drawdown pulses from the cyclic pumping of deep wells gradually propagate upward through the layers, they become greatly attenuated, or spread out over a large area and over time. The expected result is that deep pumping causes fairly constant and widespread leakage of water out of shallower strata and the creek rather than distinct pulses of drawdown associated with individual pumping cycles.

Figure 7-6 shows schematic cross-sections of the conceptual stream-aquifer system. Under predevelopment conditions (upper graph), groundwater derived from precipitation recharge followed one of two paths: it flowed to the creek and emerged as baseflow, or it flowed directly to the ocean (perpendicular to the cross section, toward the viewer). The divide between these pathways was a function of their relative permeabilities and gradients. Recharge close to the creek or far from the coast would tend to discharge to the creek, while recharge closer to the coast or far from a stream channel would tend to discharge to the ocean. Under existing conditions (lower graph), wells are a third pathway by which groundwater can exit the system. The downward gradient caused by deep wells shifts the location of the divide between flow to the creek and flow to the ocean, and it intercepts flow from both of those predevelopment pathways. Withdrawal of groundwater from storage is another potential source of water to wells, but that term may now average zero considering the apparent lack of long-term declining trends in groundwater levels.

In the context of the conceptual model, it is clear that somewhere between 0 and 100 percent of the water pumped from wells derives from flow that would have gone to the creek and the remainder comes from flow that would have gone to the ocean (or possibly new flow coming in from the ocean). Consequently, the assertion that pumping has had no impact on baseflow is equivalent to asserting that 100 percent of the water derives from intercepted ocean outflow. This would require that predevelopment outflow was at least as large as present-day withdrawals (about 5,500 ac-ft/yr of consumptive use from the Purisima) and that a perfect flow barrier exists between the creek and the deep wells.

An element of the conceptual model essential to explaining some of the observed fluctuations in baseflow is that groundwater storage in the shallow aquifers of upland areas between various branches of the stream network drains to stream channels slowly over a period of years. The storage effects of these shallow aquifers allows multi-year droughts to cause a cumulative decrease in groundwater discharge to creeks that persists for several years. Estimates of the area, specific yield, and water-level change necessary to sustain observed baseflows confirm that this element of our interpretation is reasonable.

Another important element of the conceptual model is that runoff and deep percolation below the soil zone are both nonlinear functions of precipitation. This means that a certain amount of rain has to fall at the beginning of the wet season before either runoff or deep percolation are initiated. The delay is caused by the need to replenish soil moisture storage, which is largely depleted by vegetation during each dry season. The nonlinear effect for runoff is quite apparent in streamflow data. It is not uncommon for a cumulative total of 6 inches of rain to fall during October and November before streamflow begins responding noticeably to each new storm. The effect can also be seen in plots of annual or seasonal stream discharge versus annual precipitation (e.g., Balance Hydrologics, 2003, Figure H-5; Luhdorff & Scalmanini Consulting Engineers and Linsley, Kraeger Associates, 1998, Figure 2). The data trend always intersects the precipitation axis at a value greater than zero, indicating that lesser amounts of precipitation would be associated with no flow at all. This same threshold effect is true for deep percolation of precipitation below the soil zone, which is the mechanism by which precipitation recharge enters the groundwater system. Soil moisture storage must be replenished before significant amounts of deep percolation occur. Deep percolation is less visible, but this threshold effect has been confirmed in uplands and groundwater basins on the central coast of California (Blaney et al., 1963).

The nonlinearity of runoff and precipitation recharge is important to understanding the Soquel Creek stream-aquifer system because runoff and recharge occur disproportionately in years of above-average precipitation. By the same token, a year of average precipitation will generally produce below-average streamflow and recharge. Consequently, great caution must be exercised when comparing baseflow among different years or intervals within the 52-year period of record for Soquel Creek streamflow.

## 7.5 Summary and Conclusions

Pumping from deep wells almost certainly decreases the amount of baseflow in Soquel Creek and other area streams, but the effect is small and has been masked in available historical data sets by other factors that collectively have a greater effect on baseflow. These other factors include:

- Logging and forest fires

- Grazing
- Rural and urban development
- Riparian evapotranspiration
- Streambed aggradation and degradation
- The Loma Prieta earthquake
- Groundwater pumping from shallow wells

One of the factors contributing to the lack of observed depletion is that historical flow data are not available for all stream reaches. Specifically, the only long-term flow data for Soquel Creek reflect stream-aquifer interactions upstream of the Main Street gage, whereas the greatest impact of pumping might be expected farther downstream and/or dispersed over the entire watershed. Little or no gaging data are available for Rodeo Creek and Arana Gulch.

None of the previous investigations–nor the analyses completed for this study–demonstrate the occurrence of long-term trends or pumping-related baseflow depletion in Soquel Creek. On the other hand, aquifer tests and ambient hydraulic gradients in the groundwater system near Main Street showed that downward leakage from the shallow aquifer adjacent to the creek to deep aquifers pumped by SCWD wells can and does occur. The main reason for the apparent discrepancies between the streamflow data and the groundwater data is that baseflow is affected by a number of factors other than groundwater pumping. The effect of pumping would need to be as large or larger than the effects of these other factors to be detectable in historical flow data. Based on the amount of scatter in various data plots generated for these analyses, it appears that these methods could probably detect chronic baseflow depletion as small as 0.5 cfs (224 gpm). It can be concluded that historical baseflow depletion at the Main Street gage has been less than this threshold. However, if groundwater production is further redistributed to inland wells (either existing or new) near Soquel Creek and/or other streams, such thresholds could be exceeded such that the influence of pumping on streamflow becomes discernable.

Additional specific conclusions that emerged from the review of previous investigations include the following:

- Exceptionally low baseflow during the latter half of the 1987-1994 drought represented the response of the stream-aquifer system to an exceptionally severe drought event (as measured by cumulative precipitation deficit). It was not indicative of a long-term trend in drought baseflow conditions.

- The hydraulic connection between Soquel Creek and deep aquifers in the Purisima Formation is weak and slow. Increases in deep pumping have a small attenuated effect on streamflow. The impact of historical pumping has not been measurable because it has been smaller than the effects of other factors, particularly precipitation.

- Soquel Creek is a gaining stream along its entire length except for an approximately 1-mile reach centered between Bates Creek and Soquel Drive, and this losing reach predates construction of the Main Street well. The cause of the losing reach is not clear but could result from spatial changes in aquifer transmissivity.

- None of the assertions by previous investigators that baseflow conditions changed abruptly at some point in the past is substantiated by the data. Three different investigators identified three different dates of "abrupt" changes: 1960, 1978 and 1991. Physical mechanisms capable of creating an abrupt and persistent change in baseflow include a large forest fire, a major flood, or increased pumping from a new or existing well near the creek. There have been no large fires in the watershed in recent decades, the 1955 and 1982 floods did not coincide with the dates of the purported changes, and the pumping history of the Main Street well is unlikely to have caused the baseflow change that supposedly commenced in 1991.

The interpretation presented in this section is consistent with almost all of the data presented by previous investigators (as documented in Appendix A). There are a few exceptions, however, as well as opportunities to collect additional data that would help confirm or refine the interpretation.

# 8 Summary, Conclusions, and Recommendations

The hydrogeologic conceptual model presented in this report is a comprehensive synthesis of available information and knowledge relevant to the understanding of the Soquel-Aptos groundwater system. It is intended to serve as the foundation for defining and characterizing critical groundwater issues, formulating potential solutions, and developing and applying additional methods of analysis (e.g., a groundwater model).

## 8.1 Summary of Original Contributions

This report documents a comprehensive update of the interpreted hydrogeology of the Soquel-Aptos groundwater basin. The following summarizes our original work presented in Sections 2 through 7:

- Hydrogeologic framework
  - Confirmed and further characterized the geologic units and their structure
  - Incorporated recent offshore information
  - Extrapolated the geologic structure across the entire study area
  - Subdivided the hydrostratigraphy into distinct aquifer and aquitard units
  - Defined the study area hydrogeologic boundaries and subareas

- Aquifer properties
  - Comprehensive review of available data and previous estimates
  - Reanalyzed aquifer tests and estimated vertical hydraulic conductivities
  - Assigned a probable range of aquifer property values to each hydrogeologic unit

- Groundwater occurrence
  - Evaluated SCWD monitoring- and production-well data
  - Evaluated data not currently in the SCWD database, including:
    - SCWD production well water-level records back to 1973 [38]
    - USGS water-level records dating back to the 1960s
    - City of Santa Cruz and Central Water District data
    - Remediation-site water-level records dating back to the 1980s [38]
    - Water-quality records for SCWD wells dating back to the 1940s [38]
  - Assessed historical changes and patterns in groundwater pumping
  - Calculated distance-drawdown relations representative of aquifer and pumping conditions
  - Evaluated historical water-level responses to pumping and wet and dry periods
  - Assessed occurrence of water levels near and below sea level

- Water budget
  - Defined components and relations of a conceptual water budget
  - Reviewed water-budget estimates of eleven previous studies
  - Estimated the baseflow component of six stream gage records (a total of 112 years)
  - Estimated average annual recharge for each basin subarea
  - Assessed the balance of groundwater inflows and outflows

- Saltwater intrusion
  - Reviewed assessments of seven previous investigators
  - Applied several geochemical approaches for assessing evidence of past and ongoing intrusion
  - Assessed potential intrusion pathways

[38] Our use of these data required extensive manual entry from paper copies.

  - Documented past minor intrusion in Purisima area
  - Documented significant ongoing intrusion in Aromas area
  - Calculated saltwater interface profiles along the Aromas-area coast, including the effect of upconing

- Stream-aquifer interactions
  - Evaluated seven factors affecting baseflow
  - Reviewed previous evaluations by 8 investigators (a total of 29 former analyses)
  - Conducted four original analyses
  - Assessed past and current impacts of groundwater production on streamflow.

## 8.2 Key Findings

### 8.2.1 Hydrogeology

As discussed in Section 2, we propose an alternative subdivision of the Purisima Formation into relatively distinct aquifer and aquitard units. The lower portions of LSCE units B and D are predominantly fine grained and are thus designated aquitards B and D. The remaining stratigraphy is grouped into separate aquifers consistent with their predominantly coarse-grained lithology and the distribution of production well screens. These aquifers are labeled A, BC, DEF, and F.

Purisima unit AA appears to be a less significant aquifer zone than previously implied. For example, the Main Street well draws primarily from a deep, older sandstone (possibly Santa Margarita Sandstone), and less so from unit AA. Unit AA contains some permeable zones toward its top, but is mostly fine grained and serves as an aquitard between aquifer A (by far the Purisima's most productive zone) and the underlying older sandstone, where it occurs.

Available imagery from offshore geophysical surveys reveals an expected pattern of Purisima Formation outcrops consistent with the formation's structural dip to the east and southeast. This confirms that each unit of the Purisima Formation is exposed to the ocean immediately offshore where its dipping beds are truncated by the seafloor. Exposure to the ocean is enhanced locally by infilled paleochannels that cut into the seafloor about 60 ft or more.

We have extrapolated the geologic structure of the Purisima units across the entire study area. Although consistent with available information, lithologic data are sparse away from the coastal terrace. Our interpretation provides a useful framework for layering a basinwide model. It also helps generate a map of direct recharge areas (both on and offshore) for each Purisima unit (Figure 2-10).

The Aromas Sands are informally subdivided into upper and lower units. Locally, few wells are screened in the upper unit. Consistent with previous interpretations (Thorup, 1981; LSCE, 1987a; Montgomery Watson et al., 1998), we recognize that most Aromas-area wells are also screened in the underlying Purisima-F aquifer. This interpretation has not been reflected in most prior studies for SCWD. It is also important to recognize that the alphabetical labels assigned to individual Aromas area monitoring wells do not correspond to either the stratigraphy or particular depth intervals.

We generally concur with a previous delineation of the basin boundaries (Montgomery Watson, 1998). We have provided a rationale for these boundaries that was previously lacking. For convenience we have divided the basin into Purisima and Aromas subareas divided along the western edge of the Aromas Sands outcrop.

### 8.2.2 Aquifer Properties

Section 3 provides our hydraulic property estimates for each of the basin's hydrogeologic units (Table 3-13). These provide a reasonable range of initial assumptions for use during model calibration, especially where supported by the available data. These include estimates of vertical hydraulic conductivity derived from our re-analysis of existing aquifer test data. Such data-based estimates were previously lacking, despite the importance of this parameter with regard to potential saltwater intrusion, streamflow depletion, and recharge enhancement.

Aquifer properties remain poorly documented in large portions of the basin where information is limited. Specific capacity estimates from private wells and the logs of inland test holes suggest that highly productive aquifer zones may be less common and/or relatively isolated away from the coastal terrace. This may justify modeled zones of lower permeability away from areas with proven high well capacities.

Previous models of the Soquel-Aptos area have assumed lower permeabilities than indicated by available hydraulic data for some Purisima units. Two reasons that may account for this are (1) units AA and A were combined into a single 800-ft thick layer, necessitating a low bulk permeability, and (2) groundwater discharge was otherwise excessive, preventing the simulation of a mounded inland water table. We find the evidence supporting relatively high permeabilities in aquifer zones along the coastal terrace to be credible. Permeabilities may decline away from these established aquifer zones, however. Data-based estimates of aquifer properties and insights from prior modeling can both be honored by zoning aquifer properties within model layers and defining model layers more consistently with the interpreted hydrostratigraphy.

Aquifer test results indicate that conditions in the Purisima-A aquifer are semi-confined from the Beltz wells east to SCWD's Tannery well. The deeper screened zones of this and other units tend to be more confined. Aquifer-test and water-level data for the Aromas area suggest that SCWD wells encounter unconfined to leaky conditions in the Aromas Sands and semi-confined to confined conditions in the underlying Purisima-F aquifer.

### 8.2.3 Groundwater Occurrence

In the developed Purisima aquifer, groundwater levels and the direction of flow are influenced most by pumping. Where conditions are most confined, pumping-induced drawdown is significant and widespread, extending radially many thousands of feet. Drawdown accumulates from repeated pumping cycles, is exacerbated by overlapping cones of depression and no-flow boundaries, and may require months to fully recover following significant reductions in pumping. The result is a broad, relatively flat, and fairly stable depression in the pieziometric surface.

Although groundwater levels declined during the early stages of groundwater development, levels have not trended significantly up or down during the last 30 years despite large increases in production, lowered pumping levels, and major wet and drought periods. In the Purisima area, this is because pumping-induced vertical gradients induce leakage from shallow zones, which in turn induces recharge from near-surface sources. Leakage is controlled by deep pumping levels more than by relatively small changes in the height of the water table above confining layers. As such, increased recharge to shallow zones has only a limited effect on deep water levels, and is an ineffective means for preventing saltwater intrusion.

In the Aromas area, groundwater levels have remained fairly stable near sea level as a function of high aquifer permeability, shallow unconfined conditions, interception of groundwater flow to the ocean, hydraulic connection with the ocean, and leakage to deep zones. Additionally, the managed distribution of groundwater production has minimized excessive local drawdown in both the Aromas and Purisima areas.

During recent years, there is little evidence for significant changes in onshore groundwater storage. Confined and leaky zones remain essentially "full" given that their fluctuating water levels represent changes in pressure rather than saturated thickness. Changes in groundwater storage may be more significant in the unconfined zones of inland areas away from streams. SCWD's production wells, especially those nearest the coast, have been drawing on offshore groundwater storage for many years. Without knowing the location and/or rate of movement of the freshwater-saltwater interface, the volume of storage remaining offshore and its rate of loss are unknown.

Water-level trends are a poor indicator of potential groundwater overdraft because of the influence of head-dependent boundaries (i.e., aquitard leakage, streams, the ocean). Once coastal water levels fall near or below sea level, continued or increased pumping is offset by onshore flow (i.e., intrusion) with only minimal additional drawdown. Thus, stable groundwater levels and minimal changes in onshore groundwater storage do not necessarily indicate the lack of overdraft.

Relationships between pumping and groundwater levels are needed to help mitigate potential saltwater intrusion. Unfortunately, several factors obfuscate the recognition of such relationships. First, there is a significant degree of data uncertainty due to noise, error, apparent inconsistencies, and spatially variable conditions. As such, apparent correlations between water levels and pumping may be more or less coincidental and/or locally unique and difficult to generalize. Second, data are sparse for early periods when the greatest changes in pumping occurred. Thus, the data record does not reflect the full range of stresses needed to reveal these relationships. Third, groundwater levels are influenced by the cumulative effects of both near and distant wells, and both recent and past pumping, so that the effect of changing one well's pumping is difficult to interpret. And fourth, groundwater levels are strongly influenced by head-dependent boundaries, and thus may change relatively little when pumping increases or decreases. A calibrated groundwater model can compensate for the latter two factors, and would thus provide a valuable tool for answering "what if" questions related to the effects of increased or decreased pumping.

### 8.2.4 Groundwater Budget

We used a simple mass-balance approach to estimate key components of the Soquel-Aptos groundwater budget. These estimates are highly approximate given the limitations of the approach and associated uncertainties described below. Our estimates are sufficiently detailed to avoid confusing roundoff errors when inserted into the water balance equations. However, such detail is not intended to convey accuracy. Estimates should be rounded to the nearest 1,000 ac-ft/yr when used for planning purposes.

We estimate that precipitation recharge averages roughly 4.5 in/yr in both the Purisima and Aromas areas. This amounts to about 12,200 and 3,600 ac-ft/yr for the Purisima and Aromas areas, respectively. Baseflows account for about 50 percent of the Purisima recharge and much less of the Aromas recharge. Estimated "deep" recharge supplying wells and discharge to the ocean is 6,100 ac-ft/yr (2.2 in/yr) for the Purisima area and nearly 3,000 ac-ft/yr (3.8 in/yr) for the Aromas area (including outflow to Pajaro Valley). Applied-water recharge averages about 0.5 in/yr across developed and undeveloped areas.

Our estimate of Purisima recharge is roughly the same as three previous estimates (Table 5-1). Our recharge estimate for the Purisima and Aromas areas combined is about 80 percent of the amount modeled by Montgomery Watson (1998).

Total groundwater production in the Purisima and Aromas areas is estimated at 6,700 and 3,600 ac-ft/yr, respectively, about 75 to 85 percent of which becomes consumptive use. We estimate roughly 400 ac-ft/yr of net groundwater discharge to the ocean from the Purisima area as a residual of deep recharge and consumptive use. This occurs mostly from shallow zones, whereas deeper zones are receiving leakage and subsurface inflow with the potential to become saltwater intrusion. For this reason, current average production from the Purisima area probably exceeds the sustainable yield.

In the Aromas area, we estimate that precipitation recharge and consumptive use are about equal. However, the mass balance requires some saltwater intrusion to account for subsurface outflow to Pajaro Valley and some groundwater discharge to the ocean (e.g., along the northern Aromas coastline). This indicates a significant groundwater deficit.

Our estimate of the groundwater mass balance for current average conditions assumes no net change in onshore groundwater storage, no subsurface inflows other than saltwater intrusion, and no boundary outflows other than discharge to the ocean and subsurface outflow to Pajaro Valley. Also, it does not account accurately for head-dependent flows (e.g., induced recharge, aquitard leakage, and aquifer interactions with streams and the ocean).

The recharge estimates are highly sensitive to the assumed values of evapotranspiration. A one inch per year increase in estimated evapotranspiration (4 to 5 percent) reduces the recharge estimates by nearly 25 percent. Also, (1) there is little data to support baseflow estimates for the Aromas area and (2) the assumed recharge areas are uncertain (e.g., whether to include areas north of the Zayante fault; where to draw the boundary between the Purisima and Aromas areas).

Most changes in onshore groundwater storage probably occur across interior uplands but are difficult to estimate from available data. We assume that fluctuations in shallow groundwater storage affect mostly baseflows. Aquifer-aquitard leakage rates constrain recharge to relatively deep production aquifers. Contributions from offshore groundwater storage, represented by the landward movement of the saltwater interface, could be significant despite being difficult to quantify.

Numerical modeling could provide a more accurate groundwater budget by solving the mass balance simultaneously with head-dependent hydraulics, and accounting for spatial and temporal variability. This report provides the information and assumptions needed to support such a modeling effort.

### 8.2.5 Saltwater Intrusion

There are generally three mechanisms for saltwater intrusion in the Soquel-Aptos basin: (1) in shallow aquifers, the cones of depression of coastal wells may reach the shoreline and induce seawater recharge directly into the capture zone; (2) in relatively deep aquifers, pumping depressions may extend far offshore until reaching the aquifer's seafloor exposure or other pathways such as faults, fractures, paleochannels, and general leakage; and (3) the freshwater-saltwater interface may migrate landward when onshore water levels decline to near or below sea level. The first two pathways capture seawater from above, whereas the third represents a saltwater wedge migrating along the aquifer base. An interface can be drawn locally upward from beneath a pumping well in a process called upconing. Pumping may also induce saline-water leakage from sources not associated with seawater intrusion (e.g., marine clays).

Instances of the first mechanism occurred in the past near Aptos, but are presently unlikely given that shallow coastal wells no longer operate. There is a reasonable concern that intrusion of the second type could impact the Purisima aquifer under current conditions. The third type of intrusion is actively occurring along the southern Aromas coast and represents the greatest threat to groundwater in the Soquel-Aptos area.

***Purisima Area*** – Production and monitoring wells in Purisima aquifers A, BC, and DEF exhibit no definitive signs of active saltwater intrusion. However, earlier intrusions into shallow zones are well documented and subtle indications exist of possible saltwater leakage into deeper zones.

Water quality indicators suggest that saltwater pathways exist into the Purisima-A aquifer where it is near or exposed to the seafloor offshore of the Beltz, Garnet, and former Opal wells. Saltwater entering the aquifer offshore of the Beltz wells would be detected first by City of Santa Cruz monitoring wells and would then need to migrate less than 5,000 ft to reach the nearest SCWD wells. Downward leakage provides a shorter pathway to the Garnet well. As the stratigraphy dips down further to the east, leakage into the lower Purisima units becomes significantly constrained by the low vertical permeability of overlying layers.

Previous instances of saltwater intrusion occurred where Purisima units E and F are exposed at the coast. One instance was the apparent capture of seawater by the drawdown cone of the Hillcrest well during its last years of operation. In another instance, a shallow saltwater wedge appears to have been pulled inland by the Seacliff 4 well and perhaps other nearby pumping. With the retirement of the Seacliff wells by the mid-1980s, this shallow wedge appears to have retreated and then stabilized.

The positions of the freshwater-saltwater interface within individual Purisima aquifers are mostly unknown. Interface locations probably begin at or just beyond each aquifer's seafloor outcrop (Figure 2-10), and extend further south where each aquifer dips below confining layers. Interface locations remain offshore but have probably moved landward in response to pumping. The potential for upconing is relatively low given the layered nature of the Purisma units.

The saltwater interface may be relatively close to shore where aquifers are shallow and unconfined. Thus, these units are susceptible to rather immediate intrusion. Where coastal groundwater levels persist at or below sea level in deeper, confined zones, saltwater intrusion may have further to travel from the nearest seafloor outcrop but nevertheless may be slowly moving toward pumping wells. Although shallow zones along the coast typically contain fresh groundwater above sea level, low vertical permeability may limit the downward leakage necessary to prevent deep-aquifer pumping troughs from reaching seafloor outcrops.

Fresh groundwater stored between the coast and the interface is being "mined" given that coastal groundwater levels now persist near or below sea level except in the shallowest units. Replenishment of this offshore storage is hindered by the interception of deep groundwater flow and limited recharge and leakage. Indeed, the estimated groundwater budget suggests that total pumping nearly equals the recharge available to deep wells. Although there are subtle indications of possible saltwater encroachment at depth, is possible that poor quality water is leaching from aquitards or other sources.

Groundwater levels must be managed to ensure that hydraulic gradients are adequate to prevent saltwater intrusion. It appears that this will require reduced production from some existing wells and/or groups of wells. If adequate outflow is maintained during most years, the saltwater interface can be maintained at a reasonable distance from production wells, providing at least a small storage buffer for droughts. Because groundwater production has drawn on offshore storage for many years, and the location of the interface is unknown, the current size of this storage buffer may be small.

***Aromas Area*** – Although SCWD's Aromas production wells exhibit no definitive signs of saltwater intrusion, the freshwater-saltwater interface is actively moving inland and poses a significant threat to future groundwater production. Continued onshore movement of the interface seems likely under current conditions considering that relatively steady increases in chloride concentration have occurred over the past 10 to 15 years with little change in water levels. The local encroachment of the saltwater interface appears to be part of a larger phenomenon encompassing the entire Pajaro Valley coast. As such, the causes are both local and regional.

Based on standard equations for predicting the saltwater interface and upconing profiles, upconing may present the most immediate threat of saltwater degradation to near-coast wells (e.g., Seascape, Sells, and Altivo). However, the effects of aquifer layering and anisotropy (not considered in these equations) probably reduce the potential for upconing, while amplifying the potential for horizontal interface movement.

Under current conditions, the onshore movement of the saltwater interface may spread northward, but may not reach coastal monitoring well SC-A1 unless groundwater production increases northwest of the Seascape well.

Ongoing intrusion along the Aromas area's southern coast provides evidence that maintaining groundwater levels at or just above sea level provides inadequate protection against saltwater intrusion. The observed conditions appear generally consistent with the concept of the Ghyben-Herzberg relation.

A continuation of current conditions will likely result in saltwater contamination of SCWD's most southeastern wells. The interface is already onshore and within the depth interval of production well screens. Hydraulic gradients between production wells and the coast are insufficient to prevent further inland movement.

Implementation of PVWMA's BMP may address the problem of overdraft and saltwater intrusion regionally. However, it appears that SCWD faces a serious threat of lost groundwater production from its Aromas-area wells due to saltwater intrusion before such measures have the opportunity to become effective.

Although the problem is regional, the response of water levels and chloride concentrations to changes in pumping indicate that further intrusion can be impeded locally by reductions in groundwater production in the vicinity of Seascape and La Selva Beach. However, the efficacy of relatively modest measures may be limited due to the regional nature of the problem.

The estimated water budget for the Aromas area suggests that pumping about equals available recharge. Thus, problems associated with overdraft may not be resolved by simply redistributing pumping within the Aromas area.

### 8.2.6 Stream-Aquifer Interaction

Pumping from deep wells decreases the amount of baseflow in Soquel Creek and other area streams. However, the hydraulic connection between these streams and deep Purisima aquifers is weak and slow such that increases in deep pumping have a small attenuated effect on baseflow. Furthermore, the effect of pumping on streams is masked by other factors that collectively have a greater impact on baseflow. These factors include logging, forest fires, grazing, rural and urban development, riparian evapotranspiration, streambed aggradation and degradation, earthquakes, groundwater pumping from shallow wells, and climatic variability.

This and previous studies have not demonstrated the occurrence of long-term baseflow trends or pumping-related baseflow depletions. On the other hand, aquifer tests and ambient hydraulic gradients show that downward leakage from shallow aquifers and streams to deep aquifers pumped by SCWD wells can and does occur. The primary reason for the apparent discrepancy between streamflow and groundwater data is that baseflows are affected by a number of factors other than groundwater pumping. The effect of pumping would need to be as large or larger than the effects of these other factors to be detectable in the historical record. Based on our own and past analyses of Soquel Creek, we estimate that chronic baseflow depletions as small as 0.5 cfs could be detected, and thus historical baseflow depletions at the Main Street gage have been below this threshold. If more groundwater production is redistributed to inland wells, such thresholds could be exceeded such that pumping has a detectable influence on streamflow.

Exceptionally low baseflow during the latter half of the 1987-1994 drought represented the response of the stream-aquifer system to an exceptionally severe drought, and was not indicative of a long-term trend in baseflow conditions.

Soquel Creek is a gaining stream along its entire length except for an approximately one-mile reach between Bates Creek and Soquel Drive. This losing reach predates construction of the Main Street well and is of unclear cause, but could result from spatial changes in aquifer transmissivity. Our interpretation of the available data do not substantiate past assertions that baseflow conditions changed abruptly at some past point in time. Opportunities exist to collect additional data that would help confirm or refine this interpretation.

## 8.3 Implications for Conjunctive Use

### 8.3.1 Groundwater Yield

The groundwater supply available to SCWD from the Purisima and Aromas aquifers determines the nature and amount of supplemental supply needed to meet water demands and avoid undesirable impacts. Using the simple mass balance approach presented in this report, we are unable to provide a firm estimate of groundwater yield. Highly approximate estimates are described below, and these can be improved in subsequent analysis following the review and acceptance of this report. Ideally, a calibrated groundwater flow model–consistent with a reasonable conceptual model–is needed to accurately account for head-dependent flows and spatial and temporal variability.

In the following discussion, we assume that sustainable groundwater yield is limited by total recharge, maintaining baseflows, and avoiding the potential for saltwater intrusion. Given that impacts to baseflow from groundwater pumping have historically been undetected, our evaluation of groundwater overdraft under past and current conditions is based primarily on saltwater intrusion.

***Purisima Area*** – Our estimates of groundwater recharge and consumptive use for the Purisima area leave an estimated 400 ac-ft/yr of net groundwater discharge to the ocean. This estimate is consistent with shallow coastal groundwater levels that remain above sea level. However, the persistence of deep-aquifer groundwater levels at or below sea level along the coast represents a significant potential for eventual saltwater intrusion. Thus, our representative estimates of total groundwater production (6,700 ac-ft/yr) and consumptive groundwater use (5,700 ac-ft/yr) for the Purisima area probably exceed the sustainable yield. It follows that SCWD's share of this production (up to nearly 3,800 ac-ft/yr) is not fully sustainable.

For planning purposes, SCWD has assumed that the Purisima area has a total sustainable yield of about 6,200 ac-ft/yr, of which 3,070 ac-ft/yr represents SCWD's sustainable production (see Section 5.2). SCWD has produced more than this amount from its Purisima wells every year since 1982 by an average of 260 ac-ft/yr. Based on SCWD's peak production during 1996-1997 (averaging about 3,700 ac-ft/yr), SCWD is overdrafting the Purisima area by up to 600 ac-ft/yr. Based on SCWD's recent annual production (about 3,400 ac-ft/yr), the overdraft is about 300 ac-ft/yr. Because SCWD lacks the authority to control groundwater pumping by others, its portion of the estimated sustainable yield could be negatively impacted by the increased production of others.

Our review of coastal groundwater levels, groundwater production, and saltwater intrusion indicators allows us to consider the potential benefits of reducing production from the Purisima area by several hundred acre-feet per year compared to current SCWD production of about 3,400 ac-ft/yr. Based on an inspection of the hydrograph and pumping records presented in Figure 4-11, reducing the Garnet well's production by roughly 100 ac-ft/yr or more may be appropriate given its proximity to the coast and SC-1A water levels dipping below sea level. Similarly, helping to maintain deep-aquifer water levels above sea level at SC-3 and SC-5 may require another 100 ac-ft/yr or more of reduced pumping distributed among other Service Area I wells (Figures 4-16 and 4-19); candidate wells for reduced pumping include Rosedale and Main Street given that their pumping levels have continued to decline. Maintaining SC-8 and SC-9 water levels above sea level may require a 200 ac-ft/yr or more reduction in Service Area II pumping (Figures 4-22 and 4-24); candidate wells for reduced pumping include Estates, Aptos Creek, and T. Hopkins. The sum of these rough, independent estimates (at least 400 ac-ft/yr) is generally consistent with a previous estimate of Purisima overdraft (Montgomery Watson, 1999). In making this rough estimate of overdraft, we are more concerned that it may be too low than too high. Thus, it is reasonable to assume that SCWD's sustainable production does not exceed 3,000 ac-ft/yr in the Purisima area and may be somewhat less. It may be possible to enhance this yield somewhat through additional pumping redistributions.

***Aromas Area*** – We estimate that total groundwater production from the Aromas area (about 3,600 ac-ft/yr) exceeds the sustainable yield given that saltwater intrusion is actively occurring and apparently necessary to balance the groundwater budget. It follows that SCWD's share of this production (up to 2,200 ac-ft/yr) is not fully sustainable.

For planning purposes, SCWD has assumed that the Aromas area provides it with a sustainable yield of 1,800 ac-ft/yr, exclusive of other users. SCWD has produced more than this amount for more than half of all years since 1985–recently by as much as 400 ac-ft/yr. As with the Purisima area, SCWD is vulnerable to increased pumping by others, which would effectively lower its estimated sustainable yield.

Our review of coastal groundwater levels, groundwater pumping, and saltwater intrusion allows us to independently consider the potential benefits of reducing groundwater production in the Aromas area by several hundred acre-feet per year. Based on an inspection of the hydrograph and pumping records presented in Section 4.2.4, reducing the Seascape well's production by at least 100 ac-ft/yr, and reducing the combined production of the Country Club, Bonita, and San Andreas wells by another 100 ac-ft/yr or more, may be necessary to halt the saltwater encroachment occurring at SC-A2. Although pumping from SCWD's two southeastern-most wells, Altivo and Sells, has already been reduced due to elevated chromium, their continued use remains problematic given their proximity to the coast, the ongoing encroachment of the saltwater interface at SC-A3 and SC-A4, and their proximity to still worsening conditions in Pajaro Valley. Until measures to correct Pajaro Valley overdraft become effective, it may be reasonable for SCWD to consider a combined pumping reduction of another 100 ac-ft/yr or more, meaning that these two wells might barely operate. These rough estimates sum to at least 300 ac-ft/yr of pumping reductions. As with the Purisima area, we are more concerned that this amount may be too low than too high. Finally, SCWD is considering the restoration of its Aptos Jr. High School well. This well is located favorably inland and in the northern Aromas area. Its use could offset another 100 ac-ft/yr of production from SCWD's other Aromas-area wells. Based on these rough estimates, it seems reasonable that SCWD's sustainable Aromas production does not exceed 1,800 ac-ft/yr and is probably somewhat less.

***Overall*** – These highly approximate estimates suggest that a supplemental water supply of more than 700 ac-ft/yr, combined with the redistribution of 100 ac-ft/yr of pumping to a reactivated Aptos Jr.

High School well, are needed to reduce SCWD's Purisima and Aromas pumping to less than 3,000 and 1,800 ac-ft/yr, respectively (assuming a total current demand of 5,500 ac-ft/yr). If coastal groundwater levels do not rise to satisfactory levels, or if other pumpers increase their production, greater reductions may be necessary. Meanwhile, more detailed analysis and groundwater modeling may provide improved estimates of target groundwater levels, sustainable production levels, and necessary pumping reductions.

### 8.3.2 Groundwater-Level Objectives

SCWD needs to establish preliminary groundwater-level objectives for all coastal monitoring wells, and then modify these over time based on new information and additional analysis. Relevant factors for estimating these goals include aquifer depth, thickness, structure, and hydraulic properties; the degree of aquifer confinement; potential interactions among multiple aquifer and aquitard layers; distances from the coast and seafloor outcrops; proximity to production wells; relations among historical water levels, gradients, pumping, and saltwater-intrusion indicators; application of the Ghyben-Herzberg relation; estimated or known locations of the saltwater interface; and the results of groundwater modeling.

Establishing such targets is relatively straightforward in the Aromas area given documented relations between water levels, pumping, and evidence of intrusion. Furthermore, the Ghyben-Herzberg relation seems reasonably applicable given that the Aromas Sands are fairly homogeneous (although not isotropic). This also may be the case for shallow portions of the Purisima Formation, such as aquifer DEF where the Hillcrest and Seacliff wells once operated.

Establishing groundwater-level objectives for deeper portions of the Purisima Formation is more difficult because of the strong anisotropy of the layered aquifers and uncertain and/or weak evidence of past or ongoing intrusion. While preliminary objectives can be established, it may be necessary to rely on groundwater modeling to finalize these goals, including the allowable time that water levels may fluctuate below target levels (e.g., during interruptions in the supplemental supply).

The monitored success of these objectives and the pumping modifications required to achieve them will eventually provide the ultimate indication of sustainable aquifer yield.

### 8.3.3 Restoring the Groundwater Resource

The intention of the water-level objectives is to achieve the hydraulic gradients needed to prevent saltwater intrusion. At suitable pumping rates, water levels will gradually reach an equilibrium consistent with these goals. Under leaky aquifer conditions, these goals may be achieved fairly quickly. However, under fully confined conditions, the desired water-level recovery may be slow, lengthening the period at risk to intrusion. In such cases, it may be desirable to implement larger initial reductions in pumpage in order to more quickly achieve these goals. Similarly, larger initial reductions in pumpage may be appropriate in the Aromas area where an alarming rate of intrusion poses a serious threat to continued SCWD production. In either case, larger (e.g., twice as large) initial pumping reductions can provide valuable verification of suitable cause-and-effect relations between pumping and the desired water-level recovery, as well as indicate opportunities to modify pumping rates up or down as appropriate. This management approach will undoubtedly involve an element of trial-and-error over some period of time.

SCWD intends to secure a supplemental supply of 2,000 ac-ft/yr, of which about half may be needed to correct existing overdraft, while the remainder is intended for increased future demands. As such, a suitable quantity of additional supplemental supply should be available for larger initial pumping reductions, as appropriate. Because the supplemental supply will have a significantly greater cost than the groundwater production it replaces, decisions regarding initial pumping reductions will require careful analysis. Fortunately, the successful implementation of SCWD's planned conservation measures may temporarily reduce the need for supplemental water by as much as 300 to 400 ac-ft/yr as of 2010 (Figure 8-1).

Restoring the groundwater resource could include pushing the freshwater-saltwater interface back from shore rather than simply preventing further onshore movement. However, to push the interface offshore as quickly as it migrated onshore requires an equal but opposite hydraulic gradient. The feasibility of doing so varies as a function of how low water levels had been versus how high they can be raised relative to sea level. Groundwater levels influenced by pumping have the potential to be drawn down quite low, whereas there are limits on how high water levels can be raised. In the case of the deep Purisima aquifers, for example, depressed coastal water levels have reached –30 ft msl (e.g., SC-9). As a rough estimate, stabilizing the saltwater interface and slowly pushing it back offshore might require raising levels to 5 to 15 ft msl (given the need to compensate for density differences), whereas pushing it back as quickly as it was pulled in might require levels approaching 35 to 45 ft msl, in excess of historical maximums. Offshore storage will increase more slowly than the rate of supplemental water use because of increased groundwater discharge to the ocean. The slow reversal of cation-exchange processes also delays pushing back the interface. The amount of supplemental water needed to agressively push the interface offshore may be prohibitive. This further justifies the need to arrest further onshore movement soon.

Saltwater intrusion in SCWD's southern Aromas area is part of an ongoing regional problem that extends into Pajaro Valley. The eventual implementation of both PVWMA's BMP and SCWD's proposed plans for conjunctive use might be unable to prevent the near-term saltwater degradation of SCWD's southeastern-most wells. SCWD may need to consider additional, more immediate measures, whether on its own or in cooperation with PVWMA, such as facilitating the reduction of other pumping in the Aromas area and adjacent portions of Pajaro Valley.

### 8.3.4 In-Lieu Recharge and Groundwater Storage

The conjunctive use of ground- and surface-water sources typically involves exercising the storage capacity of the groundwater basin. This usually occurs in the form of in-lieu recharge, whereby groundwater production is reduced at times when other sources are available for direct use. The unpumped groundwater accumulates as storage and is then available for later use when other sources are not.

For most SCWD production wells that draw on confined and semi-confined aquifers, the primary result of reduced pumping is a pressure response rather than a significant increase in the volume of groundwater stored onshore. Conjunctive use will result in desirable increases in groundwater levels. However, the reduction in pumping may not translate directly into an equal amount of groundwater saved for later use. This is in part because recharge is induced into the confined and semi-confined zones by the vertical gradients caused by pumping. When pumping is reduced there is less leakage into the production zones, such that shallow groundwater may instead migrate toward other points of discharge such as streams and the ocean. Groundwater storage may build up in the interior upland portions of the basin, but its connectivity and significance to the production aquifers is poorly understood.

Onshore groundwater storage is probably a more important factor for conjunctive use in the Aromas area, where unconfined zones are thicker and more widespread. A significant capacity for groundwater storage may occur between the existing depressed water table and the bottom of stream channels. Additional inland monitoring wells and groundwater modeling could help evaluate this potential.

Supplemental water used at the rate needed to achieve groundwater-level objectives will gradually push the freshwater-saltwater interface further offshore. On a long-term average basis, this may replenish the offshore storage enough to allow increased groundwater production during droughts (i.e., a temporary relaxation of groundwater-level objectives). However, offshore storage will increase more slowly than the rate of supplemental water use because of increased groundwater discharge to the ocean. Because the current position of the interface is unknown except in the southern Aromas area, reliance on offshore storage during droughts may be risky until after many years of supplemental water use and sustained achievement of groundwater level objectives.

An alternative, less conservative approach would involve some continued use of remaining offshore storage until the earliest definitive signs of saltwater intrusion become manifest. It is possible that a significant storage volume remains offshore of the Purisima and far northern Aromas areas. Once detected, a known interface location and potential problems with brackish water could then be managed using supplemental water and pumping adjustments. Given that SCWD does not fully control groundwater pumping, and given considerable uncertainties about future conditions (e.g., climatic change, drought duration and severity, energy costs associated with desalination, availability of other supplemental sources), this alternative seems far from prudent. Furthermore, use of some offshore storage will continue until a supplemental supply is established and operational.

### 8.3.5 Interruptible Supplemental Supplies

The City of Santa Cruz intends to use most or all of its proposed regional desalination plant capacity during limited periods of time coinciding with the most extreme drought conditions. Potential groundwater transfers from Pajaro Valley may be limited at times due to local groundwater conditions, conveyance infrastructure, institutional constraints, or the availability of water for transfer from elsewhere in California. As such, there may be interruptions in the supplemental supplies available to SCWD for conjunctive use. Because the groundwater response to drought conditions appears limited in developed portions of the Soquel-Aptos basin, the effect of these interruptions might not be significantly worse during droughts. Nevertheless, the developed aquifers exhibit limited onshore storage capacities and the storage remaining offshore is unknown. At times when supplemental water is available prior to potential interruptions (e.g., the early phase of a drought), SCWD could increase its use so that groundwater levels begin relatively high if and when more intensive pumping becomes necessary. Only a portion of the unpumped groundwater may be retrievable (i.e., effectively stored). As increased future demands claim larger portions of the supplemental supply, SCWD will lose some of its flexibility to reduce pumping in anticipation of supplemental supply interruptions.

### 8.3.6 Enhanced Recharge

The protection and enhancement of groundwater recharge areas can be useful elements of responsible groundwater basin management. Sources of recharge may include precipitation, runoff, applied water, imported water, and/or reclaimed water. Efforts to enhance recharge may successfully augment shallow groundwater supplies and baseflows, but may have a limited effect on deep water levels, which are mainly controlled by pumping. As such, it is an unlikely means of preventing saltwater intrusion in the Purisima area, but may have greater merit in the less confined Aromas area. Additional studies and modeling are needed to evaluate the relative benefits of targeting recharge over particular outcrop areas (e.g., as proposed for the Purisima Formation by URS, 1974) versus broadly distributed recharge enhancements.

### 8.3.7 Groundwater Injection

Groundwater injection has the advantage of introducing water directly into aquifer zones where it is most needed to restore groundwater levels. Water-level responses from injection are quick and predictable. As currently proposed, the direct use of a supplemental water supply and the associated reductions in groundwater production will probably provide sufficient means for attaining water-level objectives. However, at some time in the future the ability to selectively inject supplemental water may provide a valuable added tool for managing groundwater levels and preventing saltwater intrusion. Reasonable application of injection technology for this purpose would be considerably less ambitious than the previous proposal to inject up to 5,000 gpm of diverted Soquel Creek streamflow (Williams, 2004).

### 8.3.8 Beltz Wells

The Beltz wells are 3,800 to 6,000 ft from SCWD's Garnet well. The next closest SCWD wells are more than 9,000 ft from the Beltz wells. The Beltz wells tend to exhibit a leaky aquifer response, which limits their radius of influence. Previous modeling estimated that the 10-year capture zone for the Beltz wells pumping 1,200 ac-ft/yr extended about halfway (~2,000 ft) toward the Garnet well (Figure 8-2; Johnson, 2003). Annual production from the Beltz wells was about this much in 1987 and 1988, but recently has been about a third as much (Figure 4-4a). The simulated capture zone indicates that the Beltz wells are more likely to draw recharge from nearby surface water features (i.e., Rodeo Creek, Moran Lake, Corcoran Lagoon) than from Soquel Creek.

The Beltz wells draw from the same Purisima aquifer unit as many SCWD wells. However, the Beltz wells are not necessarily hydraulically upgradient of SCWD wells. Located near Pleasure Point, the Beltz wells are more than halfway surrounded by Monterey Bay and are relatively distant from inland recharge areas. Ultimately, the existing Beltz wells' proximity to the coast, limited access to areal recharge, and hydraulic connection to local surface water features may be more restrictive to their use and influence than consideration of their potential impacts on SCWD. Nevertheless, the Beltz wells likely contribute to a general decline in groundwater levels east toward SCWD.

Saltwater entering the aquifer as a result of Beltz pumping could eventually migrate down dip toward SCWD's production wells. Production from the Beltz wells probably would be impacted first, in which case curtailed Beltz production would probably prevent the further onshore movement of saltwater into the Purisima-A aquifer near Pleasure Point. The recent installation of additional monitoring wells by the City of Santa Cruz allows for improved management of coastal groundwater levels and early detection of saltwater encroachment into the Purisima-A aquifer off Pleasure Point. Distances between the Garnet well and seafloor exposures of the A aquifer are not substantially different than distances between the Garnet and Beltz wells.

Potential direct impacts to SCWD from operation of the Beltz wells are probably insignificant at recent rates of production (200 to 600 ac-ft/yr). The likelihood of direct impacts increases, however, during critical drought periods. The City plans to produce as much as 2 million gallons per day (mgd) for as many as 200 days per year from it Beltz wells during critical drought years occurring an average of once every 25 years (L. Almond/City of Santa Cruz Water Department, personal communication with R. Duncan/SCWD, August 6, 2004). Assuming no pumping during the remainder of such years, this amounts to about 1,200 ac-ft/yr, which is equivalent to historical maximum production.

SCWD and the City of Santa Cruz operate municipal wells in the same local area of the Soquel-Aptos groundwater basin. As such, they together impact the overall water budget and could collectively exceed the local sustainable yield (i.e., cause adverse impacts). Ideally, these two purveyors should establish some collaborative institutional mechanism with which to operate the basin for optimal yield and minimal threat of saltwater intrusion and/or other impacts.

## 8.4 Implications for Environmental Assessment

This report and its referenced data provide the hydrologic understanding and base of information needed for a programmatic EIR of SCWD's plans for conjunctive use. The documented historical conditions span several decades and include a variety of climatic and cultural conditions. One major yet unavoidable gap in our understanding is the uncertain location of the saltwater interface offshore of the Purisima area.

The effects of groundwater pumping on surface water are difficult to quantify because the combined effect of other factors has a collectively greater influence. This limitation is not critical, however, because the proposed conjunctive use will decrease, not increase, pumping, and does not in and of itself involve the redistribution of pumping to new locations.

Given some uncertainty regarding sustainable yield and possible interruptions in supplemental supply, a use-curtailment mitigation measure may be needed in the event that groundwater levels decline and persist at problematic levels at some future time (e.g., as a result of severe drought or the unknown and unprecedented consequences of climatic change).

Development of a suitable groundwater model would be appropriate for a project-specific EIR as well as ongoing groundwater management.

## 8.5 Recommendations

### 8.5.1 Need for Conjunctive Use

The results and conclusions of this study fully support SCWD's proposed development of a supplemental water supply for conjunctive use with its existing groundwater supplies.

In the Aromas portion of the SCWD service area, the freshwater-saltwater interface is actively moving inland and poses a significant threat to future groundwater production. The interface is already onshore and within the depth interval of production well screens. Hydraulic gradients between production wells and the coast are insufficient to prevent further inland movement. This is consistent with an apparent deficit in the local groundwater budget. Water-level and chloride-concentration responses to changes in pumping indicate that intrusion can be impeded locally by reductions and redistribution of SCWD production. Although implementation of PVWMA's BMP was expected to address the problem of overdraft and saltwater intrusion regionally, it appears that SCWD faces a serious threat of lost groundwater production before such measures can be effective. Furthermore, there probably is a local element to the problem that the Pajaro Valley BMP will not resolve. For these reasons, SCWD should reduce production from its Aromas-area wells, especially toward the southeast.

There are no definitive signs of active saltwater intrusion in the Purisima portion of SCWD, although earlier intrusions into shallow zones are well documented and subtle indications exist of possible saltwater leakage into deeper zones. The persistence of deep-aquifer groundwater levels at or below sea level along the coast represents a significant potential for eventual saltwater intrusion. Once saltwater is detected, efforts to remediate the aquifer will be slow. A supplemental water supply is needed to reduce pumping and restore the hydraulic gradients necessary to prevent saltwater intrusion into the Purisima aquifer.

### 8.5.2 Supplemental Water Needs

Additional analysis, and probably the use of a calibrated groundwater model, are needed to better estimate the required amounts of supplemental water. This is because several factors obscure clear-cut relationships between pumping and water levels, as discussed at the conclusion of Section 4. The experience gained from restoring groundwater levels and monitoring intrusion indicators will provide the ultimate indication of needed supplemental water. For planning purposes, it is reasonable to assume that about half of the proposed 2,000 ac-ft/yr of supplemental supply will be needed to reestablish the hydraulic gradients necessary to prevent further intrusion. In the near term (i.e., before increased demands for water), a margin of safety and the opportunity to restore groundwater levels more quickly are provided by the remaining supplemental supply and the anticipated water savings from conservation measures.

The alternative to enhance groundwater recharge does not constitute conjunctive use because it would not provide SCWD with the flexibility to adjust pumping, when and where needed, to achieve groundwater-level objectives. Regarding the Soquel Creek diversion alternative, there is significant uncertainty regarding its potential yield given possible year-to-year changes in fish bypass flow requirements (Entrix, 2004). These two alternatives are not currently under consideration as supplemental water supplies.

Based on available information, the two alternatives still under consideration–a regional desalination facility and groundwater transfers from Pajaro Valley–represent roughly equivalent sources of supplemental supply. In either case, possible supply interruptions and/or severe climatic conditions may require water-use curtailment in the event that groundwater levels decline and persist at problematic levels.

### 8.5.3 Additional Data Needs

The data needs discussed below came to light during preparation of this report. They are presented as preliminary technical concepts and are not prioritized nor evaluated in terms of costs and benefits.

1. SCWD provided the project team with paper copies of pre-1990 groundwater levels and groundwater quality data that we entered into spreadsheets for the analysis presented in Section 4. SCWD may wish to have the entered data checked for errors and added to their existing groundwater database.
2. Our understanding of the relationship between groundwater levels and pumping could be improved if pre-1984 pumping records (by well) were added to the database from SCWD's paper copy records.
3. The influence on groundwater levels by the pumping cycles of both near and distant wells and daily tides could be better understood through the use of data loggers in selected wells for limited periods. Without this understanding, these influences add significant "noise" to the monthly water level measurements.
4. The project team did not locate data for the 1987 aquifer tests of the Seascape and Sells wells. These tests benefited from having two observation wells each, which allows for reliable estimates of the storage coefficient and vertical hydraulic conductivity. These test data should be reanalyzed using a variety of solution methods. There are significant limitations associated with the Jacob-Cooper method, believed to have been used in the original analyses.
5. Instances when wells are shut down for a period of time provide opportunities to conduct aquifer tests when pumping resumes. Of particular interest are production wells with nearby wells that may be used as observation wells. Such data allow for reliable estimates of the storage coefficient and vertical hydraulic conductivity. Estimates of these parameters are needed for groundwater modeling. Wells with nearby observation wells that have not been tested in this way include: Tannery (Maplethorpe); Estates (SC-16); Madeline (SC-14); Ledyard (SC-17); and T. Hopkins (SC-17 and Aptos Creek) (also Seascape [SC-A5] and Sells [Altivo] if the 1987 test data are unavailable for reanalysis).

6. Wells with long or multiple screened intervals derive an uncertain percentage of their yield from each screened aquifer. Spinner logs provide the data needed to resolve these uncertainties. For example, a spinner log of the Main Street well could help evaluate the proportion of well yield coming from the older deep sandstone versus the Purisima AA unit. Other candidates for spinner logging include the Rosedale well (Purisima A vs. AA), the Estates well (Purisima BC vs. A), Aptos Creek (Purisima DEF vs. BC), and all of the Aromas-area wells (lower Aromas vs. Purisima F).

7. The USGS has performed age dating on groundwater samples from Pajaro Valley and used these results to help interpret groundwater recharge and saltwater intrusion (Hanson, 2003). Similar data would be very useful for helping to understand recharge and saltwater intrusion in the Soquel-Aptos basin; e.g., indicating which aquifers are recharged by local leakage versus groundwater flow downdip from distant outcrops; the degree to which saline water encountered at depth in the Aromas area results from recent intrusion.

8. Groundwater discharge to streams (i.e., baseflows) is poorly documented in many parts of the study area (e.g., Rodeo Gulch, Tannery/Porter Gulch, upper Harkins Slough, and other minor washes along the coastal margin). Seasonal reconaissances of these streams could help refine baseflow estimates used in the groundwater mass balance.

9. Concepts for new monitoring wells include the following:

   - A monitoring well approximately midway between the Garnet well and Beltz 8 might be useful for evaluating the possible influence of the Beltz wellfield on groundwater levels within SCWD (e.g., near the intersection of 41st Avenue and Bromer).

   - A monitoring well cluster between SC-A1 and SC-A2 would help document the potential northward movement of the saltwater interface already observed at SC-A2. This would provide an early warning of the potential threat of intrusion to the Country Club well.

   - LSCE (2004) recommended two new monitoring well clusters to provide better evaluation of groundwater flow conditions between SCWD's Aromas area and the adjacent Pajaro Valley. They stated that the more important location was southeast of SC-A3 and inland of SC-A4. Their other recommended location was inland between the Altivo and Seascape wells. We agree that additional monitoring is needed in this area for the reason stated. An additional or alternative location might be east or east-northeast of the Altivo and Sells wells.

   - Inland monitoring wells located away from streams could help document changes in groundwater storage (i.e., the water table) away from the coastal terrace and SCWD production wells. Possible locations 2,000 to 3,000 ft north of Soquel Drive might include the following: between Rodeo Gulch and Soquel Creek; between Soquel and Nobel creeks; between Nobel and Bates creeks and Porter Gulch; between Tannery Gulch and Borregas and Aptos creeks; between Mangels and Trout gulches; and between Valencia Creek and Freedom Boulevard. Further to the southeast, possible locations about 2,000 ft inland of State Route 1 might include between Freedom Boulevard and the inland extension of San Andreas Road; and, near the intersection of White and Larkin Valley roads. The value of the information provided by such wells is uncertain, and thus any effort to establish these wells should proceed in a stepwise fashion.

10. We are not aware of any practical method for measuring the offshore location of the freshwater-saltwater interface. However, innovative methods may arise in the future and could be applied to help estimate the interface location and volume of offshore storage from Pleasure Point to Seascape.

### 8.5.4 Additional Analysis and Modeling

Continued expert analysis and the development of one or more analytical tools are needed to further assess the conditions under which saltwater intrusion is likely to occur along the Soquel-Aptos coast. This analysis must establish the groundwater-level objectives needed to prevent intrusion, the pumping reductions needed to achieve these levels, and the corresponding sustainable yields of the basin subareas. This report has assessed the intrusion risks, confirmed the need for supplemental water, and provided rough estimates of sustainable yield. Moreover, it provides the foundation of understanding upon which to base subsequent analysis and develop and/or refine needed analytical tools.

Preliminary groundwater-level objectives for the prevention of saltwater intrusion can be derived from an expert analysis of relevant factors. These factors include aquifer depth, thickness, structure, and hydraulic properties; the degree of aquifer confinement; potential interactions among multiple aquifer and aquitard layers; distances from the coast and seafloor outcrops; proximity to production wells; relations among historical water levels, gradients, pumping, and saltwater-intrusion indicators; application of the Ghyben-Herzberg relation; and, estimated or known locations of the saltwater interface.

However, the complexity of the groundwater system hinders the expert consideration of these multiple factors. For example, an empirical relationship between pumping and water levels must consider the influence of near and distant wells, shallow and deep wells, recent and past pumping, and head-dependent boundaries such as leaky aquitards, streams, and the ocean.

One approach is to subdivide the coastline into a number of segments, e.g., one for each coastal monitoring well. The salient features of each segment can be generalized by a local conceptual model, which in turn can support the development of a relatively simple numerical model for each segment. These models would then used to provide improved estimates of the groundwater-level goals for each segment of coastline.

Another approach is to use a calibrated numerical model of the entire Soquel-Aptos flow system, or possibly two separate models, one each for the Purisima and Aromas areas. This approach has the advantage of full three-dimensional representation of the aquifer system, its groundwater mass balance, the influence of head-dependent boundaries, and the spatial and temporal variations of hydraulic stresses.

SCWD is currently updating the numerical code of its IGSM model. The assumptions underlying the IGSM model need to be evaluated relative to this conceptual model. Also, the capabilities of the model should be assessed relative to SCWD's modeling needs. That evaluation may conclude that further modifications of the model are warranted. Alternatively, there may be some efficiency in developing a new model on the basis of this conceptual model and the experience gained from the IGSM.

As mentioned previously in this report, potential uses for a calibrated model include the following:

- Predicting water level responses to pumping, assessing the risks of saltwater intrusion, and evaluating sustainable yield.
- Estimating the length of time that groundwater levels may fluctuate below target levels without causing significant risk of saltwater intrusion (i.e., utilizing groundwater storage in the coastal zone during interruptions in supplemental supply).

- Evaluating potential groundwater impacts from the City of Santa Cruz's planned use of its Beltz wells during future droughts.
- Guide the preparation of groundwater-level contour maps by accounting for multiple aquifer zones, averaging the effects of daily pumping cycles, and providing consistent water-level estimates in areas with little data.
- Using reverse particle tracking to evaluate the source of groundwater flow to each well (e.g., leakage across aquifer layers versus lateral flow from aquifer outcrops).
- Using forward particle tracking to evaluate the fate of enhanced recharge (i.e., the proportion that contributes to baseflow versus wells).
- Provide a means for performing the analyses needed for project-specific EIRs.

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## Appendix A

# Evaluation of Previous Stream-Aquifer Interaction Investigations

This appendix presents a detailed review and critique of 29 previous efforts to evaluate changes in baseflow and the effects of factors that influence baseflow, especially groundwater pumping. The initial objective of the review was to clearly identify and summarize what we do and do not know about stream-aquifer interactions and historical baseflow patterns in the Soquel area. By examining the assumptions, data, and analysis of each investigation, it was possible to draw appropriate conclusions that reconciled some of the apparent discrepancies among the studies. This process led to the formulation of the conceptual model of the stream-aquifer system described in Section 7. This review comments on the consistency of the data sets and prior analyses with our conceptual model.

The previous investigations represent a large body of good analysis by competent hydrologists. This review was conducted with the benefit of hindsight and familiarity with all of the studies completed through 2003, which the investigators obviously did not enjoy at the time of their studies. Consequently, what may now appear to be weaknesses of a particular study may simply reflect the state of knowledge at the time it was done. The emphasis of the review was on whether the investigator's conclusions were logically supported by the data and analysis. It was intended to be rigorous, which is essential to achieving a useful synthesis of the previous studies. Also, many of the investigations had narrower purposes than achieving the broad understanding sought by the present review. To build a complete picture of the stream-aquifer system, the review frequently points out factors that were not considered or conclusions that were not explicitly stated in individual studies.

The previous studies are grouped below by method of analysis and arranged chronologically within each group. This organization facilitates a point-by-point comparison among different studies that used the same technique and also shows the evolution of thought as new data were obtained. Each evaluated analysis is numbered sequentially so that comments relevant to multiple analyses can be cross-referenced rather than repeated in full. Complete citations for the referenced work are provided in Section 9. To facilitate navigating through the reviews, the groupings and associated analyses are as follows:

1. Hydrogeology of creek alluvium and Purisima Formation (Analyses 1-2)
2. Aquifer test of a well near the creek (Analyses 3-4)
3. Comparison of stream and ground-water elevations along the length of the creek (Analyses 5-7)
4. Mapping small streamflow gains and losses along the length of the creek (Analyses 8-10)
5. Well versus stream water quality (Analysis 11)
6. Correlation between streamflow fluctuations and possible causative factors (Analyses 12-14)
7. Correlation between groundwater fluctuations and possible causative factors (Analyses 15-16)
8. Comparison of baseflow trends with other streams unaffected by pumping (Analyses 17-19)
9. Comparison of Soquel Creek baseflow and rainfall averages for different periods (Analyses 20-21)
10. Changes in the frequency distribution of low flows over time (Analyses 22-25)
11. Baseflow recession patterns (Analysis 26)
12. Precipitation-runoff modeling (Analyses 27-29)
13. Groundwater modeling (Analyses 30-31)

## 1. Hydrogeology of Creek Alluvium and Purisima Formation

***Concept and Methods –*** The layering and texture of the alluvium and underlying Purisima Formation along Soquel Creek may include fine-grained layers capable of greatly impeding flow between the creek and the alluvium or between the alluvium and the Purisima Formation. Borehole geologic and geophysical logs are used to investigate layering.

***Inherent Limitations –*** Borehole geology is not a direct measure of pumping effects on baseflow. At best, it can only be used to infer vertical permeability at a point. Vertical flow is governed by permeability over a wide area and also by the hydraulic gradient.

### *Analysis 1: Todd Engineers (2001)*

*Method* – Todd developed a geologic cross section between the O'Neill Ranch test hole and Main Street well, using e-logs for both wells.

*Results* – The formation materials were divided into two categories (relatively high and relatively low hydraulic conductivity), and these alternated in a tilted layer-cake of perfectly continuous layers of constant thickness. The thickest low-permeability layer is above the screen of the Main Street well.

*Conclusion* – "A direct hydraulic connection between the proposed production well and Soquel/Rodeo Gulch Creeks is not apparent."

*Limitations and Comments* – An inherent limitation of this type of analysis is the assumption that fine-grained layers are continuous over hundreds of acres based on borehole logs that sample a few square ft. Discontinuities caused by erosional periods, incision by ancient streams, or textural variations associated with lateral facies changes are not uncommon in many depositional environments, and these can create pathways for significant amounts of leakage.

### *Analysis 2: Balance Hydrologics (2003)*

*Method* – Reviewed previous geologic investigations (LSCE, 1991; Todd Engineers, 2001; Johnson, 2001b) and well logs near the creek.

*Conclusion* – Hydraulic connection between alluvium and Purisima Formation generally exists along the main stem of Soquel Creek except where locally diminished by silt or clay layers at the contact.

*Limitations and Comments* – Available borehole stratigraphic data are sparse, but the conclusion is reasonable and would not likely be disputed by any of the hydrogeologists who have studied the area.

## 2. Aquifer Test of a Well Near the Creek

***Concept and Methods –*** Look for break in slope (recharge boundary) or gradual deflection (leakiness) in a plot of drawdown versus time at an observation well near the pumping well. Also measure streamflow upstream and downstream of the well before and during the test.

***Inherent Limitations –*** The short duration of typical aquifer tests (1-3 days) may fail to detect gradual leakage at a steady rate over periods of years to decades.

### *Analysis 3: LSCE (1991)*

*Method* – LSCE conducted an 8-hr pumping test of the newly completed Main Street well in 1986 and a 72-hr pumping test of the same well in 1991. Water levels were measured in two monitoring wells located about 39 ft from the pumping well: well SC-18AA perforated opposite the lower half of the production well screen, and well SC-18A perforated opposite the upper half.

*Results* – Semi-log drawdown plots for the 8-hr test showed no deflections that would indicate the presence of a recharge boundary (i.e., the creek). For the 72-hr test, the drawdown plot for the shallower monitoring well exhibited a flattening of the slope, which normally indicates a leaky or recharge boundary. Applying an equation that assumes horizontal flow, LSCE calculated a distance of 1,600 ft to the recharge boundary, whereas Soquel Creek is only 195 ft from the well.

*Conclusions:*

1. The apparent recharge observed in well 18A after nearly one day of pumping "is probably some delayed leakage from shallower portions of the Purisima sandstone at the Main Street site."
2. "Given that typical District pumping cycles are shorter than the time in which vertical leakage was apparent, the direct effects of pumping on shallower water levels are not routinely occurring."

*Limitations and Comments:*

1. The formula for calculating distance to a recharge boundary assumes a homogeneous, unlayered aquifer system, which is not the case. This two-dimensional analysis is of questionable applicability to the very three-dimensional flow system near the Main Street well.
2. The absence of observable leakage during a single pumping cycle does not mean that cumulative, chronic drawdown caused by repeated pumping cycles will not induce leakage. Groundwater levels do not fully recover between pumping cycles, and the long-term drawdown corresponds to the time-averaged pumping rate. Aquitard storage absorbs short-term drawdown effects, attenuating them into a chronic downward hydraulic gradient from the shallow aquifers (and the creek) to the deep aquifers pumped by the well. The accuracy of the conclusion hinges on the meaning of the phrase "direct effects", which is ambiguous. If it means that high-frequency water-level fluctuations do not propagate rapidly up to shallow aquifers, the conclusion is correct. If it means that deep pumping has no effect on shallow aquifers, the conclusion is incorrect or at least unsubstantiated.
3. The study did not identify the source of water pumped by the Main Street well. The analysis appears to conclude that the source is neither long-term storage depletion nor baseflow depletion. The only remaining source is intercepted ocean outflow, but it is hydrogeologically improbable that SCWD's wells would be hydraulically isolated from the creek and adjacent alluvial aquifer. It also remains to be demonstrated that precipitation recharge on the surface outcrops of the pumped aquifers—wherever they are—is sufficient to supply the thousands of acre-feet per year pumped by SCWD.

***Analysis 4: Todd Engineers (2001)***

*Method* – Todd reinterpreted the drawdown curve for well SC-18A from LSCE's 1991 aquifer test (see Analysis 3, above).

*Conclusion* – The drawdown "fluctuations" toward the end of the test were caused by variations in pumping rate rather than leakage. "Therefore, the pumping test conducted on the Main Street production well does not indicate a direct connection between pumping of the well and the stream during 72 hours of pumping."

*Limitations and Comments:*

1. As with the LSCE (1991) report, the term "direct" is ambiguous. At a minimum, use of the qualifiers "direct" and "during 72 hours of pumping" in Todd's conclusion suggests an unwillingness to further conclude that downward head gradients caused by repeated pumping cycles over months and years would also have no effect on the creek.
2. Johnson (2001b) also reanalyzed the 1991 aquifer test data and found that the Hantush-Jacob solution for leaky aquifers best fit the data. He also noted that the data began departing from a confined drawdown pattern after only 200 minutes of pumping, in contrast to the 1,300 minutes asserted by LSCE (1991). The earlier departure means that measurable leakage would commence during the course of each normal pumping cycle.
3. Yet another analysis of the 1991 aquifer test data is described in Section 3 of this technical memorandum. The purpose of the reanalysis was to obtain estimates for a more complete set of aquifer parameters. This exercise also confirmed that drawdown during the second and third day of the test was clearly departing from a purely confined pattern into a leaky pattern.

4. Daniels (2004) suggested that flow through the gravel pack of the Main Street well could bypass the confining layers in the Purisima Formation and transmit pumping stresses directly to shallow aquifers. The top of the screened interval of the well casing is 180 ft below the ground surface, but the top of the gravel pack is only 60 ft below the ground surface. This hypothesis can be evaluated by applying the Darcy equation to estimate the downward flow of water through the gravel pack, assuming a borehole radius of 1.17 ft, a casing radius of 0.67 ft, a gravel pack hydraulic conductivity of 2,000 ft/day, a groundwater level in the shallow zone adjacent to the top of the gravel pack of 20 ft msl, and static and pumping water levels in the well of –29 and –44 ft msl, respectively. The resulting estimate of gravel pack flow while the well is on is 16 gpm, which is equivalent to 2.1 percent of the total discharge of the well and 3.6 percent of a 1-cfs baseflow in the creek. Flow down the gravel pack decreases when the well is off. The time-averaged flow over the past several years (during which the well was operated an average of 9.3 hours per day) is estimated to be 12 gpm. Thus, it appears that the gravel pack may function as a short-circuit pathway for vertical flow across the Purisima confining layers, but because of the small cross-sectional area and moderate gradient, the flow amounts to only a very small percentage of either the total well production or of baseflow in Soquel Creek.

## 3. Comparison of Stream Elevation and Groundwater Elevation along the Length of the Creek

***Concept and Methods –*** Water-level difference between a stream and nearby wells indicates the direction of seepage between the stream and aquifer.

***Inherent Limitations*** – The hydraulic gradient between the creek and adjacent shallow aquifer indicates only the direction of flow, not the rate of flow. If permeability is very low, seepage rates may be negligible.

***Analysis 5: LSCE (1985b)***

*Method* – LSCE compared water levels in various wells (mostly small private wells) along the main stem reach of Soquel Creek with LKA's measurements of streamflow gains and losses.

*Results* – Groundwater levels were higher than the creek along gaining reaches and lower than the creek along losing reaches, as expected. However, "the differences between streambed and groundwater elevations are not great."

*Conclusions* – "It would appear that there is some groundwater recharge along the creek." However, the generally small difference in water level between the aquifer and the creek, "combined with the permeability of the Purisima Formation, suggests that recharge is not great."

*Limitations and Comments:*

1. The number of wells, well locations, water-level elevations, and corresponding streambed elevations used as the basis for the conclusions were not documented in the two-page letter report.
2. No data are presented regarding the permeability of the Purisima Formation. However, the observation of water levels indicating locally gaining and losing reaches is consistent with the conceptual model.
3. The depths of most of the wells were not known. Consequently, it is not clear whether the groundwater levels represent conditions in the shallow alluvial aquifer adjacent to the creek channel or conditions in deeper Purisima aquifers.

***Analysis 6: LSCE (1998c)***

*Method* – Plotted historical profiles of streambed elevation along the lowermost 3.5 miles of Soquel Creek and groundwater levels from shallow wells near the creek. The groundwater levels were from various dates prior to 1984, and the creekbed profiles were from 1973 and 1986.

*Results* – General relationships between shallow groundwater levels and the creek were clear and constant in spite of substantial differences between the creekbed profiles and a mixing of data from wells of various or unknown depths. Groundwater levels were consistently higher than the creek near monitoring well SC-10 (more than 1 mile upstream of Main Street), lower than the creek near Main Street, and higher than the creek within 1 mile of the coast.

*Conclusion* – "The data suggest that Soquel Creek is a gaining stream near the coast and in the vicinity (and upstream) of SC-10, and a losing stream in the vicinity of SC-18 (Main Street)."

*Limitations and Comments:*

1. Only three data points are shown for the reach downstream of the Main Street well, and well depth is unknown for two of them (data from Bloyd, 1981).
2. The conclusions are consistent with the data.
3. The observed pattern of gaining and losing reaches raises an important question regarding the low groundwater levels near Main Street. All of the data predated construction of the Main Street well, which therefore could not have been responsible for the observed low water levels. Other potential causes include the following:
   a. Pumping by shallow private wells within perhaps a half-mile of Main Street could have lowered the water table elevation in the alluvium.
   b. The dip of the Purisima Formation could have deflected the drawdown of deep production wells upward and westward. If strata tapped by the Rosedale, Maplethorpe, Tannery and Monterey wells happen to intersect the creek alluvium near Main Street, drawdown from those wells could be asymmetrically focused in that area.
   c. The reach of relatively low groundwater levels could have resulted from a transition in permeability where Soquel Creek crosses onto coastal terrace deposits (Brabb, 1997). Although the terrace deposits are not thick, their sandy texture suggests a much higher permeability than the Purisima Formation. The relatively high permeability could rapidly convey groundwater radially over a broad area. This down-valley increase in aquifer transmissivity relative to creekbed permeability could potentially lower the water table at the transition point resulting in the observed losing reach of the creek in that area.

***Analysis 7: LKA and LSCE (2003)***

*Method* – Water-level differences between the creek and six shallow monitoring wells at four sites along the main stem reach of Soquel Creek were measured monthly for 2 years.

*Results* – The direction of the hydraulic gradient remained quite constant over time at all sites, but the magnitude of the gradient varied seasonally. Two wells indicated gaining-stream conditions and three indicated losing-stream conditions. Water levels in a cluster of five wells of different depths at Main Street revealed a continuous downward gradient from the creek to the Main Street production well.

*Conclusions* – "There appears to be a direct hydraulic connection between shallow ground water and surface water in Soquel Creek at all four monitoring sites… There is some leakage from the shallow, unconfined aquifer to deeper, confined aquifers."

*Limitations and Comments:*

1. Part of the downward hydraulic gradient at Main Street predates the Main Street well, but most of the present gradient was probably caused by the well. LSCE and LKA's previous study (1998) documented that water levels in a deep monitoring well (SC-18A) and a nearby private water well were 18–21 ft above sea level prior to construction of the Main Street production well. In August 2002, after 14 years of Main Street well operation, the static water level in SC-18A was 12 ft below sea level. In other words, the total water-level difference between the creek and the monitoring well increased from 3 ft to 36 ft during that period. Given that leakage is proportional to water-level gradient, there presumably was an eleven-fold increase in the leakage rate. However, if the leakage rate was very

small to begin with, the eleven-fold increase might still be only a small percentage of well pumping or baseflow (see "inherent limitations" for this method of analysis, above).

2. The conclusion that shallow groundwater levels are higher than the creek and that the creek gains flow downstream of the Main Street well was based on a single monitoring well (the Nob Hill well), that reportedly might be influenced by unusual site conditions (B. Kraeger/LKA, personal communication with G. Yates).
3. Additional analysis of shallow groundwater levels along the lower end of the creek was completed for the present study using data from existing monitoring wells at groundwater contamination sites. The method and results are described in Section 7.3.

### 4. Mapping Small Streamflow Gains and Losses along the Length of the Creek

***Concept and Methods –*** If pumping induces stream infiltration, this seepage should be detectable as a decrease in surface flow near the well during low-flow periods. Flow is measured at numerous points along the creek while a well is operating. The flow gains or losses between measurement points are compared with the location and pumping rate of the well.

***Inherent Limitations –*** The accuracy of streamflow measurements is at best plus-or-minus about 5 percent. The expected range of potential streamflow depletion by SCWD wells is 0-2 cfs, which means that their impact could not be reliably measured at flows greater than 40 cfs, or possibly less. Fortunately, all of the previous investigations focused their analysis on periods when flows were typically less than 10 cfs.

***Analysis 8: LKA (1986)***

*Method* – LKA measured flow gains and losses along four reaches totaling 5.6 miles of the main stem reach of Soquel Creek upstream of Main Street on two dates in autumn 1984.

*Results* – Measured gains and losses were small (± 0.1 to 0.67 cfs). One reach changed from losing to gaining while the others remained the same.

*Conclusion* – "It appears that there will be little water contributed to groundwater recharge in the length of channel studied."

*Limitations and Comments* – The measured flow gains and losses are within the range that could plausibly be associated with variations in subsurface flow through the alluvium (see Section 7.1, "Inventory of Factors that Potentially Affect Baseflow").

***Analysis 9: Balance Hydrologics (2003)***

*Method* – Balance Hydrologics plotted dry-season hydrographs of the difference in flow between the upper gages (sum of west branch and east branch) and the Main Street gage for each year during 1984-1995.

*Results* – The stream is almost always gaining at the beginning of the dry season (~June 1$^{st}$), even in dry years. During the subsequent 4 months (until October 1$^{st}$), the stream transitions to a smaller gain (in wet years) or losing (dry years). Late-summer gains and losses were usually in the range of –2 to +3 cfs, but were as much as –4 and +4 cfs.

*Conclusions* – The investigators listed several mechanisms as possible causes of the differences between years: (1) annual precipitation, (2) variations in timing and location of direct diversions or shallow well pumping, and (3) weather-related variations in riparian ET. They also noticed a correlation between gaining conditions and years of above average precipitation or years "that were immediately preceded by one or two such years."

*Limitations and Discussion:*

1. The net gain or loss in baseflow along the main stem reach changed by 4-6 cfs between the beginning of June and the beginning of September. This change is much greater than total estimated pumping by all private pumpers upstream of Main Street (0.40–0.8 cfs, as explained in Section 7.1). Year-to-year

differences in the magnitude of gain or loss are similarly much larger than total private pumping. Therefore, the seasonal and inter-annual changes in gain and loss rates cannot be primarily attributable to changes in private pumping.

2. The observed patterns of dry-season gains and losses—including the shift over time from gaining to losing conditions—are consistent with the conceptual model of the stream-aquifer system presented in Section 7, which hypothesizes a shallow aquifer system in the upper watershed area that derives most of its recharge from precipitation, and leaks water at a fairly steady rate to deeper aquifers. Precipitation recharge raises the water table above the creek level in winter, causing groundwater to flow from the shallow aquifer into the creek (gaining conditions). The water table declines in summer in the absence of precipitation recharge and in the presence of downward leakage. This decreases the rate of seepage into the creek as the season progresses, and—if the water table falls below the level of the creek—reverses the direction of seepage (losing conditions). Note that the creek can switch from gaining to losing during the summer even in the absence of groundwater pumping or ET. This transition would occur when the recharge flow from the previous wet season decreases to a level smaller than the down-valley transmissivity of the alluvium. The recognition that gaining conditions are affected not only by current-year precipitation but by precipitation during the preceding 1-2 years is an important corroboration of the shallow groundwater storage effect that is central to the conceptual model. However, the investigators did not apply the same storage process to explain 1-2 year lags in baseflow effects associated with dry conditions.

***Analysis 10: Balance Hydrologics (2003)***

*Method* – Flow was recorded flow at 15-minute intervals at four locations between the confluence of the forks of Soquel Creek and Walnut Street during August-October 2001. In summer 2002, flow was measured manually several times at five main stem locations and two tributaries.

*Results* – The upper reach (forks to Whitehead residence) was consistently gaining; the middle reach (Whitehead residence to Main Street) was sometimes gaining and sometimes losing; the lower reach (Main Street to Walnut Street) was consistently losing. In 2002, a fourth reach between Walnut Street and the Nob Hill site below Highway 1 was consistently gaining.

*Conclusions* – The following possible causes of flow gains and losses were listed but not evaluated: (1) shallow well pumping in excess of recharge rates could decrease flow gains or increase flow losses in the creek, (2) periods of increased air temperatures could increase ET-related losses along the reaches, and (3) channel geomorphology may affect baseflow and apparent gains and losses if the streambed is relatively aggraded at one of the measurement locations.

*Limitations and Comments:*

1. The increase in baseflow depletion between Main Street and Walnut Street during the warm spell of September 25-30, 2001 was larger than can be explained by riparian ET or private pumping along that reach. The loss increased by approximately 1 cfs during the period when the reference ET (ETo) at the De Laveaga Park CIMIS station increased by 0.06 inches per day. The reach is only 0.3 mile long, and a riparian corridor 2 miles wide would have been necessary to increase ET losses by 1.0 cfs. The loss along that reach also exceeded the total estimated pumping of all private users throughout the watershed upstream of Main Street (0.4–0.8 cfs) and thus could not have been caused entirely by the small number of private wells along the Main Street–Walnut Street reach. Given the difficulty of accurately gaging small flows (0.8-1.8 cfs), it is possible that the decrease in flow at Walnut Street was overstated as a result of measurement error. The flows during that period were estimated from pressure-transducer measurements of stage converted to flow using a rating curve. Direct physical measurements of flow—which are more accurate—were made on only a few dates.

2. The gains and losses along the measurement reaches were small enough to be caused by variable proportions of surface versus subsurface flow along the length of the creek. However, those proportions would remain quite constant during the course of the dry season and thus could not explain

to observed fluctuations in gain/loss rates over periods of days.

## 5. Well Versus Stream Water Quality

***Concept and Methods –*** If the major-ion composition of well water is different from that of the stream, it may be from a different source.

***Inherent Limitations –*** Water quality changes as water percolates from the creek or land surface through the groundwater system. Dissolution and precipitation of minerals, cation exchange, adsorption, and commingling with older water in the basin deposits can cause the relative and absolute concentrations of individual ions to change. These processes must be considered when drawing conclusions regarding differences in water quality.

### *Analysis 11: LSCE (1991)*

*Method* – LSCE created a trilinear plot of cation and anion compositions for the Main Street well and nearby monitoring wells SC-18AA and SC-18A (screened opposite the bottom and top, respectively, of the Main Street well screen).

*Results* – The ionic composition of the production well was more similar to that of the deep monitoring well than the shallow monitoring well.

*Conclusion* – The production well could not be drawing water down from the creek because that water would have to pass through the horizon monitored by the shallow well en route, in which case the production well quality would be similar to the shallow well quality.

*Limitations and Comments:*

1. The data are insufficient to conclude that groundwater is not moving downward from the creek and shallow aquifers. Both monitoring well screens overlap the depth interval of the production well screen, and the production well presumably draws water from all of the strata in its screened interval. The fact that the quality of the pumped water is more similar to the deep monitoring well than the shallow well simply means that a higher percentage of the flow derives from the deep interval or that the deep water-quality type is present throughout most of the rest of the production well's screened interval (i.e., –290 to –500 ft bgs). It does not mean that the downward flow is zero.

2. The trilinear diagram in this study did not include the quality of creek water. However, a diagram generated several years later by the same investigators (B. Daniels/SCWD, personal communication) did include the composition of creek water, which turned out to be closer than either of the monitoring wells to the composition of water from the Main Street production well. The differences in quality among the wells shows that groundwater quality is variable with depth. As a result of this variability, the similarity in quality between the creek and the production well does not necessarily mean that a significant percentage of the well discharge is creek water that reaches the well screen by some high-permeability pathway. Flow down the gravel pack is one such possible pathway, but hydraulics calculations indicate that it would supply only about 2 percent of the well discharge (see comments on Analysis 4). Another potential pathway that avoids passage through overlying layers is through the dipping aquifer unit from its outcrop recharge area to the well screens at depth.

## 6. Correlation Between Streamflow Fluctuations and Possible Causative Factors

***Concept and Methods 1 –*** Evaluating the magnitude and timing of short-term fluctuations in baseflow may suggest the relative importance of factors that affect it.

### *Analysis 12: Balance Hydrologics (2003)*

*Method* – Flow was gaged at 15-minute intervals at four locations along the main stem of Soquel Creek during August-October 2001. The timing and magnitude of the fluctuations were compared with hourly air temperatures at Corralitos.

*Results* – Diurnal flow fluctuations of 0.5-0.8 cfs paralleled the diurnal temperature fluctuations.

*Conclusions* – The diurnal fluctuations are "likely due to changing shallow aquifer water demands and evapotranspirative water demands from riparian and other vegetation, both closely linked to air temperature." It was noted that pumping from shallow alluvial wells had not been measured.

*Limitations and Comments* – The correlation of diurnal flow and temperature fluctuations is clear. The magnitude of the flow fluctuations is within the plausible range of ET-related streamflow depletion along a 1-2 mile reach upstream of each gaging location (see Section 7.1). The flow fluctuations are too large to be attributable to private well pumping along the creek because (1) most of that pumping is for domestic use, which is not strongly diurnal, and (2) pumping from wells more than a few hundred feet from the creek, or more than a few miles upstream, would cause flow depletions out of phase with depletions by closer wells, which would diminish their combined effect to a magnitude smaller than the observed fluctuations.

***Analysis 13: Balance Hydrologics (2003)***

*Method* – The investigators compared streambed aggradation and degradation with multi-year shifts in baseflow at the Main Street gage.

*Results* – The streambed elevation at Main Street aggraded about 0.5 ft during 1987-1994.

*Conclusion* – The aggradation "may account for periods of flow loss documented in 1989, 1990, 1991 and 1994."

*Limitations and Comments* – See discussion on streambed aggradation and degradation in Section 7.1. Streambed aggradation is not a likely cause of significant changes in measured baseflow over time.

***Concept and Methods 2*** – If there is a strong correlation between annual groundwater production and summer baseflow, pumping is likely a significant factor affecting baseflow.

***Inherent Limitations –*** This method would fail to detect pumping effects if they are much smaller than effects caused by other factors.

***Analysis 14: LSCE and LKA (1998)***

*Method* – The investigators created scatter plots and calculated regression lines of August streamflow versus SCWD annual groundwater production from the Purisima Formation.

*Results* – There was a large amount of scatter in the plot (i.e., low correlation coefficient).

*Conclusion* – "The two data sets are not meaningfully correlated. Conversely, this data does not show an impact on stream baseflow by Soquel Creek Water District at any level."

*Limitations and Comments:*

1. The relationship between pumping and baseflow might have been clearer if the baseflow data had been stratified or normalized by annual precipitation, although normalizing on a year-by-year basis would not reflect multi-year storage effects expected per the conceptual model. Nevertheless, the plot demonstrates that the impact of pumping on baseflow is much smaller than the effects of other factors.

2. The comparison of annual pumping with baseflow in a single month is reasonable. Municipal pumping is relatively constant to begin with, and the attenuation that occurs when drawdown propagates upward through the layered aquifer system results in a fairly constant leakage from the shallow system. This leakage would be expected to increase gradually over years and decades in response to steady long-term increases in groundwater pumping.

## 7. Correlation Between Groundwater Fluctuations and Possible Causative Factors

***Concept and Methods –*** Comparing the timing and magnitude of observed groundwater-level fluctuations with possible causes (e.g., pumping cycles, fluctuations in creek stage, ET) can reveal which cause is dominant.

### *Analysis 15: LSCE and LKA (1998)*

*Method* – The investigators plotted a hydrograph of monthly water levels in monitoring well SC-10 (approximately 1 mile upstream of the Main Street well) during 1984-1997 and compared these elevations to the adjacent creekbed and water surface of Soquel Creek.

*Results* – Water levels in the well showed seasonal fluctuations over a range of about 4 ft and averaged about 8 ft higher than a single measurement of the creek water surface elevation in January 1997 (and 11 ft higher than the creekbed elevation).

*Conclusions* – "It is clear from the hydrograph that the uppermost aquifer is in direct hydraulic connection with the stream at SC-10, and it appears that the reach of Soquel Creek adjacent to SC-10 is a gaining reach."

*Limitations and Comments:*

1. The data included in the analysis are consistent with the conclusions drawn by the investigators but are insufficient to draw strong conclusions. For example, the report failed to note that well SC-10 is at the edge of the alluvium about 1,100 ft from the low-flow channel. If the hydraulic conductivity of the intervening materials is low, groundwater discharge to the creek could be negligible. Or, if a private well were located in the alluvium between SC-10 and the creek, the creek could have been losing water in that area even though the water level in SC-10 was higher than the creek.
2. The generalization that the reach is usually gaining is not fully substantiated in the report because the elevation of the creekbed and creek surface were only measured on a single date, and those elevations were extrapolated as horizontal lines throughout the 1984-1997 period (i.e., implicitly assumed to have remained constant). A stage hydrograph for the Main Street gage could have been superimposed to demonstrate that groundwater fluctuations at SC-10 paralleled stream stage fluctuations, which would provide more convincing evidence of hydraulic connection and continuity of gaining conditions over time. However, the normal range of stage fluctuations is probably much less than 8 ft, and Balance Hydrologics (2003; Figure G-11) has since estimated that the bed elevation along the main stem fluctuated over a range of only about1 ft during 1984-1997. Thus, the conclusion that the reach is always or almost always gaining is probably true.
3. January 1997 was exceptionally wet, so the measured stream stages and groundwater levels might have been unusual. For example, the flood of New Years Day 1997 could have elevated groundwater levels in the alluvium and created a pulse of precipitation recharge on the hillslopes above SC-10 that maintained a high groundwater elevation for several weeks after streamflow receded.

### *Analysis 16: LKA and LSCE (2003)*

*Method* – Water levels in a cluster of wells of different depths at Main Street were monitored with pressure transducers every few minutes during several months of normal well operation, and also during a 72-hr shut-down of the Main Street well.

*Results:*

1. Water levels in a deep monitoring well (SC 18A; screened 180-310 ft below the creekbed) tracked the pumping cycles and water levels in the Main Street well. The next shallowest well was much shallower (SW-1, screened 10-20 ft below the creekbed) and experienced no drawdown during the pumping cycles.
2. When the Main Street well was turned off for 3 days, the water level in SW-1 gradually rose 0.08 ft over 3 days, indicating a leaky connection to the deeper aquifers.
3. Fluctuations of 0-0.02 ft in creek stage over periods of hours did not correlate with fluctuations of 0.08 ft in well SW-1 (120 ft from the creek and screened 10-20 ft below the creekbed).

*Conclusions:*

1. The deep zone pumped by the Main Street well is very confined.
2. The lack of pumping-cycle drawdown in SW-1 “indicates that pumping of the Main Street well, at least in the short term, is not the cause of the losing reach.”

*Limitations and Comments:*

1. All of the data are consistent with the conceptual model presented in this memorandum. Specifically, the lack of short-term (scale of hours) correlation between water levels in deep and shallow wells combined with the small correlation observed over slightly longer time periods (3 days) is the type of response to be expected in a leaky aquifer system, especially for wells of such different depths (160 ft between their screened intervals). The lack of correlation between the tiny, hourly fluctuations in creek stage and shallow well water levels is meaningless, as the intervening aquifer would be expected to attenuate such high-frequency noise to an immeasurably small magnitude.
2. The phrase “at least in the short term” is ambiguous in the same way that the term "direct" was ambiguous in prior investigations of pumping impacts on baseflow (see Analyses 3 and 4, above). Storage effects and low permeability inevitably attenuate short-term drawdown stresses as they propagate through a layered aquifer system. The conclusion ignores the much more important fact of the large and continuous downward head gradient from the creek to the Main Street well. Even when the pump was off, the water levels in the deep aquifers were more than 50 ft lower than the water level in the creek and more than 20 ft below sea level. These water levels can only have been caused by pumping at the Main Street well (with possibly minor contributions from pumping by other deep wells).

## 8. Comparison of Baseflow Trends with Other Streams Unaffected by Pumping

***Concept and Methods –*** The large effects of climate (wet and dry years) on baseflow can be filtered out of the flow data set by comparing relative changes in baseflow trends between two nearby watersheds. Specifically, if baseflow in stream "A" changes from one period of years to a more recent period, while the average remained unchanged in nearby stream "B", then the change in stream "A" must have been caused by something other than climatic conditions. Previous investigators have applied several methods for detecting baseflow trends in paired watersheds: (1) comparing average baseflow during two different time periods, (2) plotting double-mass curves of dry season baseflow, and (3) calculating regression equations relating dry-season baseflow in one stream with dry-season baseflow in the other. Double-mass plots are constructed by calculating the cumulative total of a hydrologic variable (such as stream discharge in August) over a period of many years, then plotting the time series for one stream against the corresponding time series for a reference stream. If hydrologic conditions in both watersheds remain basically unchanged, the resulting curve will be a straight line. If conditions change in one watershed, the curve will have a deflection beginning in the year when the change occurred.

***Universal Limitations –*** Comparing between watersheds introduces new variables into the trend analysis, including: (1) differences in geology and storage response during long droughts, (2) differences in logging, grazing, fire and/or development history, and (3) differences in private well pumping upstream of the respective gages. Also, low flows are intrinsically difficult to gage accurately over extended periods because the stage-discharge relation can be significantly altered by in-channel vegetation, debris jams, or minor changes in bed topography.

### *Analysis 17: LSCE and LKA (1998)*

*Method* – The investigators calculated average baseflow in August and September from gaging records for the West Branch of Soquel Creek and Soquel Creek at Main Street for the periods 1959-1972 and 1984-1996 (the two periods of record for the west branch gage).

*Results* – Average baseflow was lower in the more recent period for both months and both stations. The percentage decrease for the Main Street gage was slightly smaller than for the West Branch gage in August, and slightly higher in September.

*Conclusions* – "Lower flows in the more recent period are due to variability in rainfall and not increased recharge from the stream to the aquifer."

*Limitations and Comments:*

1. Comparing two gages within the same watershed helps to minimize the effects of extraneous factors that can be more significant when comparing between watersheds (geology, precipitation gradients, different fire and development histories, etc.). However, localized factors within the West Branch watershed could potentially cause a large percentage decrease in West Branch baseflow but a smaller percentage decrease in main stem baseflow. Possible local factors include logging, fire, grazing, and residential development. The investigators did not identify or compare any localized factors between the West Branch watershed and the rest of the Soquel Creek watershed.

2. The investigators correctly noted that the West Branch gage would not be significantly influenced by groundwater pumping whereas the Main Street gage is close to shallow and deep wells that could potentially deplete baseflow.

***Analysis 18: Johnson (2001b)***

*Method* – Johnson prepared a double-mass plot of August flow in Soquel Creek at Main Street and the San Lorenzo River at Big Trees for WYs 1951-2000.

*Results* – Johnson pointed out: (1) a slight chronic downward departure beginning in the late 1970s; (2) a "sharply downward" departure during the 1987-1994 drought; (3) no departure during the 1959-1966 drought.

*Conclusions:*

1. There were significant changes in Soquel Creek baseflow conditions.

2. The causes of baseflow depletion are "likely varied."

3. SCWD pumping clearly induces leakage from shallow aquifers near Soquel Creek and "may draw directly from streams."

*Limitations and Comments:*

1. The analysis cites only downward departures, but there were also upward departures in the double-mass plot in the early 1950s, early 1980s, and late 1990s. These compensating bends are evident in Figure A-1, which is the double-mass plot updated through 2002. It shows that the double-mass relationship "recovered" to its previous trend following 1994. If total SCWD groundwater pumping were the cause of baseflow depletion in Soquel Creek, it would have had a gradually increasing effect over the entire period of record and would appear as a continuous downward curvature in the plot. If the Main Street well were a significant cause of streamflow depletion, it would have caused a clear departure from the previous trend beginning in 1988. This is illustrated in Figure A-1 by the curve showing how the cumulative departure graph would look if 100 percent of the Main Street well's August production were derived from baseflow depletion upstream of the Main Street gage. The pattern is clearly distinct from the observed historical pattern. Thus, if the historical data reflect some depletion from operation of the Main Street well, the amount of depletion is much smaller than the total pumping rate of the well.

2. The analysis presented data only for August. Other dry-season months show generally similar patterns but also large anomalies that cast uncertainty on assigning causes to particular deflections in the relationship. For example, Figure A-2 shows a double-mass plot of September flows for the same two stations. There is a conspicuous discontinuity in the relationship between the watersheds that occurred in 1959—larger than the deflections Johnson relied upon for his conclusions. An examination of

streamflow and precipitation records indicates that the discontinuity reflects real differences in the responses of the two watersheds to an unusual large storm in September 1959.

3. No data or analysis were presented to rule out other possible causes of changes in the baseflow relationship (see Section 7.1).

***Analysis 19: Johnson (2001b)***

*Method* – The investigator created a scatter plot and linear regression line relating August flows in Soquel Creek and the San Lorenzo River for WYs 1951-2000 (the same data set used for the double-mass plot in Analysis 18).

*Results* – At the low end of the data range (baseflows of 0-75 ac-ft/month, equivalent to 0-1.2 cfs), Soquel Creek flow was lower relative to the San Lorenzo River for years after 1978 and higher in years prior to 1978.

*Conclusion:*

1. There were significant changes in Soquel Creek baseflow conditions.
2. The causes of baseflow depletion are “likely varied."
3. Although the investigator noted that the causes of the apparent decline in baseflow are "likely varied", the only factor subsequently mentioned was groundwater pumping. The statement regarding this factor was that “the progressive lowering of groundwater levels in the Soquel area, especially since SCWD’s Main Street well began to operate in 1988" is a “significant difference” between the two watersheds.

*Limitations and Comments:*

1. Similar to Jackson (2001), Johnson identified 1978 as the dividing point between unaffected baseflow and impacted baseflow, yet no physical change was identified that commenced around 1978 that would have depleted baseflow. However, all of the low-flow points for the post-1978 period were from the 1987-1994 drought, so it would be equally reasonable to consider any potential causative factors that changed sometime during 1978-1987.
2. If pumping is the cause of the depletion, it should be evident throughout the flow range, not just at low flows (equally visible on the arithmetic scale). As discussed in Section 7.1, the expected maximum potential impact of SCWD pumping from the Purisima A and AA aquifers is on the order of 2 cfs, which is equivalent to 120 ac-ft/month. A pumping impact of this magnitude would have appeared in the scatter plot as a very noticeable downward shift of recent years relative to early years throughout the range of August baseflows. But the plot clearly shows no change in moderate and high August baseflows.
3. SCWD pumping from the A and AA aquifers was actually lower during 1987-1994 than during prior or subsequent periods, which is opposite of the pattern that would cause increased flow depletion during that period. This can be seen in the upper graph in Figure 7-4, which shows annual production from the Main Street well and from all SCWD wells in the Purisima A/AA units during WYs 1966-2002 (no pre-1966 data were available). Although Main Street well production increased during 1987-1994, it continued to increase throughout the 1990s. It should have noticeably lowered the baseflow values for 1995-2000 in the scatter plot, but it did not.
4. The picture emerging from Analyses 18 and 19 is that the exceptionally low flows during the early 1990s do not appear to be manifestations of a long-term trend or abrupt change in the stream-aquifer system but rather a response of the system to an exceptional dry period. Demonstrating the unusual conditions during the 1987-1994 drought requires a systematic comparison of precipitation conditions between that period and prior droughts. In several of his analyses (Analyses 18, 19, and 26), Johnson compared baseflows during 1987-1994 with baseflows during 1959-1966, asserting that the two periods were “roughly comparable.” However, the 1959-1966 and 1987-1994 droughts are not equivalent. The differences can be seen by ranking annual precipitation and annual Soquel Creek

discharge during WYs 1951-2002 and comparing the sequence of years that occurred during each of those droughts. The ranked data are shown in Table 7-2 and are divided into three approximately equal groups designated here as wet, normal and dry years. The 1959-1966 drought had more interspersed normal years (1959, 1962, 1963, and 1965), and the three driest years of the later drought were drier than all but one of the years during 1959-1966. In particular, the driest two-year sequence of the earlier drought (1960-1961) was preceded and followed by two normal-to-wet two-year sequences (1958-1959 and 1962-1963). In contrast, the three driest years of the later drought (1987, 1988, and 1990) had only one intervening normal year (1989), and that year was at the low end of the normal range. Thus, the earlier drought was in fact a much smaller event when measured in terms of intensity times duration. The difference is visually obvious in the plot of cumulative departure of precipitation at Santa Cruz (lower graph in Figure 7-4). Droughts appear as downward trends in the cumulative departure curve and wet periods as upward trends. Droughts that are intense or prolonged appear as large "valleys" in the curve. The 1959-1966 drought was a modest dip in the trend of the curve, whereas the 1987-1994 period is the largest valley in the entire period of record. In other words, the cumulative precipitation deficit during the 1987-1994 drought was clearly much worse than during the 1959-1966 drought. Thus, the lower baseflows during the 1987-1994 drought are not an indication of a trend or change in the system and appear instead to simply reflect the large magnitude of that drought compared to previous ones.

## 9. Comparison of Average Soquel Creek Baseflow and Average Precipitation for Different Periods

***Concept and Methods –*** By comparing average baseflow during hydrologically similar periods of years, changes in baseflow over time may be detectable.

***Inherent Limitations*** – Low flows are difficult to gage accurately, so some apparent changes could simply reflect rating curve errors or minor changes in vegetation or channel shape at the gage.

### *Analysis 20: LSCE and LKA (1998)*

*Method* – The investigators plotted time series of annual precipitation (Santa Cruz and Watsonville) and August baseflow (Soquel and Aptos Creeks). They divided each time series at the midpoint and calculated separate regression lines for the first and second halves of the time series.

*Results* – The regression slopes for precipitation and baseflow did not change consistently from the early to late periods.

*Conclusions* – "Because of the relatively small sample size, it is not possible to draw conclusions from the regressions developed for the data...."

*Limitations and Comments* – A standard test for slope significance (Iman and Conover 1983), confirms that none of the regression slopes was significantly different from zero at a 90 percent confidence level. The large effect of current-year precipitation on baseflow appears to conceal any small trends that might be present from other factors. Some method of normalizing the data to remove the precipitation factor is probably necessary to investigate the effects of less influential factors on baseflow.

### *Analysis 21: Todd Engineers (2001)*

*Method* – The investigators calculated the average July-August baseflow of Soquel Creek at Soquel for the entire 1951-2000 period of record and three pairs of subsets for that period (the paired periods divided the 50-year record at 1975, 1980, and 1990, respectively). Annual precipitation at Santa Cruz was similarly tabulated, and the ratio of baseflow to precipitation (cfs/in) was calculated for each period.

*Results* – The 1971-1990 period had the lowest average July-August baseflow and the lowest ratio of baseflow to precipitation. The 1991-2000 period had the highest values for both of those parameters.

*Conclusion* – The low value for average baseflow during 1976-2000 was attributed to the inclusion of two droughts during that period, and the high average baseflow during 1991-2000 was cited as evidence that baseflow had not experienced a long-term decline. The investigators concluded: “Thus, no significant long-term decline in baseflow is apparent from these stream gaging records.”

*Limitations and Comments:*

1. The arbitrary decadal date windows selected to divide the record into two parts resulted in periods with dissimilar hydrologic conditions, such as the greater number of droughts during the 1976-2000 period. Unless years with similar precipitation amounts are compared, the effects of other factors will likely be masked by the large effects of precipitation. Consequently, the analysis is not adequate to conclude that there has been no change in baseflow.

2. The fact that 1991-2000 had the highest ratio of baseflow to precipitation does not support the conclusion that there has been no long-term decline in baseflow, because that was by far the wettest period evaluated. Wet years create disproportionately large amounts of precipitation recharge (which is what supports stream baseflow) because soil moisture storage must first be replenished before infiltrated precipitation begins generating deep percolation. This is the nonlinear relationship between deep percolation and precipitation described in the conceptual model. Thus, the high ratio of baseflow to precipitation in the 1990s is not indicative of a trend over time but simply a reflection of how the stream-aquifer system functions during wet periods.

## 10. Changes in the Frequency Distribution of Low Flows over Time

***Concept –*** Evaluating the frequency distribution of low flows for different periods of time provides a more complete picture of the baseflow regime than average flows during those periods. The years selected for analysis can be stratified by climatic conditions (e.g., wet, normal, and dry years) to partially control for variability related to precipitation. Two methods can be used to evaluate frequency distributions. The first is to plot complete flow-duration curves, which involves ranking all the daily flows in each analysis period and plotting them against their percentile. The second is to select a small number of specific flow magnitudes (e.g., 0, 1, 2, 3 and 4 cfs) and plot the number of days in each analysis period that flows are less than or equal to those values.

***Inherent Limitations –*** As with all evaluations of low-flow records at gaging stations, those data are vulnerable to significant errors in the stage-discharge rating curve caused by minor changes over time in channel vegetation, debris jams, and bed form.

### *Analysis 22: New analysis for this memorandum*

*Conclusion* – The methods and results of this analysis are described under "Analysis 1" in Section 7.3. The results indicate that the 1987-1994 period stands out as an unusual event but not a trend. Groundwater pumping could not have been the primary cause of low flows during that period because it would have similarly affected prior and subsequent years.

### *Analysis 23: Jackson (2001)*

*Method* – Jackson evaluated low flows in Soquel Creek at Main Street for dry years only, defining dry years as ones that had at least one day of flow less than or equal to 1 cfs. He tabulated and plotted time series bar graphs of the number of days in each dry year that flow was less than selected values.

*Results* – During the 17 identified dry years, zero flow occurred only in 1977, 1988, 1992 and 1994. The number of days of zero flow in 1992 and 1994 (29 and 42 days, respectively) was much larger than the number of days in 1977 and 1988 (8 and 1 day, respectively) in spite of much lower annual precipitation during those earlier dry years.

*Conclusion* – There was a “dramatic jump in the number of days with zero discharge observed in 1992 and 1994 compared to previous dry years.” He also concluded that “the response of the watershed during a drought has changed because there is an abrupt increase in the number of zero discharge days after 1991.”

*Limitations and Comments:*

1. No physical explanation was offered for the change in watershed response to drought, specifically a physical mechanism that could deplete flows only during droughts, and not during other years, and that could abruptly alter the system beginning in 1991. This interpretation is complicated, however, by the October 1989 earthquake's significant impact on baseflows (Figure 5-9). Although Jackson did not explicitly state that the Main Street well was the likely cause of baseflow depletion, that is the implied conclusion given that general topic of his report was the impacts of a proposed new well and that 1991 was shortly after the Main Street well began full production.
2. The conspicuously high incidence of zero-flow days during 1987-1994 is less evident in the frequency of slightly larger flows. This is shown by bar graphs of the number of days each year that flow is less than or equal to 0, 1, 2 and 4 cfs, respectively. The 1976-1977 and 1987-1994 droughts stand out the most in the number of zero-flow days and progressively less at the 1, 2 and 4 cfs thresholds. If general groundwater pumping were the cause of declining baseflow, there should be upward trends evident in all of the graphs consistent with the history of gradually increasing groundwater pumping. But no such trends are evident. If the Main Street well were the primary cause of zero-flow days, then the absence of zero-flow days in 1990 and 1991 (both very dry years with full Main Street well pumping) is unexplained (other than as a residual of increased baseflows following the October 1989 earthquake).
3. Defining dry years on the basis of number of low-flow days precludes an examination of relationships between baseflow, total annual runoff, and annual precipitation. For example, 1962 and 1971 both had days of flow less than 1 cfs even though annual precipitation and annual streamflow were close to average (see Table 7-2). The mechanism causing the large number of low-flow days in those years is unexplained. Conversely, 1960 had low precipitation and low annual discharge but no days of flow less than 1 cfs. Jackson addresses the link between low flows and precipitation in Analysis 28, below.

***Analysis 24: Balance Hydrologics (2003)***

*Method* – The investigators plotted the number of days flow at the Main Street gage on Soquel Creek was less than 2, 4 and 6 cfs for each year during 1952-1999. They also plotted histograms of flow distribution for flows less than 30 cfs in class intervals of 2 cfs (0-2, 2-4, 4-6 cfs etc.). The data were grouped by decade for this analysis.

*Results* – Both graphs showed that:

1. 1952-59 had many fewer days of flow <2 cfs and slightly fewer days of flow from 2-4 cfs than any of the subsequent decades (see Balance Hydrologics' Figure H-8).
2. Baseflows during wet years appear to remain unaffected.
3. A footnote referencing Appendix D-2 stated: “A similar figure produced for data collected by the USGS at the Pescadero gage has been included in Appendix D. Note the similar trends between the Soquel and Pescadero gages.”
4. “A key observation for this period is that cumulative precipitation departure conditions in the 1950's were similar to those conditions recorded during the 1976-77 drought and the 1987 to 1994 drought." Also: “Rainfall conditions in the region were reasonably similar during the 1950s, 1960s, 1976-77 drought as well as the 1987-1994 drought."

*Conclusions:*

1. “Dry period baseflows have declined by roughly 2-4 cfs since the 1950s."
2. "The decrease was not gradual (evident in all dry years after the 1950s)."
3. The report listed the following mechanisms as possible factors contributing to the decline in baseflow (no analysis provided):
    a. Droughts and shorter periods of large negative precipitation departures.

b. Increased groundwater pumping over the past 50 years, shallow and deep, along the creek and in Purisima recharge areas.
c. Gradual lowering of regional potentiometric surfaces along the creek.
d. Aggraded channel conditions during 1988-1994.
e. Lingering effects of droughts prior to 1952.
f. Fires and regrowth of upland forest vegetation.
g. Increased ET losses as in-channel vegetation grew back after 1955 flood.

*Limitations and Comments:*

1. The decadal periods used for comparison were not climatically equivalent. The grouping of years by decade biased the results because there were no dry years (on an annual streamflow basis) during 1952-1959, whereas subsequent decades all had at least 3 years in the dry category (see Table 7-2).
2. As a result of the decadal grouping, there were almost no days of flow less than 2 cfs during 1952-1999 and consequently there appeared to be a sudden change beginning in 1960 (see Balance Hydrologics Figure H-8). Some of the potential causative factors listed by the investigators could cause abrupt shifts in baseflow conditions (e.g., fires or a flood event causing channel aggradation or degradation), but no such changes were documented around 1960, and in any case those changes would be expected to gradually shift back to the prior condition over a couple of decades. Most of the potential causative factors—including groundwater pumping—typically change gradually and would cause a gradual increase in baseflow depletion, not a step increase.
3. The similar pattern in Pescadero Creek rules out SCWD pumping as a primary cause of the observed variations in baseflow and supports a more regional factor such as precipitation.
4. The statement that "cumulative rainfall departure conditions in the 1950's were similar to those conditions recorded during the 1976-77 drought and the 1987 to 1994 drought" is not supported by the data. As discussed above (see Analysis 19 and Figure 4, or Balance Hydrologics Figure H-14), the magnitudes of the 1976-1977, and especially the 1987-1994, droughts were much larger than the 1959-1966 drought, and only one year of that drought was included in the 1950s data set. The lack of dry years during 1952-1959 was the reason there were very few days of flow less than 2 cfs.

***Analysis 25: New analysis for this memorandum***

*Conclusion* – The method and results for this analysis are described under "Analysis 2" in Section 7.3. The analysis compared the time series of cumulative departure of precipitation with the time series of number of zero-flow days and revealed that zero-flow days have occurred only during the latter parts of the two largest droughts in the period of record for Soquel Creek flow. It was concluded that the conceptual model of the stream-aquifer system—in which baseflow is sustained by discharge from shallow aquifers that can accumulate storage increases and decreases over multi-year wet and dry periods—is sufficient to explain the observed occurrence of zero-flow days in Soquel Creek.

## 11. Baseflow Recession Patterns

***Concept and Methods*** – The rate of dry-season baseflow recession could be a fairly sensitive indicator of pumping-related streamflow depletion. Comparing recession rates among various periods of years would reveal whether recession rates have changed over time.

***Inherent limitations*** – Baseflow magnitude is strongly influence by annual precipitation, and a comparison among different years could lead to incorrect conclusions unless those years were climatically similar. Also, baseflow recession is affected by numerous factors including those that also affect precipitation recharge. Thus, correctly identifying the cause of a change in recession rate may be difficult.

***Analysis 26: Johnson (2001b)***

*Method* – Johnson compared average dry-season streamflow recession patterns in Soquel Creek at Main Street for 1959-1966 and 1987-1994, both of which were dry periods. He also compared recession curves for the third and eighth year of each of those periods (1961 vs. 1989 and 1966 vs. 1994).

*Results* – The hydrographs showed that average flows during the later drought between August and October were about 1.4 cfs lower than during the earlier drought. For the single-year comparisons, flows were about 1 cfs lower during those months.

*Conclusions* – There have been significant changes in Soquel Creek baseflow conditions. The causes of the decline in baseflow are "likely varied." However, "groundwater pumping contributes to a cumulative impact on baseflows."

*Limitations and Comments:*

1. As explained in detail in the discussion of Analysis 19, the 1959-1966 and 1987-1994 periods were not climatically similar; the later period was a more severe drought in terms of cumulative precipitation deficit.
2. The text of the report stated that average streamflow recession during 1959-1966 was being compared with average recession during 1987-1994. However, the legend for his Figure 2 indicates that the two wettest years of the earlier drought (1963 and 1965) were omitted from the averaging. These wet years would be expected to have lingering effects on baseflow for the next 1-3 years, according to the current conceptual model, and therefore exerted an upward bias on baseflows during 1964 and 1966 .
3. The report text also asserted that the earlier drought had been preceded by a dry period (1953-1957), while the later drought was preceded by a wet period (1978-1986). The former period omitted 1958, which was the year immediately preceding the first drought and which was the third wettest year in the entire record (see Table 7-2). Consistent with the current conceptual model, one would expect the three years preceding a drought to have the most noticeable lingering effect on baseflow during the drought. In these two cases, average precipitation during WYs 1956-1958 was 37.3 in/yr (123 percent of long-term average), whereas average precipitation during 1984-1986 was considerably lower at 31.6 in/yr (104 percent of long-term average). Thus, based on carry over effects from prior years, one would expect the earlier drought to have higher baseflow.
4. The conclusion regarding the cumulative impact of pumping on baseflow warrants some clarification. A conclusion that groundwater pumping affects baseflow is supported by the studies of hydrogeology and aquifer tests (see Analyses 1-4, including Johnson's analysis of the 1991 Main Street well test) although is not substantiated on the basis of this baseflow analysis alone. The term "cumulative" is used in the sense of a CEQA or NEPA environmental impact analysis, in which the effects of pumping on baseflow are considered as additive to the effects of other factors such as droughts. It is not intended to imply that pumping effects accumulate over time. The conclusion is consistent with the conceptual model, in which baseflow depletion caused by well pumping would be superimposed on baseflow declines caused by precipitation deficits.

## 12. Precipitation-Runoff Modeling

***Concept and Methods –*** Streamflow is strongly affected by precipitation. One of the ways to detect the effects of other factors is to evaluate changes in the relationship between precipitation and runoff. Methods of analysis include scatter plots and regression lines relating annual or seasonal streamflow to annual precipitation, multivariate regression models that relate current-month streamflow to weighted values of precipitation in a series of prior months (also known as the "antecedent precipitation index" method), and distributed-parameter computer models that simulate hydrologic processes such as interception, infiltration, depression storage, direct runoff, soil moisture storage, and interflow over short time intervals at a sub-watershed scale.

### *Analysis 27: LSCE and LKA (1998)*

*Method* – Average August and September baseflow in Soquel Creek at Main Street was plotted against annual precipitation (Santa Cruz and Watsonville precipitation were both tested) for WYs 1953-1996. The dataset was divided at the midpoint of the analysis period, and separate linear regression equations were calculated for 1953-1974 and 1975-1996. A similar analysis was completed for Aptos Creek using the periods 1959-1972 and 1971-1985 (equal halves of its shorter period of record).

*Results* – For Soquel Creek, the regression lines for the later period were lower (shifted downward, with a lower Y-axis intercept) than for the earlier period. Also, the slope was usually steeper, meaning that baseflow was lower for a given amount of annual precipitation during the later period. For Aptos Creek, the relationship was the opposite; baseflow appeared to be greater in the second period for the same amount of precipitation.

*Conclusions* – The investigators noted that dry years during 1975-1996 were generally drier than dry years during 1953-1974. They concluded that “the reduced stream baseflow in the recent years appears to be primarily due to drought conditions and precipitation variability. The data do not indicate any correlation between reduced baseflow and lowered groundwater levels.”

*Limitations and Comments:*

1. The investigators were aware that simply dividing the period of record in half created two periods with substantially different distributions of annual precipitation. They consequently attributed some of the differences between the early and late regression lines to these differences in precipitation. However, they did not attempt to overcome this limitation by normalizing the data, selecting sub-periods with more similar precipitation patterns, or otherwise controlling variability caused by precipitation differences. One would expect the larger number of low-precipitation years during the second half of the Soquel data set, and the inclusion of the two largest droughts in that period, to result in a lower regression line. Furthermore, the differences between Soquel and Aptos creeks is explained by the fact that the second half of the Aptos Creek record ends in 1985, before the largest drought in the period of record. This one drought event could account for all of the observed differences between the four data sets (two periods for each of two creeks).
2. No statistical tests were completed to determine whether the slopes and intercepts of the regression lines for the two periods were significantly different. Because of the large amount of data scatter, it visually appears that some of the regression lines are probably not statistically different at a meaningful significance level.
3. The fact that precipitation has a large effect on baseflow is an insufficient basis to conclude that other factors have little or no effect.

### *Analysis 28: Jackson (2001)*

*Method* – Jackson developed regression models of baseflow in each of three dry-season months (July, August, and September) versus an antecedent precipitation index consisting of weighted averages of precipitation during each month of the preceding wet season, as well as total precipitation for each of the two years before that. Jackson developed separate regression equations for each of the three dry-season months for the 1951-1977 and 1978-2000 periods.

*Results:*

1. For all three months, the regression lines for 1978-2000 had steeper slopes and more negative Y-axis intercepts. This means that in dry years (low values of the precipitation index [X-axis]) baseflow was smaller in 1978-2000 than for a year during 1951-1977 with the same precipitation index. Scatter plots clearly showed the difference between the two periods for dry years.
2. Summer baseflow was found to be significantly correlated with precipitation during each of the preceding winter months (Oct-May) as well as total precipitation for the water year before that.

*Conclusions* – Jackson concluded that "the late-summer discharge at the USGS gauge, Soquel Creek at Soquel, has declined in recent years."

*Limitations and Comments:*

1. Dividing the data set into two periods before and after 1978 is inconsistent with the conclusion from the other analysis in Jackson's report that asserted an abrupt change had occurred beginning in 1991 (see Analysis 23). The lowest points in the regression plot are from the 1987-1994 period, which suggests that the low flows represent the response of the stream-aquifer system to that particular large drought event rather than a long-term trend as suggested by Jackson's two regression periods.
2. Linear regression may be an inappropriate model for comparing the two periods, because the visually-apparent differences are almost exclusively at the low end of the range of data. The regression lines continue upward through the rest of the data, suggesting that changes also occurred in moderate and high baseflows. At high flows, the regression lines cross each other, implying that in wet years baseflow has increased since 1977. The difference in regression slopes stems as much from two wet-year outliers as it does from differences in low flows. The logical effect of pumping-induced streamflow depletion would be two parallel lines, with the 1978-2000 line lower than the 1951-1977 line. This is because drawdown from deep wells reaches shallow aquifers as a diffuse, relatively constant leakage. It is difficult to identify a factor or combination of factors that would increase baseflows in wet years and decrease baseflow in dry years, and no explanation is offered by Jackson. This suggests that the low plotting positions of data points for 1987-1994 reflect exceptional conditions during that drought rather than a permanent shift in the hydrologic system (as implied by the regression approach).
3. The discovery of a correlation between summer baseflow and precipitation as much as 20 months earlier is evidence that shallow groundwater storage buffers baseflow fluctuations over periods of 1-2 years. This explains the lingering effects of droughts or exceptionally wet years, which can noticeably affect baseflow for 1-2 years following the return to normal precipitation conditions.
4. A new effort to correlate baseflow with antecedent precipitation was completed for this investigation and is described in Section 7.3, "New Analyses."

***Analysis 29: Balance Hydrologics (2003)***

*Method* – The investigators plotted total June-August Soquel Creek discharge at Main Street versus annual precipitation at Watsonville and calculated a linear regression line.

*Results* – The plot had a fair amount of scatter ($r^2 = 0.71$), and visual inspection of the points by decade did not reveal an obvious trend over time.

*Conclusions* – The investigators noted that precipitation patterns changed from alternating annual or two-year wet/dry cycles during 1952-1981 to longer multi-year wet/dry cycles since then. No conclusions were drawn regarding long-term trends in the precipitation-baseflow relationship.

*Limitations and Comments:*

1. One of the reasons the decadal data groupings did not exhibit obvious differences is that the 1987-1994 drought was split in half at the boundary between the 1980s and 1990s decades.
2. The 95-percent confidence interval for the precipitation-baseflow regression equation is a span of about 2,000 ac-ft of total discharge during June through August. This is equivalent to a constant flow of 11 cfs. Consequently, effects of pumping that are expected to be less than 2 cfs could easily be lost in the scatter of the data.

## 13. Groundwater Modeling

***Concept and Methods –*** Creeks and rivers are often included in groundwater flow models as head-dependent boundary cells. Seepage to or from the creek is calculated during simulations as part of the solution of the overall system of groundwater flow equations. During calibration, streambed conductance is commonly calibrated so that simulated groundwater levels near the creek match measured water levels and the volume of seepage is consistent with observed streamflow gains and losses, the overall groundwater budget, and groundwater levels near the creek. Thus, groundwater modeling can be a useful tool for identifying gaining and losing reaches, estimating seepage rates, and investigating the effects of pumping on streamflow.

***Inherent Limitations*** – The modeling solution may not be unique. That is, equally good calibration results may be obtainable for various combinations of streambed conductance, aquifer transmissivity, and seepage flux.

### *Analysis 30: Essaid (1991)*

*Method* – Essaid simulated the long-term movement of the saltwater-freshwater interface in the Purisima aquifers using SHARP, a numerical groundwater flow model that simulates the movement of a sharply-defined interface. As a preliminary step, she estimated long-term average basinwide groundwater balances, in which outflow to the ocean equals precipitation minus ET, streamflow, and pumping. She also tabulated similar basinwide budgets from four prior investigations. Precipitation recharge over the watershed was simulated as a uniform leakance-controlled flux.

*Results* – The simulated predevelopment precipitation recharge at the land surface was 12,800 ac-ft/yr, which was close to the average of estimates from prior studies. Of this, 12,000 ac-ft/yr (94 percent) discharged to creeks as baseflow, while only 800 ac-ft/yr discharged directly to the ocean. Simulations of conditions in 1985 showed that 81 percent of basinwide pumping was derived from streamflow depletion while 19 percent was derived from intercepted outflow to the ocean.

*Conclusions* – "Most of the water that has been withdrawn from the basin is derived from captured baseflow and additional induced recharge [from the creek]" .

*Limitations and Comments:*

1. The representation of precipitation recharge by means of a leaky boundary condition is unconventional but consistent with the conceptual model presented in this memorandum. In essence, the boundary condition reflects a shallow groundwater storage unit separate from the deep groundwater flow system that (1) receives inflow from precipitation infiltration at prescribed rates independent of deep groundwater levels and creek elevations, (2) leaks water to deep aquifers across a leaky confining layer, and (3) simultaneously drains to creek channels. It appears that drainage to creeks was assumed to equal the difference between the precipitation recharge rate and the deep leakage rate. Thus, it was not simulated by groundwater flow equations subject to reasonable parameter values.
2. The high proportion of pumping supplied by streamflow depletion appears to be at odds with historical streamflow records, which show little or no depletion by pumping. Other reviewers of the model have noted that the calibrated transmissivity of the Purisima aquifers is much lower than the values indicated by aquifer tests and the measured specific capacities of wells (Todd Engineers, 2001). As a result, the model may simulate too much discharge to streams and too little outflow to the ocean. Because discharge to streams represents a large percentage of the total flux through the system in Essaid's model, pumping disproportionately depletes streamflow rather than ocean outflow. Essaid attributed the apparent discrepancy in transmissivity values to real differences between the average bulk hydraulic conductivity of the entire formation thickness and the higher hydraulic conductivity of the thin, relatively coarse-grained layers that supply most of the water to wells. However, Essaid also acknowledged that "the parameter values obtained by this trial and error process of model calibration are not unique" although they are "constrained on the basis of available hydrologic information." It seems plausible that a different combination of parameters (higher recharge leakance and higher aquifer transmissivity) could have produced an equally acceptable calibration with greater ocean outflow and a greater percentage of well pumping derived from intercepted outflow.

***Analysis 31: Montgomery Watson, Ali Taghavi Associates, and LSCE (1998)***

*Method* – A regional groundwater flow model of the Soquel-Aptos area was developed using the Integrated Ground and Surface Water Model (IGSM). IGSM incorporates numerous aspects of a hydrologic system in addition to groundwater flow, including land use, precipitation runoff, ET, water use, and head-dependent stream-aquifer interaction. The flow domain for the Soquel-Aptos model extended from Santa Cruz to Watsonville and inland to the Zayante and San Andreas Faults. In the Soquel area, Branciforte, Soquel and Aptos Creeks were included in the model. Hydrology was simulated monthly during WYs 1982-1993.

*Results:*

1. In the average annual groundwater balance, discharge to streams was 1.5 times greater than subsurface outflow to the ocean. However, both of these flows were much smaller than groundwater pumping, which consumed 94 percent of the precipitation recharge (including deep percolation of applied irrigation water).
2. Sensitivity analysis showed that simulated outflow to the ocean was quite sensitive to the hydraulic conductivity of the aquifers and to streambed hydraulic conductivity. These parameters strongly influence the proportion of outflow going to creeks versus the ocean.
3. The calibrated hydraulic conductivity of Purisima units AA, A and B were two orders of magnitude smaller than estimates based on well tests. Calibrated conductivity for units C, D, and E ranged from an order of magnitude smaller to an order of magnitude larger than measured values. The relative permeability of the two sets of units in the calibrated model was opposite their relative permeability estimated from well tests.
4. The simulated distribution of gaining and losing reaches along Soquel Creek differed from the measured distribution in some locations, and gains and losses in some reaches appeared too responsive to precipitation events or pumping stresses.
5. The simulated hydrograph of monthly flow at the Main Street gage matched the measured hydrograph reasonably well overall, but seasonal baseflow declines during 1989-1993 were slightly too rapid and large.

*Limitations and Comments:*

1. The IGSM code used for the model has received technical criticism in the past because it solves boundary conditions explicitly based on head values from the previous time step (LaBolle and Fogg, 2001). This can cause incorrect results in systems with extremely nonlinear boundaries or rapid stress changes. However, for typical groundwater basins—and the Soquel-Aptos basin appears to be in this category—the model performs well and gives the same result as other codes.
2. Because IGSM uses a fixed monthly time step, it is incapable of simulating short-term precipitation-runoff processes. These processes are typically nonlinear functions of antecedent soil moisture, depression storage, precipitation intensity, etc. By lumping these processes into monthly averages and relying on calibration to gaged monthly stream discharge, IGSM may not be able to correctly distinguish between relatively rapid precipitation runoff or interflow and baseflow derived from groundwater discharge. Consequently, its ability to simulated the effects of recharge enhancement through modified grazing practices and associated changes in soil permeability is questionable.
3. The excessive baseflow recession during 1989-1993 could have resulted from underestimating the storativity of shallow aquifers in inland areas or overestimating the streambed hydraulic conductivity. The observed baseflow pattern is more consistent with the conceptual model of the stream-aquifer system presented in this memorandum, in which shallow aquifer storage in upland areas plays an important role in attenuating the effects of annual variations in precipitation recharge.
4. Large one-month spikes in simulated flow in the East Branch of Soquel Creek but not in the West

Branch seems unsupported by geologic differences. The investigators offer no explanation. The brief spikes in baseflow suggest that recharge drains from shallow upland aquifers to the creeks too quickly. Similarly, prominent one-month spikes in baseflow depletion during the summers of 1991-1993 along the reach from the confluence to monitoring well SC-10 suggests that the hydraulic connection between wells and the creek is overestimated in that area.

5. The model does not include small coastal drainages, including Arana Gulch, Rodeo Creek Gulch, Escalona Gulch, Tannery Gulch, and several unnamed ravines. These could function as discharge points for shallow groundwater and consequently play an important role in determining the feasibility of increasing groundwater storage through enhanced recharge in developed areas near the coast.

## Summary and Conclusions

The approaches used in the analyses of stream-aquifer interaction reviewed in this appendix can be grouped into three general categories: groundwater flow hydraulics, water quality, and long-term baseflow trends. The analyses using groundwater flow hydraulics collectively lead to the conclusion that groundwater pumping from shallow and deep wells depletes stream baseflow because there is nothing preventing them from doing so. Specifically, the investigations of hydrogeology (Analyses 1 and 2) found no impermeable layers along the bed of Soquel Creek or within the alluvium. Although investigators pointed out the presence of confining layers within the Purisima Formation, none of them suggested that these were perfectly extensive and impermeable. Clay layers impervious to stream percolation would have to also be impervious to precipitation percolation, which would be inconsistent with the lack of overdraft in the deep aquifers. Water-level gradients between the creek and deep aquifers are also downward throughout the coastal area. Although water levels in surficial aquifers downstream of Walnut Avenue are higher than Soquel Creek (Analyses 6 and 7) and contribute to streamflow gains near the coast (Analyses 6, 7 and 9), the downward gradient between the surficial aquifers and deep aquifers causes leakage that intercepts shallow groundwater that would otherwise flow to creeks.

Most of the analyses of drawdown at the Main Street well (Analyses 3 and 4 and Section 3) concluded that prolonged pumping at the well causes leakage and measurable drawdown in nearby shallow monitoring wells. The apparent discrepancy among the investigations as to whether the Main Street well has a "direct" impact on streamflow (i.e., measurable depletion over the duration of a single pumping cycle) appears to stem more from legal semantics than groundwater flow hydraulics. Cyclic pumping of deep wells over many years causes chronic downward hydraulic gradients, which by Darcy's Law, must induce a downward flow of water from the shallow aquifer, and the creek to which it is hydraulically coupled.

Groundwater flow models constitute another means of applying groundwater flow hydraulics to the question of stream-aquifer interaction. In both of the models reviewed here (Analyses 30 and 31), the groundwater flow system was assumed to be hydraulically coupled to local creeks, and groundwater pumping consequently depleted baseflow. Beyond this, not much can be concluded from the models because of unresolved discrepancies between measured and calibrated hydraulic conductivities and vertical water-level gradients.

The one analysis that attempted to elucidate stream-aquifer interactions based on a comparison of water quality types was inconclusive (Analysis 11). Although the proportions of major ions in the Main Street well water were similar to the proportions in Soquel Creek water, both samples were within the range of variability of other nearby deep wells. One plausible short-circuit flow path between the creek and the well (flow down the well's gravel pack) is not capable of conveying sufficient flow to dominate the quality of the pumped water.

The conclusion that emerges from the review of the many analyses of long-term baseflow trends and precipitation-runoff relationships (Analyses 17-29) is that the exceptionally low baseflows during calendar years1992-1994 were not part of a trend or shift in the characteristics of the stream-aquifer system but rather a response of the system to an exceptionally large cumulative precipitation deficit. Many of the analyses did not adequately filter out the large effects of annual precipitation on baseflow, leading either to unsupported conclusions that there had been a trend or shift toward decreased baseflow (Analyses 17, 18, 19, 21, 24, 26 and 27) or an inability to draw any conclusions because of excessive scatter in the data (Analyses 14, 20 and 29). Some of the previous analyses suggested that baseflow is affected not only by precipitation during the previous winter but also the winter before that (Analyses 9 and 28), which corroborates a key element of the present conceptual model.

The analysis methods most capable of detecting long-term trends or changes in baseflow are the ones that filter out or explicitly account for the large effects of precipitation, which is highly variable from year to year. The best methods are (1) double-mass plot comparing cumulative stream discharge between two stations (Analysis 18), (2) regressions of baseflow at one station versus another, where trends over time appear as trends in the regression residuals (Analysis 19), and (3) regressions of baseflow versus antecedent precipitation, where trends also appear in the residuals (Analysis 28). Methods that classify years by hydrologic category before evaluating for trends (Analyses 22 and 23) partially filter out the effects of precipitation variability, but not as completely as the aforementioned methods.

The smallest impact of pumping on baseflow that would be detectable in long-term flow records can be estimated by examining the double-mass and regression plots in Analyses 18, 19 and 28. It appears that the smallest long-term change in baseflow that could reliably be detected would be on the order of 0.5 cfs. A change of this magnitude would probably be visually and statistically detectable as a deflection in the double-mass plot or a trend in the residuals of the regression plot.