TODD GROUNDWATER

July 8, 2014

MEMORANDUM

To: Kim Adamson and Taj Dufour, Soquel Creek Water District

From: Gus Yates and Iris Priestaf, Todd Groundwater

Re: Peer Review of Technical Water Resources Studies Prepared for Soquel Creek Water District—Final

EXECUTIVE SUMMARY

Technical reports completed by HydroMetrics Water Resources Inc. (HydroMetrics WRI) during 2009-2013 were reviewed for technical accuracy and soundness of conclusions. Collectively, the reports documented a sequence of analytical steps that estimated 1) protective groundwater elevations to prevent seawater intrusion, 2) the amount of groundwater outflow to the ocean that would be associated with maintaining those levels, 3) the overall sustainable yield of the basin given the outflow requirements, and 4) the amount of yield available for use by Soquel Creek Water District.

There are no fatal flaws in the work completed by HydroMetrics WRI. It is consistently of high quality and in many respects state-of-the-art. The statistical approach used in some steps of the analysis is a valuable means of disclosing and quantifying uncertainty. That approach was not carried throughout the analysis, however. For some steps, conservative assumptions were made instead that collectively might have led to an estimate of available yield several hundred acre-feet per year too low. In a few instances, alternative assumptions or methods could be applied that are not necessarily more accurate but that could corroborate the original results or help characterize uncertainty.

The biggest challenge for managing groundwater resources in the Soquel-Aptos basin is not weaknesses in technical analysis but weakness in correlations between pumping, water levels and water quality. Data for those variables often do not exhibit the patterns expected from the physical laws governing groundwater flow. As a practical matter, this circumstance underscores the need for an adaptive management approach. The time frame for achieving protective groundwater elevations is long enough that pumping rates and other management measures can be adjusted to reflect ongoing results from monitoring.

INTRODUCTION

HydroMetrics WRI has completed a number of technical studies and annual reports for Soquel Creek Water District (SqCWD) since 2009 that estimate the groundwater levels needed to prevent seawater intrusion and the groundwater yield available to SqCWD when it operates the basin to achieve those water levels. SqCWD has reached a critical juncture where significant decisions must be made based on the results of those studies. To provide greater assurance that SqCWD is on the right path, Todd Groundwater completed a thorough, independent peer review of technical studies completed in recent years. These included nine reports and documents specifically identified by SqCWD as central to their decision-making process. This memorandum documents the results of that review.

The review is organized around eight questions that SqCWD posed to guide the effort. Most of the questions address the three main steps in the HydroMetrics WRI approach to managing groundwater resources in the Soquel-Aptos basin, which can be summarized as follows:

- Identify the groundwater **elevations** needed to prevent seawater intrusion.
- Estimate the groundwater **outflow** required to maintain those elevations.
- Calculate the long-term groundwater **yield** available to SqCWD after accounting for the outflow requirement.

The questions ask whether the approach, analysis and conclusions for each of those steps are appropriate, reasonable, defensible and adequate. We applied the following criteria to make a determination:

- The analysis is consistent with hydrogeological principles.
- The analysis is consistent with available data.
- The conclusions are supported by the data and analysis.
- The assumptions and methods are consistent with studies of similar basins.

THE EIGHT QUESTIONS

The questions posed by SqCWD collectively address all of the work undertaken by HydroMetrics WRI to develop objectives and strategies for managing the basin and preventing seawater intrusion. Each of the questions is discussed and answered below. Note that the order of the questions has been modified slightly from the original list to facilitate a logical sequence to the discussion.

Question 1: Is the approach of managing to protective elevations an appropriate way to assess basin overdraft?

Overdraft results when average annual groundwater withdrawals exceed the long-term sustainable yield of a groundwater basin, which is the amount of water that can be withdrawn annually from a basin without producing an undesirable result (Todd and Mays, 2005). Undesirable results can include depletion of groundwater available for future uses, reduced pumping rates or physical damage to wells, land subsidence, depletion of stream base flow, dewatering of wetland or riparian vegetation, deterioration of water quality, and seawater intrusion. Of these, seawater intrusion and depletion of stream base flow are of the greatest concern in the Soquel-Aptos basin.

A possible shortcoming of the protective-elevation approach to managing overdraft is that it ignores base flow depletion, which merits equal consideration. The Los Osos groundwater basin in San Luis Obispo County illustrates the risk associated with focusing too exclusively on only one undesirable effect of overdraft. From 1980-2005 virtually all groundwater management was focused on nitrate contamination from septic systems, which had become quite serious and necessitated an expensive sewer and wastewater treatment project. While water managers and technical consultants were focusing their attention on nitrate contamination, seawater intrusion advanced inland and in 2005 suddenly appeared at a major municipal supply well.

Managing the Soquel-Aptos basin to achieve protective groundwater elevations near the coast is an appropriate way to prevent seawater intrusion. This determination was reached by considering alternative approaches and by reviewing management approaches that are being used in other basins impacted by intrusion. The main alternative technical approach to estimating and managing intrusion is a water-balance approach. This can be applied at the basin scale, calculating intrusion as the residual in the water balance after accounting for all other inflows, outflows and storage changes. In addition to large potential errors due to uncertainties in the estimates of the other water balance items, the whole-basin balance can conceal localized intrusion that is offset by excess outflow along other segments of the coastline.

Groundwater flow models that do not incorporate density effects are another approach to quantifying and managing intrusion. Intrusion is predicted whenever and wherever the simulated ocean boundary flux is landward rather than seaward. The fresh groundwater modeling approach improves on the whole-basin water balance approach by providing greater spatial and temporal resolution, but it will still indicate intrusion only if onshore water levels drop below sea level. Freshwater models are not capable of detecting intrusion caused by or accelerated by the density difference between seawater and fresh groundwater. Therefore, preventing intrusion by means of protective groundwater elevations that reflect density effects has advantages over the water-balance approach and the fresh groundwater modeling approach. Methods for selecting protective levels are discussed in Question 2.

Finally, groundwater models that do incorporate density effects are the most accurate means of estimating the rate of intrusion and the location of the saltwater-freshwater interface, but they are more time-consuming and expensive to implement. The models can be two-dimensional cross-sections models—like the ones developed by HydroMetrics WRI for the Soquel-Aptos basin—or fully three-dimensional models.

The history of seawater intrusion in other California basins was researched to identify water-level conditions leading up to the onset of intrusion, technical methods used to predict intrusion, and management measures implemented to control intrusion. Information for nine basins is presented in **Appendix A**. In most cases, water levels declined from above sea level to below sea level too rapidly to discern the role of density as a factor promoting intrusion. The most common response to intrusion has been to decrease groundwater pumping near the coast, often by delivering surface water as a substitute supply. Protective elevations were an explicit part of the management program in only a few instances, and were usually estimated using the relatively simple Ghyben-Herzberg approach. For the Seaside basin, protective elevations were estimated using SEAWAT numerical cross-section models. That approach is the same as the one implemented for the Soquel-Aptos basin and was also done by HydroMetrics WRI.

Question 2: Is the approach that HydroMetrics WRI used to determine protective elevations appropriate?

Protective groundwater elevations are designed to account for the density difference between fresh groundwater and seawater. If the densities were the same, any groundwater level greater than sea level would prevent intrusion. Because seawater is 2.5 percent denser than fresh groundwater, onshore water levels must be higher than sea level to counterbalance the greater density of seawater and prevent intrusion. Several options are available for calculating protective elevations. They are listed below in increasing order of complexity and difficulty of implementation, along with basins where they have been applied:

- Ghyben-Herzberg with no outflow correction (Santa Cruz)
- Ghyben-Herzberg and estimated seaward gradient (Salinas Valley)
- Glover equation (Ghyben-Herzberg with outflow correction)
- Numerical x-z cross section model with layers (SqCWD)
- Numerical 3-D model (Los Osos)

The Ghyben-Herzberg equation does not account for outflow to the ocean that invariably occurs when water levels near the coast are high enough to counterbalance the density of seawater. This outflow would be associated with a water-level gradient that slopes toward the ocean. Without a correction for outflow, the protective elevation estimated using the Ghyben-Herzberg equation would have a constant value equal to one-fortieth the depth to the base of the aquifer. Generally, accounting for outflow increases the protective elevation at any given distance inland from the coast—in order to provide a gradient driving the flow of fresh water in addition to balancing the density difference—but it also shifts the interface seaward to make room for the offshore groundwater discharge area. The most common form of outflow correction is the Glover equation, which assumes a single aquifer with isotropic hydraulic conductivity, meaning horizontal and vertical permeability are the same (Glover, 1964).

Numerical models offer the additional capability of simulating the effects of aquifer layering and vertical flow across aquitards. This capability is essential to evaluating groundwater outflow and protective elevations for the multi-layered Purisima Formation in the Soquel-Aptos basin. However, once the analysis includes layering, hydrogeologic uncertainty becomes the dominant source of error. That is, assumptions regarding the continuity of aquitards and the vertical hydraulic conductivity of aquifers and aquitards can influence the estimated protective elevation more than density effects alone.

HydroMetrics WRI employed a two-dimensional cross-sectional numerical model to estimate protective elevations. They addressed hydrogeologic uncertainty by employing a statistical Monte Carlo approach to estimating hydraulic conductivities. This is an advanced approach to characterizing uncertainty that has been used in other seawater intrusion studies. For example, cross-sectional intrusion models developed for three sites on the Alaskan island of Amchitka were found to be sensitive to four parameters with a large range of uncertainty: hydraulic conductivity, recharge, and longitudinal and transverse dispersivity (Hassan and others, 2004). For each variable, 100 values were randomly selected from within a range of plausible values, and the resulting flow and concentration distributions were summarized statistically. The Monte Carlo approach acknowledges the uncertainty of hydrogeologic parameters and the sensitivity of results to their values. For example, Ranjan and others (2007) demonstrated that for a simple homogeneous, unconfined aquifer crossing the coastline: 1) decreasing horizontal hydraulic conductivity by a factor of 10 lowered the simulated interface by a factor of three, and 2) doubling the outflow approximately halved the inland extent of the interface at a given depth.

HydroMetrics WRI used a similar number of random parameter estimates (99) as Hassan and others (2004) but only applied the approach to horizontal and vertical hydraulic conductivity. Dispersion was deliberately not included in the HydroMetrics WRI models, to focus the analysis on the position of the saltwater-freshwater interface rather than the thickness of the transition zone.

The statistical approach to simulating protective water levels requires the user to select a percentile of the output distribution to use as a management objective. In this case, the 70th percentile of simulated protective elevations was chosen. Selecting the percentile is a subjective process in which the cost of achieving a higher percentile is balanced against the decreasing probability that the higher percentile is actually necessary to prevent intrusion. In almost all of the cross-section models, the water level corresponding to the 100th percentile was only 1 foot higher than the 70th-percentile elevation. The additional outflow required to raise the simulated water levels at the coastline by 1 foot at each cross section was calculated for this review from the relationship between outflow and elevation evident in graphs and tables in the HydroMetrics WRI reports (Figures A-3 through A-33 in the January 2009 report; Table 2 in the September 2009 report, and Table 3 in the April 2012 report). The results indicated that total outflow from the Purisima and Aromas areas would have to be increased by 1,400 acre feet/year (AFY) to raise coastal water levels uniformly by 1 foot and thereby reach the 100th percentile of protection. This is a large amount of water in the context of yield available to SqCWD. Given the substantial uncertainty not only in the HydroMetrics WRI analysis but in raw data relating pumping to water levels and water quality, the cost of achieving the additional protection appears unwarranted. Selection of the 70th percentile for water levels and flow represents a reasonable balance between risks and benefits.

One inherent limitation of cross-sectional models creates a potential source of error for the Soquel analysis. Cross-sectional (vertical slice) models assume there is no flow across the sides of the model. If the aquifers and aquitards of the Purisima Formation were horizontal or dipped directly seaward, that assumption would be valid. However, they dip from west to east, more or less perpendicular to the vertical slices used for the cross-section models. The vertical slice models therefore rule out the possibility of groundwater outflow diagonally upward in the plane of bedding to a nearshore outcrop that is off to the side of the cross section. The flow distance is longer, but the hydraulic conductivity along the aquifer is sufficiently greater than the hydraulic conductivity across the aquitards that this pathway for outflow is plausible. For dips of 2-5 degrees, the diagonal distance to the sea floor along the aquifer unit is 10-30 times greater than the vertically upward path across the aquitards. However, if the hydraulic conductivity contrast is greater than 30:1, then flow along the plane of the aquifer could account for most of the outflow. This appears to be the case. For example, the horizontal hydraulic conductivity of the A aquifer is approximately 12 feet/day (ft/d) whereas the vertical hydraulic conductivity of the overlying B aquitard is 0.04 ft/d, which corresponds to a ratio of 300:1 (HydroMetrics WRI, January 2009, Table A-1).

It is not necessary to develop a three-dimensional model to correct this potential error in the cross-section models. The effect of diagonal flow on the estimates of protective elevation and groundwater outflow can be investigated by modifying one or two of the existing cross-section models. By tilting the model to lie in the plane of the aquifer and scaling the equivalent freshwater head to the tangent of the dip, the model could be used to simulate diagonal flow along the aquifer unit and the associated elevations and outflow rates.

In summary, the method used by HydroMetrics WRI to estimate protective groundwater elevations is more sophisticated and more accurate for layered systems than the more common approaches of applying the Ghyben-Herzberg method or the Ghyben-Herzberg method with simple flow corrections. However, it is recommended that one or two of the cross-section models be tested for the possibility of diagonally-upward flow perpendicular to the cross section as described above.

Question 3: Based on the protective elevations, a post-recovery pumping goal of 4,000 AFY was established to maintain the basin at protective levels after recovery. Is the selection of 4,000 AFY as a post-recovery pumping goal defensible and reasonable for preventing overdraft after recovery?

The post-recovery pumping goal represents the long-term sustainable yield of the basin available to SqCWD. It was estimated by means of the second and third steps of the HydroMetrics WRI approach. The second step translated protective elevations into outflow requirements, and the third step incorporated the outflow requirements into water balance calculations that indicated SqCWD's share of basin yield.

Required Outflows to Prevent Intrusion

Maintaining protective groundwater elevations will result in a certain amount of groundwater outflow to the ocean. The cross-section models that were used to estimate protective elevations were also used to estimate the associated outflow. Groundwater models ensure consistency between flows and water levels by simultaneously enforcing conservation of mass and the Darcy equation for groundwater flow. Furthermore, the statistical approach employed to incorporate uncertainty in estimating protective elevations was also applied to the estimates of outflow. That is, for each of the 100 sets of parameters implemented in the models, the inland constant-head boundary was adjusted until the saltwater wedge was completely offshore. The protective elevations and associated boundary flows were recorded from each simulation. This means that the estimates of outflows were fully consistent with the estimated protective elevations, and the statistical distributions were also consistent.

Potential model errors described earlier for protective elevations also apply to outflows. The major concern is the possibility of substantial flow through the sides of the vertical slices represented by the models; that is, flow diagonally upward through the aquifer unit to the point where it intersects the ocean floor. Again, tests of cross-section models tilted into the plane of the aquifer could reveal whether the diagonal outflow path is significant and whether it affects the estimates of protective elevation and associated outflow.

HydroMetrics WRI calculated outflow along the entire coastline as the sum of outflows for ten intervals, each centered on a cross-section model. This is a reasonable method for spatially extrapolating model results.

Water Balance Approach

The third step in the HydroMetrics WRI approach used a very different set of data and tools. It consisted of estimating the surface water and groundwater balances for the entire Soquel-Aptos basin—including the required outflows to maintain protective elevations—and then calculating the amount of yield available to SqCWD as a residual in the overall water balance. This approach is conceptually correct but is inevitably subject to large uncertainty simply because the SqCWD yield (4,000 AFY) is more than an order of magnitude smaller than large flows in the water balance, such as precipitation (110,500 AFY) and evapotranspiration (72,700 AFY). The large flows are difficult to measure at the scale of the entire basin, and small percentage errors in those estimates become large percentage errors in the SqCWD yield estimate[1]. For example, an uncertainty of +/- 5 percent in either precipitation or evapotranspiration—which is an optimistic level of accuracy—corresponds to an uncertainty of 91 to138 percent in the estimate of SqCWD yield.

HydroMetrics WRI also concluded that actual evapotranspiration is the source of the most uncertainty in the estimate of deep recharge, which is the primary input to the calculation of basin yield (HydroMetrics WRI, 2011, page 67).

In spite of these limitations, a water balance approach is reasonable and appropriate. An alternative approach based on well hydraulics would produce inaccurate results. That approach would involve applying analytical functions such as the Theis Equation to predict drawdown around a municipal well. If the calculated drawdown did not extend to the coastline, it could be concluded that seawater intrusion would not occur. However, drawdown functions for pumping wells are based on numerous simplifying assumptions and relatively short durations that do not apply to the heterogeneous conditions and spatial and temporal scales relevant to intrusion analysis in the Soquel-Aptos basin.

PRMS Watershed Model—General

The Precipitation-Runoff Modeling System (PRMS) model is a good choice for estimating groundwater recharge in upland parts of the basin because topographic, land cover and hydrologic conditions in that area match the conditions for which the model was designed. Specifically, PRMS was designed to simulate stream flow in undeveloped watersheds with moderate to high relief, where rainfall infiltration not lost to evapotranspiration eventually discharges as base flow in streams. In a typical application, PRMS models are calibrated to match gaged stream flows at the bottom of the watershed, which in this case included 10 gages in the Soquel, Aptos and Corralitos Creek watersheds.

PRMS was designed for modeling surface water. The “deep recharge” term in the model—which is the most important output for groundwater studies—was included in the model almost as an afterthought to dispose of excess water mass not recorded at the stream gages. There are few parameters for the deep recharge calculation and no means to check the simulated deep recharge.

PRMS is not well suited to areas with urban or agricultural land uses, groundwater pumping, and two-way interactions between streams and aquifers. Although the coastal plain part of

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[1] The residual in the watershed water balance is actually total basin recharge (10,800 AFY). However, uses of that recharge by other pumpers and for ocean outflow were considered fixed, so that uncertainties in the water balance residual passed through to the yield available to SqCWD.

the Soquel-Aptos basin is included in the area simulated by PRMS, the accuracy of the recharge estimate is unknown and likely worse than in the upland parts of the basin due to substantially different hydrologic conditions. The coastal plain is downstream of the calibration gages and is almost completely covered by urban land uses. Groundwater recharge in the coastal plain area has not been considered in detail in previous studies of the basin, so there are no reliable prior estimates of recharge in that area that can be compared with the recharge simulated by PRMS. Johnson and others (2004) assumed 15 percent of groundwater pumping returned to the Purisima aquifers, but without direct evidence of that flow or a discussion of urban hydrology or hydrogeologic constraints.

PRMS Watershed Model—Details

PRMS is a highly parameterized model, which creates a risk of inaccurate or non-unique calibrations. The ultimate goal, however, is calibration to observed stream flows, and the agency that developed the software (U.S. Geological Survey) has found that results are typically sensitive to only 18 of the 240 parameters in the model. These were the parameters selected for calibration by HydroMetrics WRI. Simulated stream flows produced by the calibrated model match measured flows quite well. Peak daily flows are frequently under-simulated at some gages, but HydroMetrics WRI correctly emphasized simulation of monthly and annual total runoff. Those longer time scales are more relevant to groundwater recharge and basin yield, and it is consequently important to match the measured stream flow mass balance at those time scales.

Like deep recharge, simulated stream flow reflects the difference between precipitation and evapotranspiration. Non-unique combinations of those variables could result in equally good simulated stream flows. In other words, a slightly higher estimate of precipitation could be balanced by additional evapotranspiration or additional deep recharge and still produce similar results for stream flow. This means that the good stream flow calibration does not guarantee a good calibration of deep recharge.

Given their large contributions to the water balance, precipitation and evapotranspiration estimates were the focus of the review effort. Six rain gages in and near the basin were used as sources of rainfall data, with values at each of the 312 simulated sub-watersheds extrapolated from the gage locations by inverse-distance weighting. This is a standard approach. Including multiple rain gages decreases the influence of anomalies at any single station. However, no discussion was provided regarding the similarity and consistency of rainfall among the stations. The stations covered a range of elevations, so orographic influences on precipitation were incorporated to at least some extent. The 1984-2009 calibration period is representative of long-term average conditions and includes dry and wet periods. There are no alternative methods for producing superior estimates of daily rainfall over a 26-year period in each sub-watershed.

The estimates of daily evapotranspiration (ET) do not appear to be quite as reliable as the estimates of precipitation. Unfortunately, PRMS does not provide an option to directly use reference ET (ETo) data reported by meteorological stations in California's CIMIS network (including the De Laveaga station located within the basin). Although ET is less spatially and temporally variable than precipitation, the coastal location and rugged topography of the basin create the potential for large local ET differences (gradients). Because summer fog is common at low elevations along the coast, steep increases in ETo with distance from the coast have been observed in several Central Coast basins (DWR, 1975). The average gradient was 3 percent per mile, which could amount to a 20-25 percent variation in ETo across the Soquel-Aptos basin. The potential ET data used in the PRMS model was obtained from nationwide modeling on a 10-mile grid based on pan evaporation data (which are even sparser). This spatial resolution is not adequate to reflect coastal ET gradients. HydroMetrics WRI selected the Jensen-Haise option for preparing potential ET in PRMS, and it includes a term that reflects elevation. So elevation effects on ET are captured to some extent in the model. One ET parameter was adjusted during calibration to match average potential ET over the basin as estimated from the nationwide grid. It would be worthwhile to also compare the Jensen-Haise estimates of daily ETo with measured values at the De Laveaga CIMIS station, although that station represents only a single point within the basin.

The plot of deep recharge versus annual precipitation (HydroMetrics WRI 2011, Figure 34) indicates that deep recharge does not commence until annual rainfall exceeds a threshold of about 16 inches/year. This is substantially higher than the threshold for typical semiarid regions. **Figure 1** shows the relationship of groundwater recharge and annual rainfall compiled from 30 studies of recharge in basins around the world (Bedinger, 1987). Data from the PRMS model are also shown, converted to an average one-dimensional flux over the 65-square-mile basin. The average threshold for initiating recharge was approximately 10 inches of annual rainfall. The discrepancy could stem from the conceptual differences between PRMS and the other studies. The other studies were mostly for basins where all percolation below the root zone becomes groundwater recharge. In PRMS, percolation below the root zone becomes shallow groundwater, some of which flows to streams. Only the remainder becomes deep recharge. The Soquel-Aptos PRMS model could be compared with the other studies by adding stream base flow to deep recharge.

In some basins, the estimate of groundwater recharge can be improved by linking a recharge model to a groundwater flow model and jointly calibrating the two (Yates and others, 2002; HydroMetrics WRI, 2011). Joint calibration is effective when recharge creates noticeable changes in groundwater levels and other components of the groundwater balance can be accurately estimated. In the case of the Soquel-Aptos basin, the additional accuracy achieved by joint calibration of PRMS and a groundwater model could be limited by difficulties in calibrating the groundwater model itself. These difficulties would arise from the lack of a strong short-term correlation between pumping and water levels, as described below under “Relationship Between Pumping and Water Levels”.

Other Water Balance Items

In 2012, HydroMetrics WRI updated the basin-wide groundwater balance of Johnson and others (2004) to include the new estimate of rainfall recharge produced by the PRMS model as well as revised estimates of outflow to the Pajaro Valley basin, septic system recharge and City of Santa Cruz production. These water balance items are all added or subtracted from total basin yield to obtain the estimate of yield available to SqCWD. Consequently, the accuracy of estimating those items is as important as the accuracy of the PRMS estimate of total recharge.

Some of the water balance items—or the assumptions and parameters used to estimate them—might be less accurate than alternative assumptions. These issues are discussed individually below for the Purisima and Aromas areas separately, and compiled into an alternative water balance and yield estimate.

Purisima Area Yield Estimate

The PRMS model estimated that total rainfall recharge to the Purisima area averages 6,600 AFY. Items subtracted from total recharge to obtain SqCWD yield are listed in **Table 1**, along with alternative estimates.

The first item subtracted by HydroMetrics WRI was recharge along the western margin of the Purisima outcrop area, corresponding roughly to the watersheds of Arana Gulch and Rodeo Creek. The PRMS model indicated that average annual rainfall recharge in that area is 1,200 AFY. The apparent purpose of this subtraction was to ensure that the estimate of SqCWD yield did not encroach on yield needed to supply City of Santa Cruz wells. In the future, pumping by the City is expected to average 540 AFY (HydroMetrics WRI, April 2012, page 25). An alternative estimate that continues the statistical approach used earlier for estimating protective groundwater elevations would be the 70th percentile of historical annual production from the Santa Cruz Live Oak well field during 1968-2011. That estimate turned out to be nearly identical (550 AFY). If recharge were only needed to supply groundwater pumping, the subtraction of 1,200 AFY of recharge would be too high by 650 AFY. However, recharge presumably needs to also supply groundwater outflow associated with maintaining protective elevations. That outflow has not been calculated for the 3 miles of coastline west of SC-1. If the necessary outflow per linear foot of coastline equals the average of the SC-1 and SC-2 cross-section models, then the required outflow west of SC-1 would be 339 AFY. This suggests that the 1,200 AFY subtracted from PRMS recharge exceeds the City's recharge requirements by 311 AFY (1,200 – 550 – 339 = 311). This excess could be added to the SqCWD yield instead.

The second item subtracted from PRMS recharge was the amount of groundwater outflow needed to maintain protective groundwater elevations in the SqCWD part of the Purisima area. The 70th percentile of simulated outflow obtained from HydroMetrics WRI modeling was 775 AFY. That estimate is retained in the alternative adjustments column in the table.

The third item subtracted from recharge was the consumptive use of groundwater by non-SqCWD pumpers. This number is the net result of calculations of gross use and return flow for indoor and outdoor uses by Cabrillo College and other non-SqCWD pumpers, as detailed on **Table 2**. Alternatives are proposed for two parameters in those calculations. The first is the assumption that 20 percent of outdoor use (irrigation) returns via deep percolation to Purisima units tapped by water supply wells. This percentage is probably too high. Urban irrigation efficiency has increased in recent decades due to increased awareness of the need to conserve water and increased deployment of drip irrigation, micro-sprinklers, and large-droplet spray heads. Also, some of the irrigation water not consumed by plants does not return to the aquifer but is lost to spray evaporation or overspray onto impervious surfaces. Furthermore, excess applied water that does percolate past the root zone might not reach underlying aquifers. It could accrue to shallow groundwater zones that lose some water to seepage into creeks and gulches that drain the coastal plain. Data are not available for these details of urban irrigation and return flow; the alternative estimate of 10 percent return flow is considered reasonable based on professional judgment.

An alternative is also proposed for the assumption that only 75 percent of indoor water use in non-sewered residential areas becomes recharge via septic system percolation. HydroMetrics WRI carried this assumption forward from Johnson and others (2004), who in turn copied it from a prior source. A much higher percentage of indoor use probably becomes wastewater. The California Department of Water Resources (1983) estimated that 98 percent of indoor use becomes wastewater. Losses to ET at the leach field are probably also small due to the depth of the leach lines and typical cover of shallow-rooted vegetation. The alternative estimate in the table assumes that 98 percent of indoor use becomes recharge.

A fourth adjustment not included in the HydroMetrics WRI calculations is groundwater recharge from leaking water and sewer pipes. SqCWD staff recently completed an audit of the water distribution system and found that “apparent losses” averaged 7.4 percent of total water production during 2010-2013 (Mead 2014). Those losses consist primarily of pipe leaks, all of which are assumed to percolate back to water supply aquifers for this analysis. Multiplying post-recovery production of 2,800 AFY for the Purisima area and 1,200 AFY for the Aromas area by 7.4 percent produces pipe leak recharge estimates of 207 and 89 AFY, respectively. Fewer studies are available for sewer pipe leaks, which are probably a smaller percentage of annual flow because the pipes are not pressurized and leaks are more likely to self-seal. Sewer pipe leaks are not included in the alternative recharge estimate but would tend to increase recharge and, hence, yield available to SqCWD.

The alternative estimate of SqCWD consumptive use yield was obtained by applying the alternative estimates of subtractions and additions to the PRMS recharge estimate. The consumptive-use yield was then multiplied by a factor related to the return flow percentage to obtain the SqCWD post-recovery pumping yield. The return flow percentage represents deep percolation of applied irrigation water, for which the alternative estimate is smaller than the HydroMetrics WRI estimate. The resulting alternative estimate of SqCWD post-recovery pumping yield for the Purisima area was 3,646 AFY, or 845 AFY more than the HydroMetrics WRI estimate. This estimate is probably too high, as discussed under “Limitations of Alternative Water Balance Calculations”, below.

Aromas Area Yield Estimate

Alternative estimates of selected water balance items were similarly developed for the Aromas area, as shown in **Table 3**. Once again, SqCWD yield was derived from the PRMS recharge estimate by applying a series of subtractions and additions. The first adjustment was to subtract groundwater outflow to the Pajaro Valley groundwater basin. Results from two groundwater models developed by others were appropriately discarded by HydroMetrics WRI due to clear inconsistency with the PRMS recharge estimate. Outflow was instead calculated using the Darcy equation for groundwater flow and integrating along the length of the boundary. This method is reasonable, although uncertainty in transmissivity resulted in a nine-fold range of uncertainty in outflow. HydroMetrics WRI selected the maximum estimate of outflow (370 AFY) for use in the water balance and yield calculations. To be consistent with the statistical approach applied to earlier steps in the yield analysis, it would be appropriate to use the 70th percentile estimate of outflow. For example, selecting a transmissivity equal to 70 percent of the range between minimum and maximum produces an outflow of 271 AFY.

The second adjustment was to subtract ocean outflow required to maintain protective groundwater elevations. The tilted-aquifer issues that raise concerns about cross-section modeling in the Purisima area do not apply to the Aromas aquifer, so no alternative outflow estimate is proposed.

The third adjustment was to subtract consumptive use by non-SqCWD pumpers. As in the Purisima area, this involved a number of parameters and types of users, as presented in **Table 4**. The alternative estimates are based on assumptions that irrigation return flow equals 10 percent of applied water and that septic system percolation equals 98 percent of indoor water use, as described above for the Purisima area. These assumptions have opposite effects on the estimate of consumptive use, which wound up with a value of 673 AFY.

The fourth adjustment was an addition of recharge from pipe leaks, which were assumed to equal 7.4 percent of SqCWD post-recovery pumping in the Aromas area, or 89 AFY.

The alternative subtractions and additions were applied to the PRMS recharge estimate to obtain the SqCWD post-recovery consumptive use yield, and that value was converted to the SqCWD post-recovery pumping yield using a multiplier that reflects the return flow percentage. The resulting estimate of pumping yield was 1,438 AFY, or 241 AFY greater than the HydroMetrics WRI estimate.

Limitations of and Adjustments to Alternative Water Balance Calculations

The alternative estimate of SqCWD post-recovery pumping yield for the Purisima area could be as high as 3,646 or 845 AFY more than the HydroMetrics, WRI estimate. The alternative estimate for the post-recovery pumping yield for the Aromas area could be as high as 1,438 or 240 AFY more than the HydroMetrics, WRI estimate The differences are the net result of adjustments that increased the calculated yield (a smaller deduction for Santa Cruz yield, inclusion of pipe leaks, and a higher percentage of septic system return flow) and adjustments that decreased the calculated yield (smaller percentage for irrigation return flow). The largest contribution to the difference in yield estimates stemmed from the alternative approach to meeting City of Santa Cruz groundwater needs. In the original analysis, those needs were met twice: once by the subtraction of 1,200 AFY of recharge along the western margin of the Purisima area and a second time by including the City's consumptive use in the demand for non-SqCWD pumpers.

The alternative yield calculations are individually plausible, but together they produce a yield that conflicts with historical water levels. SqCWD production during 1984-2004 was fairly constant and only slightly greater than the alternative yield estimate, yet it resulted in coastal groundwater levels below protective elevations. This indicates that one or more of the adjustments that produced the alternative yield was overly optimistic.

Three major sources of uncertainty that could easily reduce the alternative yield estimate are listed at the bottom of Table 1. The first two relate to groundwater outflow requirements to maintain protective elevations. The examples in the table show the reduction in yield if the outflow estimates are revised upward by 50 percent. In the Santa Cruz area west of Soquel Point, the B aquitard is absent and the Tu, AA and A aquifers are exposed on the ocean floor immediately offshore. This condition could require a much higher rate of outflow to prevent a saltwater wedge from extending onshore than was calculated using cross section models farther to the east. If the true outflow requirement is 50 percent larger than the initial estimate, the alternative yield would be reduced by 170 AFY

In the SqCWD Purisima area there is the possibility of diagonal flow along the planes of Purisima aquifer units from their depths at the cross-section model locations to the sea floor. Because horizontal hydraulic conductivity within the aquifer units is 50-300 times greater than the vertical hydraulic conductivity across the overlying aquitard (HydroMetrics WRI, January 2009 Table A-1), it is plausible that this flow path is more permeable overall than the flow path across the aquitards simulated in the vertical cross section models. This would likely result in a larger outflow requirement to maintain protective elevations. If the outflow requirement is revised upward by 50 percent, the alternative yield estimate would be reduced by 388 AFY.

Finally, there are hydrogeologic reasons to suspect that some recharge in the coastal plain area does not percolate down to water supply aquifers but is instead lost to seepage into local creeks, gulches and the ocean. The number in Table 1 is the amount by which the alternative yield estimate would be reduced if one-third of coastal plain recharge is lost to those outflows.

Together, the three reductions would bring the alternative yield estimate back down to the HydroMetrics WRI estimate for the Purisima area. None of these considerations apply to the alternative yield estimate for the Aromas area. Limitations in that area are the same for both yield estimates and stem from uncertainty in the return flow percentages for irrigation and for indoor water use in residences with septic systems.

Historical water levels and trends provide another basis for evaluating the alternative yield estimates for the Purisima and Aromas areas. An analysis of the cumulative historical groundwater storage deficit (see details under Question 4, below) revealed that if the Purisima yield were truly as large as the alternative estimate of 3,646 AFY, there would have been no accumulated deficit. Furthermore, the analysis estimated that the current storage depletion in the Purisima area is about 5,100 AF. To end up with that much depletion, the yield must have been less than 3,040 AFY. A reasonable estimate is the average of that estimate and the HMWRI estimate, or 2,900 AFY.

In the Aromas area, water levels in the deep screens at SC-A1 and SC-A2 rose consistently during 2010-2012, and they remained level at SC-A8 and SC-A3. This suggests that SqCWD pumping during that period (1,476 AFY) was close to the sustainable yield. However, water levels at three of the deep well sites were still below protective elevations, and rising trends do not necessarily indicate that pumping is less than safe yield until water levels have reached protective elevations. Recent Aromas pumping has been similar to the alternative yield estimate (1,476 AFY and 1,438 AFY), and those values are 240-280 AFY greater than the HMWRI sustainable yield estimate. For planning purposes, it would be reasonable to assume an Aromas sustainable yield of 1,300 AFY.

The adjustments and limitations described in this section support a conclusion that the sustainable yields of the Purisima and Aromas areas are likely greater than the HMWRI estimates, but not by a lot. The recommended planning yields of 2,900 AFY and 1,300 AFY are together only 200 AFY greater than the HMWRI estimate of total sustainable yield. Fortunately, some of the uncertainty in the yield adjustments could be minimized with a modest amount of additional investigation, as described in the "Recommendations" section below.

Relationship between Pumping and Water Levels

There is an implicit assumption in the HydroMetrics WRI calculation of post-recovery yield that a decrease in pumping will cause an increase in water levels. This is absolutely consistent with all groundwater theory and is readily apparent in most basins. Furthermore, one would expect higher water levels to be associated with lower concentrations of total dissolved solids (TDS) and chloride in wells near the coast. Finally, one would expect TDS and chloride concentrations to have parallel trends because both are relatively conservative solutes. For unknown reasons, however, these relationship are tenuous in the Soquel-Aptos basin. This adds additional uncertainty to the conclusion that limiting municipal pumping to the post-recovery yield will successfully achieve protective water levels.

The 2012 Annual Review and Report (HydroMetrics WRI, 2013) included hydrographs for 95 wells. For most of the wells, time-concentration plots of TDS and chloride were also presented. The plots for each well were visually compared with bar graphs of pumping at nearby municipal wells to evaluate whether the data conformed to the expected relationships between pumping, water levels and water quality. Results of the analysis for 85 wells with relatively complete data are summarized in **Appendix B**.

Figure 2 shows an example of a well where all three expected relationships are evident: periods of decreasing pumping at the Estates well correspond to periods of rising water levels at nearby coastal monitoring well SC-5A. As water levels rose, TDS and chloride both decreased. In contrast, **Figure 3** shows an example where none of the expected relationships were present. At the Seascape well, water levels in the production well appeared to be unaffected by pumping, and chloride and TDS had opposing trends that were both inconsistent with water levels. The visual comparisons revealed that only 29 percent of the water-level hydrographs could be confidently correlated with pumping at a nearby well, with another 28 percent showing weak or intermittent correlation. Among wells within 3,000 feet of the coast, only 41 percent consistently showed increases in TDS and chloride correlated with decreases in water levels, and an additional 40 percent exhibited weak or intermittent correlation. TDS and chloride trends were more reliably correlated with each other; only 14 percent of the wells had conflicting trends. The most surprising result of the inventory was the low level of correlation between pumping at a municipal well and water level in that well. Only two out of sixteen wells showed a strong correlation, and there was no correlation at half of the wells.

The reason for the lack of correlation between pumping, water level and water quality is unknown. Annual variations in recharge do not obviously affect water levels in these confined aquifers. Most non-municipal wells are relatively small and would not be expected to strongly influence the observed water levels, particularly in the municipal wells themselves. Regardless of the cause of the poor correlation, it adds tremendous uncertainty to conclusions that a selected amount of pumping will achieve a predictable water-level result. HydroMetrics WRI appears to have reached a similar conclusion with the following statement:

> "The amount of the post-recovery yields that can be safely pumped by SqCWD's existing and planned wells is a major unknown factor that requires adaptive management." (HydroMetrics WRI, April 2012, p. 26)

Question 4: Based on the protective elevations, a recovery pumping goal of 2,900 AFY was established to recover the basin to protective levels within a time period of approximately 20 years. Is the selection of 2,900 AFY as a recovery pumping goal defensible and reasonable for restoring the basin within a 20-year period?

The question contains two elements. The first is whether 20 years is a reasonable time frame for achieving protective elevations. HydroMetrics WRI selected this time frame as the fastest schedule that could be achieved given the availability of supplemental supplies to substitute for groundwater pumping. This practical limitation is an important consideration. Another philosophical consideration involves balancing the cost and hardship of a faster schedule against the risk of intrusion and diminished sense of progress associated with a slower schedule. The 20-year horizon appears reasonable with respect to both considerations and is comparable to typical time frames for planning and implementing other types of major water supply projects.

The second element is whether 2,900 AFY over a 20-year period correctly represents the pumping reduction needed to achieve protective elevations. It appears that this reduction is larger than necessary. It was calculated based on historical water balances and an assumption that the basin functions as a perfect storage vessel with fixed inflows and outflows. That is, it assumes that a storage deficit caused by excess pumping as much as 30 years ago is preserved to the present day. This concept ignores head-dependent inflows and outflows that tend to counteract the increase in pumping and the lowered water levels:

- Induced seepage from streams
- Decreased groundwater outflow to the ocean
- Landward movement of the saltwater interface
- Increased groundwater flow from inland parts of the basin toward coastal pumping depressions.

These processes buffer the impact of excessive pumping on groundwater levels. The extent to which they have done so over the past 30 years can be estimated by comparing total historical excess pumping with the present amount of storage depletion. Cumulative SqCWD pumping in excess of its sustainable yield during 1984-2011 totaled 10,100 AF for the Purisima area[2] (HydroMetrics WRI 2012, page 26). Water levels in 2012 at the five coastal monitoring locations in the Purisima area averaged 8 feet below the protective elevations (range: 0 to 22 feet). The current volume of depleted storage can be estimated by multiplying the needed water-level recovery by the applicable geographic area and an appropriate storativity factor. The largest storativity factor tabulated for the Purisima units by Johnson and others (2004) was a specific yield of 0.10. This would correspond to the maximum estimate of groundwater storage depletion. Assuming water levels need to be raised an average of 8 feet along 5 miles of coastline and extending 2 miles inland, the net cumulative storage depletion would be 5,120 AF. This is only about one-half of the cumulative historical excess pumping in the Purisima area, which implies that changes in head-dependent boundary flows have absorbed the other half of the excess pumping.

Unfortunately, the head-dependent flow responses that counteracted water-level declines during the period of excess pumping will work in reverse during the period of refilling. In other words, the assumption that historical storage depletion is preserved can be more accurately described as an assumption that head-dependent boundaries have equal but opposite effects during the draining and refilling phases of groundwater storage. This is a reasonable assumption that was deliberately included by HydroMetrics WRI in the calculations of recovery pumping.

HydroMetrics WRI calculated the pumping reductions necessary to achieve recovery by dividing total historical excess pumping into a 20-year refilling period. For the Aromas area, the result was a pumping reduction of 575 AFY below the sustainable pumping rate, and for the Purisima area the reduction was 505 AFY. The recovery pumping goal of 2,900 AFY was obtained by subtracting these amounts from the estimated sustainable amount of SqCWD pumping, which was 4,000 AFY.

[2] Cumulative overdraft in the Aromas area during that period was estimated to be 11,500 AF, for a total of 21,600 AF.

The accumulated storage deficit during 1984-2011 was re-calculated using the adjusted alternative estimates of sustainable yield in the Purisima area (2,900 AFY) and Aromas area (1,300 AFY). The calculations of historical deficits accounted for septic system percolation in the SqCWD service area that occurred during 1984-2011 but that was omitted from the estimates of future sustainable yield. Septic system percolation was assumed to equal 98 percent of indoor water use at homes with septic systems, which differed from the HMWRI assumption of 75 percent. The historical calculations revealed that the necessary pumping reduction to defray the accumulated deficit becomes smaller by an amount greater than the increase in assumed sustainable yield. This is because an increase in assumed sustainable yield decreases the number of years during the historical deficit period when pumping exceeds the yield, and the intervening years of below-yield pumping intermittently pay back some of the cumulative storage deficit. For example, increasing the sustainable yield of the Purisima area from 1,200 AFY to 1,300 AFY decreased the number of deficit years during 1984-2011 from 24 to 22. The cumulative deficit decreased to 5,700 AF, a reduction of 33 percent.[3] A similar analysis for the Aromas area found that the adjusted alternative yield estimate—which is 100 AFY greater than the HMWRI estimate—decreased the estimate of accumulated historical storage deficit to 6,440 AF, a decrease of 32 percent.

An alternative recovery pumping goal can be calculated by dividing the total historical storage deficit (12,100 AF) by 20 years, and subtracting the result from the sustainable yield (4,200 AFY), which produces a value of 3,600 AFY. This is 700 AFY greater than the HMWRI estimate. The recovery pumping estimates are subject to the same uncertainties that apply to the yield estimates, which were described in the response to Question 3. For example, the change in assumed historical septic system return percentage accounted for 150 AFY of the change from the HMWRI recovery pumping estimate.

Question 5: Do you agree that the basin is in overdraft based on groundwater levels below protective elevations and therefore long-term sustainable yield is being exceeded?

On the basis of water levels, yes. As long as coastal groundwater levels remain below protective elevations, the question is not if intrusion will occur, but when. If there were unusual geologic conditions known to prevent or retard the onshore movement of seawater—such as are present in the Westside Basin near Daly City and San Bruno (Appendix A)—it could be argued that Soquel-Aptos groundwater levels could safely remain below protective elevations. However, there is no evidence of such geologic barriers in this case. On the contrary, the hydrogeologic evidence points to the possibility of near-shore intrusion pathways along bedding planes that were not fully considered in the HydroMetrics WRI cross-section models. Previous modeling studies of the Soquel-Aptos and Pajaro Valley areas identified near-shore infiltration as the most likely pathway for intrusion. For example, Essaid (1992) concluded that “the most immediate potential cause for seawater intrusion is

[3] These comparisons all assume 98 percent septic system return flow. Thus, they are not directly comparable with the HMWRI results.

pumping in shallow Purisima subunits near the coast that could induce downward leakage of seawater through ocean floor outcrops." Bond and Bredehoeft (1987) similarly concluded for the Pajaro Valley that "vertical leakage through the sea floor initially is the main pathway of seawater intrusion to the onshore portion of the aquifer". Finally, water-quality evidence of incipient historical intrusion at the Soquel Point, Moran Lake, Beltz #2, SC-8 and SC-9 wells further supports a conclusion that seawater can readily enter the Purisima aquifer units where they crop out on the ocean floor (Johnson and others, 2004; Hopkins Groundwater Consultants, 2011).

The occurrence of seawater intrusion is an "undesirable effect" that clearly meets the definition of overdraft. Unless SqCWD opts to undertake more expensive and aggressive measures such as the injection barriers used in Los Angeles and Orange counties, maintaining water levels at or above protective elevations is the only practical means of preventing intrusion.

Water balance calculations provide another indicator of overdraft that might not agree with the water-level indicator, primarily due to lags in the water-level response to changes in pumping. For example, water levels might still be below protective elevations even though the water balance is positive and water levels are rising. Conversely, rising water levels are not by themselves proof that pumping is below the sustainable yield, because losses to ocean outflow increase as water levels rise. Therefore, pumping within sustainable yield can only be confirmed when water levels are above protective elevations and not declining. During the transition from overdraft to sustainability, water levels and water balances both need to be considered in determining whether or how much additional corrective action is needed.

Question 6: What is the sustainable yield of the basin?

The foregoing discussion points out the considerable uncertainty associated with various aspects of the analysis and data limitations underlying HydroMetrics WRI's estimate of sustainable yield. Nevertheless, it remains the best available estimate. The total yield available to groundwater pumpers equals the 10,800 AFY of recharge estimated by the PRMS model minus the 2,725 AFY of outflow required to maintain protective groundwater elevations, or 8,075 AFY.

Basin yield is not a permanent, fixed quantity. It is affected by pumping locations and patterns of water use and wastewater disposal. The estimated yield could change in the future for any of a number of reasons, including:

- Quantification of constraints or opportunities related to stream flow depletion.
- Detection of new or accelerated seawater intrusion at coastal monitoring wells.
- Sewering areas presently served by septic systems, or increasing recycled water use within the basin.
- Improved analysis of urban hydrology and recharge in the coastal plain area.

- Revised water balance estimates based on groundwater modeling.

Estimating the sustainable yield available to SqCWD involves a number of additional assumptions and calculations. As described earlier, the HydroMetrics WRI estimate of 4,000 AFY involved highly conservative assumptions and could be too low by several hundred acre-feet per year.

Question 7: Are the Target Groundwater Elevations for the City of Santa Cruz coastal monitoring wells listed in the Cooperative Monitoring/Adaptive Groundwater Agreement correct?

The recommended protective elevations for City of Santa Cruz coastal monitoring wells were developed by Hopkins Groundwater Consultants (2011) based on the Ghyben-Herzberg formula without correction for outflow. That is, the recommended elevations listed in Table 1 of that report all equal one-fortieth of the depth of the bottom of the well screen (in feet below mean sea level (msl)). This approach considers only the elevation of the bottom of the well screen or aquifer; it does not consider distance from the coast. In practice, the protective elevations would create outflow to the ocean because they are above sea level. This outflow would necessarily be accompanied by a water table (or potentiometric surface) that slopes toward the ocean. Thus, at distances far from the coast, the simple Ghyben-Herzberg estimate of protective elevation would be lower than an elevation that considers outflow, but near the coast it would be higher. The Pleasure Point, Soquel Point and Moran Lake monitoring well locations are all close to the coastline, where the Ghyben-Herzberg estimate of protective elevation is probably conservatively high. Corcoran Lagoon is 2,500 feet inland, and additional analysis would be needed to determine whether the Ghyben-Herzberg protective elevation is higher or lower than the flow-corrected estimate. The difference would likely be on the order of a few tenths of a foot at most.

For monitoring well SC-1A operated by SqCWD, Hopkins calculated a Ghyben-Herzberg protective elevation of 6.2 feet above msl. However, the text recommends a protective elevation of 7 feet above msl for that well. The revised elevation would create a gradient (and groundwater flow) from SqCWD toward Santa Cruz's Live Oak well field. The stated rationale for this deviation is that it would help Santa Cruz maintain protective elevations. The recommendation would obviously work out favorably for Santa Cruz, but it is inconsistent with the well-by-well approach used by SqCWD to estimate protective elevations and associated outflows.

Question 8: Does the Soquel-Aptos Groundwater Basin Annual Review and Report adequately summarize the status of the basin?

The Annual Review and Reports (ARRs) need to be useful for multiple audiences. What is adequate for one audience might be insufficient or excessive for another. For example, an interested stakeholder or SqCWD customer may simply wish to be informed of the "state of the basin", whereas a technical consultant or informed water manager might want extensive tables of data to support various types of analysis. Accordingly, this review of the

2012 ARR includes some comments on the general accessibility of the ARR and its fulfillment of its purposes. Specifically, as part of the implementation of the 2007 Groundwater Management Plan (GMP), the stated purposes of the ARRs are to summarize groundwater conditions in the Soquel-Aptos basin, document the status of groundwater management activities, and recommend any amendments to the GMP.

The ARRs are described as living documents to be updated annually. Annual updates are needed, given the importance of groundwater supply and the seriousness of current issues. Many water management agencies use annual reports as a means of detecting emerging problems and gaging the success of management programs and projects. Adherence to a consistent organization from year to year is helpful in finding information and cost-effective.

It would be preferable for each ARR to focus on the current year. Appending the information for the current year to a document that contains similar information for prior years rapidly results in an ARR that is bulky and difficult to navigate. In its fourth year, the ARR is already 388 pages long. For the reader, scrolling through the document or flipping through pages is slow, particularly when figures and tables are provided at the end on the section. Comparison between years or basin subareas requires scrolling/flipping back and forth. It is easy to get lost because there are multiple versions of each section that look similar. For example, there are four versions of Section 7 that at first glance are distinguishable only by the footer. Accordingly, it is recommended that each ARR be a stand-alone document that focuses on a single year. Cumulative historical data are still available in the time-series graphs showing groundwater pumping, water-levels and water-quality, so for many purposes referring to prior-year reports would not be necessary. Nevertheless, ARRs for prior years can simply be available as separate documents online. If ARR content and organization remain consistent from year to year, readers who want to compare information over a period of years can readily do so.

The availability of ARRs is fair but could potentially be improved. They are posted and available for downloading from the SqCWD website, but unlike other important water planning documents (the Urban Water Master Plan, Groundwater Management Plan, Well Master Plan, etc.) they are not listed on the top-level “Water Supply” pull-down menu. Instead, they are available among other reports under Publications/Water Supply Reports. If the ARRs are intended to be easily accessed, including them on the “Water Supply” pull-down menu would be helpful.

The Executive Summary needs to be clear and easily understood by all interested readers. It is helpful to begin paragraphs with simple, key declarative statements. For example, a paragraph might begin with “there is an ongoing risk of seawater intrusion” and then explain. The Executive Summary should be reviewed for jargon such as *post-recovery pumping yields*, which are not immediately understandable. For the purpose of the summary, those concepts can be expressed in simpler terms, or the reader can be referred to the relevant report section. The figures in the Executive Summary are not easily understood and are attempting to convey too much information. For an Executive Summary, it would be better to show a few, key selected hydrographs and then refer the reader to a later section or appendix for more details.

Once streamlined into an annual report, a certain amount of introductory material will need to be repeated each year for the ARR to be complete as a stand-alone document. This would include a basic description of the Soquel-Aptos basin and why it is subdivided into Western Purisima, Central Purisima, and Aromas areas. Readers already familiar with the basin can simply skip this introductory material.

Many annual report users do not *read* the reports, they *search* them for specific data. For these users, a consistent format is much appreciated. Short paragraphs and subheadings are helpful. Consistent numbering of tables and figures is easily achieved in basic data appendices, which change little from year to year.

Another means of creating tiered levels of information for different audiences is to shift some of the basic data tables and figures—such as the lengthy sets of hydrographs—into appendices. The ARRs present most information as graphs rather than tables. Some readers might want to access the actual numbers. Appendices are an appropriate place to put tables of data that are not overwhelmingly extensive, such as monthly groundwater production, monthly climate data summaries and quarterly or semiannual water-level measurements. Data sets that are too bulky to include in the report (for example, water quality data or data-logger records of water levels) can be made available in digital format either posted on the website or available by request from SqCWD staff.

The ARR text refrains from needlessly describing information presented in tables and figures, which is good. The tables and figures speak for themselves. The contour maps are attractive, and easy to read and interpret.

Section 6.2, Recommended Revisions to Basin Management Objectives, provides a list of recommended changes to be included in some future update of the GMP. The content and level of detail seem out of place in an ARR. It sounds like an internal discussion between SqCWD staff and consultants that would be more appropriate to document in a separate memorandum.

Sections 6.1 and 6.3, Status of BMOs and Elements, respectively provide bulleted summaries on the status of each of the BMOs and elements that are relevant and informative—telling the story of what happened in the past year.

The four versions of Section 7.1 present nine separate priorities for the WY 2009 ARR, thirteen for 2010, sixteen for 2011, and seventeen for the 2012 ARR. Some priority actions have been accomplished (sometimes needing more than one year), but the list is getting longer and longer. This suggests that problems are cropping up at a quickening pace, or that priorities are not getting done, or that some items are not really priorities. So, the list of priorities—which should be compelling—is in danger of becoming discouraging or tiresome. It may be more effective to acknowledge several long-term goals (secure supplemental supply), to define a short list of specific objectives for the coming year (complete well master plan), and to weed out items that were initiated or completed in prior years or are not really priorities. For example, implementation of the well master plan may be important. However, once it is started, it should continue without being highlighted as a priority. It is recommended that the ARR be concluded with a short list of priorities that effectively and positively point the way to next year's work.

Additional minor comments on the content and organization of the 2012 ARR include:

- There is no map showing the location of rain gages. It would be desirable to include a map in an appendix.
- Redefine Section 2.1 "Annual Precipitation" as "Rainfall and Recharge". Otherwise the recharge discussion may be overlooked.
- The list of abbreviations should include RPE (reference point elevation).
- The hydrographs have different vertical scales. That allows for the various groundwater elevation ranges across this basin, but hinders hydrograph-to-hydrograph comparison. The annotations are interesting and useful in interpreting the hydrographs.
- The chemographs and hydrographs with highlighted 2008-2012 trends are useful. Why is 2008-2012 selected for highlighting? Where is the discussion of these trends, particularly those that appear counter-intuitive?
- Section 7.2 presents current data inadequacies. While these may have originated as recommendations (hence their inclusion in Section 7), they now appear as generalized complaints. It would be more effective to present these data problems earlier in the document in Section 6, where they can be considered more positively in the context of BMOs and elements.

RECOMMENDATIONS

This peer review indicated that the estimated long-term sustainable yield for SqCWD production of 4,000 AFY might have been too low by several hundred acre-feet per year. If so, the pumping reduction required to recover coastal groundwater levels to protective elevations was overestimated by an even larger amount. Several relatively minor additional studies could substantially reduce uncertainties that contribute to the discrepancy between the HMWRI yield estimate and the alternative yield estimate:

- Modify one or more of the cross-section models to estimate rates of groundwater outflow to the ocean along the planes of the Purisima aquifer units, and revise the estimates of outflows needed to maintain protective groundwater elevations accordingly.
- Construct one or two cross section models to simulate protective elevations and groundwater outflow along the Santa Cruz coastline segment between Soquel Point and the San Lorenzo River.
- Compile groundwater elevation data for shallow monitoring wells in the coastal plain area and compare those with invert elevations of nearby creeks and gulches to investigate the possibility that some shallow groundwater discharges to those waterways or directly to the ocean.
- Complete a literature and/or field investigation of the percentage of indoor water use that percolates back to the water table at residences with septic systems.

Given the large cost of implementing additional measures to further reduce SqCWD pumping, it is recommended that the above studies be completed first, to help determine how much reduction is in fact necessary.

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*Indicates key document identified for review.

Table 1. Calculation of SqCWD Pumping Yield in the Purisima Area

Yield Calciulation Step	HMWRI Estimate (AFY)	Alternative Estimate (AFY)	Basis for Alternative	Possible Additional Analysis
PRMS deep recharge	6,600	6,600	PRMS deep recharge has uncertainty but no obvious bias. Accept HMWRI value	
Subtract recharge west of SC-1	-1,200	-889	The subtraction of recharge in the Arana Gulch and Rodeo Creek watersheds was apparently to provide for recharge to City of Santa Cruz wells. The 70th percentile of production from those wells was only 550 AFY during 1968-2011. Additional recharge might be needed to sustain outflow associated with protective groundwater elevations near the City's wells. If the average outflow per unit width of coastline in the SC-1 and SC-3 models (0.214 AFY per linear foot) is applied to the 3 miles of coastline between the SC-1 model and San Lorenzo River, an outflow estimate of 339 AFY is obtained. The pumping and outflow estimates total 889 AFY.	The outflow requirements west of Soquel Point need to be modeled. Results from the SC-1 and SC-3 models are applicable to the coastline between SC-1 and Soquel Point because the B aquitard is present between the sea floor and the A aquifer, and the alignment of the coastline is the same. The B aquitard is absent between Soquel Point and the San Lorenzo River, which potentially increases the amount of outflow needed to maintain protective elevations. Thus the total outflow required for the Santa Cruz part of the Purisima area might exceed 339 AFY. Additional cross sectional models in that area should account for the location of Santa Cruz pumping and whether recharge in the inland parts of the watersheds flows south toward the coast or east down the dip of the formations.
Subtract 70th percentile protective outflow	-775	-775	Protective outflow might be larger if a permeable flow path exists from Purisima aquifer units to the sea floor along the plane of the dipping aquifer (i.e. diagonally upward to the sea floor outcrop of the aquifer).	Test this alternative flow path hypothesis by modifying one or more existing cross-section models to a tilted position in the plane of the aquifer.
Subtract non-SqCWD consumptive use	-1,992	-1,606	See return flow calculation table (Table 2).	
Add pipe leaks	0	207	A recent audit of SqCWD water production and deliveries indicated that "apparent losses" (leaks) amounted to 7.4% of total water production during 2010-2013. This percentage is multiplied by the post-recovery SqCWD pumping target of 2,800 AFY to obtain the alternative pipe leak estimate. 100% of the leaking water is assumed to return to water supply aquifers.	
SqCWD consumptive use yield (AFY)	2,633	3,537		
SqCWD return flow percentage	6%	3%	Equals 10% return flow of the 30% of total water use that is used for irrigation. HMWRI assumed 20% return flow.	
SqCWD post-recovery pumping yield (AFY)	2,801	3,646		
Possible reductions in alternative yield				
1. Increased ocean outflow:				
a. Santa Cruz area (AFY)		-170	If modeling indicates that outflow requirement is 50% greater than the initial estimate.	These possible reductions relate to the major sources of uncertainty in the alternative yield estimate and support the recommendations for additional cross-section modeling and evaluation of shallow coastal plain hydrogeology.
b. SqCWD Purisima (AFY)		-388	If tilted cross-section models indicate an outflow requirement 50% larger than the vertical models.	
2. Decreased coastal plain recharge (AFY)		-204	If one-third of recharge from rainfall, irrigation, septic systems and pipe leaks discharges to creeks, gulches and the ocean before percolating down to water-supply aquifers.	
Reduced alternative yield (AFY)		2,886		

Table 2. Consumptive Use and Groundwater Return Flows in the Purisima Area

Return Flow Calculation Step	HMWRI Estimate	Alternative Estimate	Basis for Alternative	Possible Additional Analysis
Cabrillo College				
Total pumping (AFY)	95	95		
Outdoor use (%)	42.5%	42.5%		
Outdoor use return (%)	20%	10%	20% return flow for urban irrigation seems high because: 1) Over-irrigation is rare due to public awareness of chronic water shortages, 2) a susbtantial part of irrigation inefficiency is losses to sprinkler spray evaporation, 3) another substantial part is overspray onto impervious surfaces, and 4) some of the recharge on the coastal terrace might not make it down to the Purisima production aquifers (for example, it might seep into coastal creeks and gulches that act as drains for shallow groundwater, listed from west to east: Soquel Creek, Noble Creek, Escalona Gulch, Tannery Gulch, Borregas Creek, unnamed gulch along State Park Drive, and Aptos Creek).	1. Field and literature surveys of sprinkler spray and overspray losses. 2. Hydrogeologic analysis of shallow groundwater flow in the coastal terrace area, using water levels from existing shallow monitoring wells (Geotracker sites). 3. Field surveys of dry-season flow and phreatophyte distribution along coastal gulches.
Outdoor use return (AFY)	8	4		
Consumptive use (AFY)	87	91		
City of Santa Cruz				
Total pumping (AFY)	540	0	Yield needed to supply City of Santa Cruz wells is already more than covered by the subtraction of 1,200 AFY of recharge west of SC-1.	
Total use return (%)	0	0	HMWRI's estimate of 540 AFY is consumptive use. Total pumping and return flow were not estimated independently.	
Total use return (AFY)	0	0		
Consumptive use (AFY)	540	0		
Other Non-SqCWD Pumpers				
Total pumping (AFY)	2,128	2,128	Equals 2,668 AFY total minus 540 AFY Santa Cruz.	
Outdoor use (%)	56%	56%		
Outdoor use return(%)	20%	10%	See note under "Cabrillo College" above.	
Outdoor use return (AFY)	299	119		
Indoor use (%)	24%	24%		
Indoor use return (%)	75%	98%	The amount of indoor water use that becomes wastewater is more than 75%. DWR (1983) estimated 98%. Losses to evapotranspiration at the leach field are also probably small because leach fields are typically covered with shallow-rooted plants to avoid root clogging of leach drains.	Additional literature review related to consumptive losses during indoor use and septic percolation.
Indoor use return (AFY)	473	493		
Consumptive use (AFY)	1,355	1,515		
Total consumptive use (AFY)	1,982	1,606		

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Total use return (%)	0	0	HMWRI's estimate of 540 AFY is consumptive use. Total pumping and return flow were not estimated independently.	
Total use return (AFY)	0	0		
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Total pumping (AFY)	2,128	2,128	Equals 2,668 AFY total minus 540 AFY Santa Cruz.	
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Indoor use return (AFY)	473	493		
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Total consumptive use (AFY)	1,982	1,606		

Table 3. Calculation of SqCWD Pumping Yield in the Aromas Area

Yield Calciulation Step	HMWRI Estimate (AFY)	Alternative Estimate (AFY)	Basis for Alternative	Possible Additional Analysis
PRMS deep recharge	4,200	4,200	PRMS deep recharge has uncertainty but no obvious bias. Accept HMWRI value.	
Subtract groundwater outflow to Pajaro Valley basin	-370	-271	HMWRI calculated outflow based on water-level gradients and Darcy's law. The outflow associated with the maximum estimated transmissivity was used in the yield calculations. The alternative estimate invokes the spirit of the statistical approach used in the protective elevation and outflow calculations. The 70th percentile of outflow to Pajaro is estimated as 70% of the range between the smallest and largest transmissivity values: (40 AFY + (70%)(370 - 40 AFY) = 271 AFY.	
Subtract 70th percentile protective outflow	-1,950	-1,950		
Subtract non-SqCWD consumptive use	-754	-673	See return flow calculation table (Table 4).	
Add pipe leaks	0	89	SqCWD pipe leak rate is approximately 7.4% of annual production (see Purisima yield table notes). Mulitplying this percentage by 1,200 AFY of post-recovery Aromas production obtains a leak estimate of 89 AFY. All of this is assumed to percolate back to groundwater.	
SqCWD consumptive use yield (AFY)	1,126	1,395		
SqCWD return flow percentage	6%	3%	Equals 10% return flow of the 30% of total water use that is used for irrigation. HMWRI assumed 20% return flow.	
SqCWD post-recovery pumping yield (AFY)	1,198	1,438		

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SqCWD post-recovery pumping yield (AFY)	1,198	1,438		

Table 4. Consumptive Use and Groundwater Return Flows in the Aromas Area

Return Flow Calculation Step	HMWRI Estimate	Alternative Estimate	Basis for Alternative	Possible Additional Analysis
Other Non-SqCWD Pumpers				
Total pumping (AFY)	1,403	1,403		
Outdoor use (%)	52%	52%		
Outdoor use return(%)	20%	10%	20% return flow for urban irrigation seems high because: 1) Over-irrigation is rare due to public awareness of chronic water shortages, 2) a susbtantial part of irrigation inefficiency is losses to sprinkler spray evaporation, and 3) another substantial part is overspray onto impervious surfaces.	See Purisima notes.
Outdoor use return (AFY)	146	73		
Indoor use (%)	48%	48%		
Indoor use return (%)	75%	98%	The amount of indoor water use that becomes wastewater is more than 75%. DWR (1983) estimated 98%. Losses to evapotranspiration at the leach field are also probably small because leach fields are typically covered with shallow-rooted plants to avoid root clogging of leach drains.	See Purisima notes.
Indoor use return (AFY)	503	657		
Consumptive use (AFY)	754	673		

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Indoor use return (AFY)	503	657		
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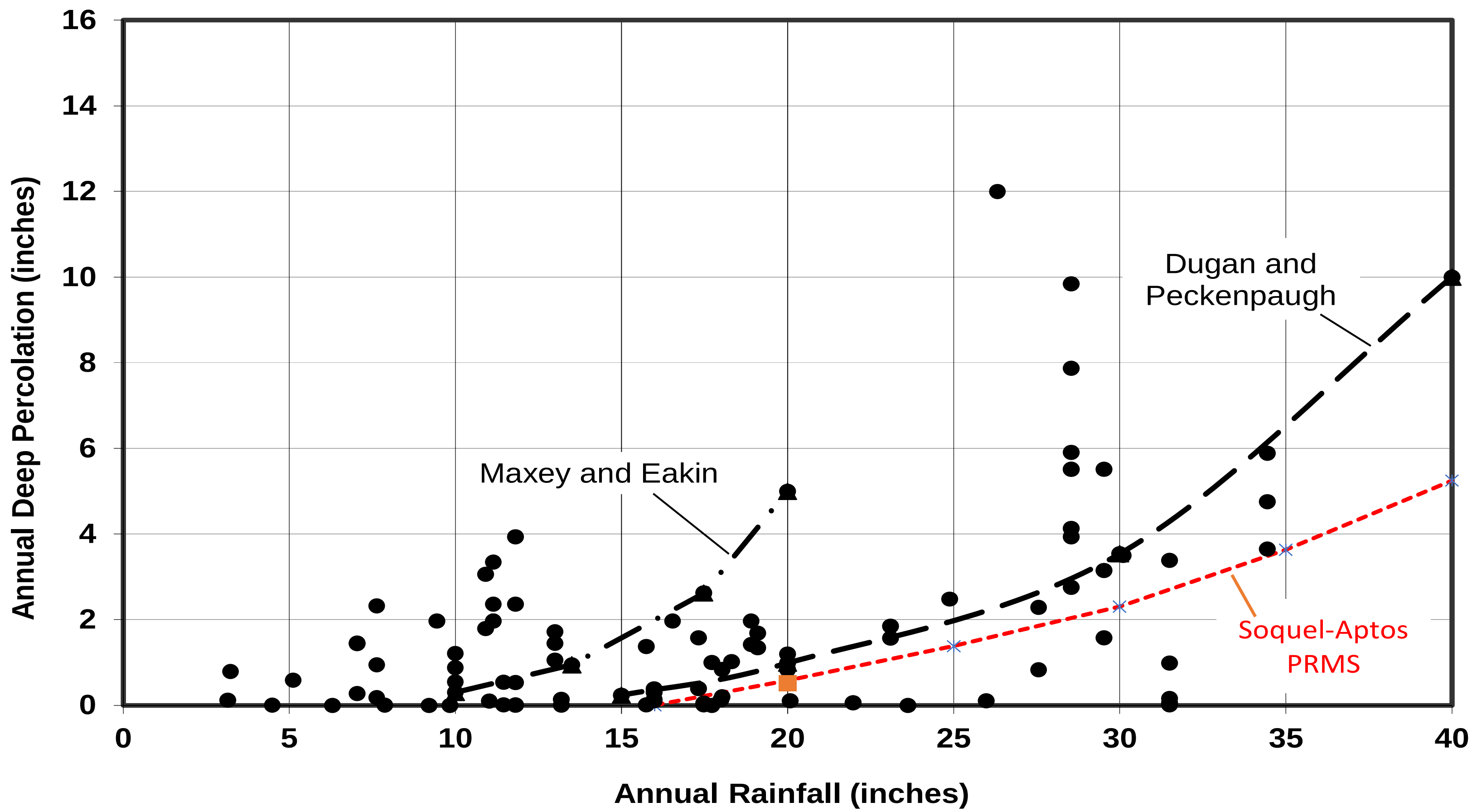
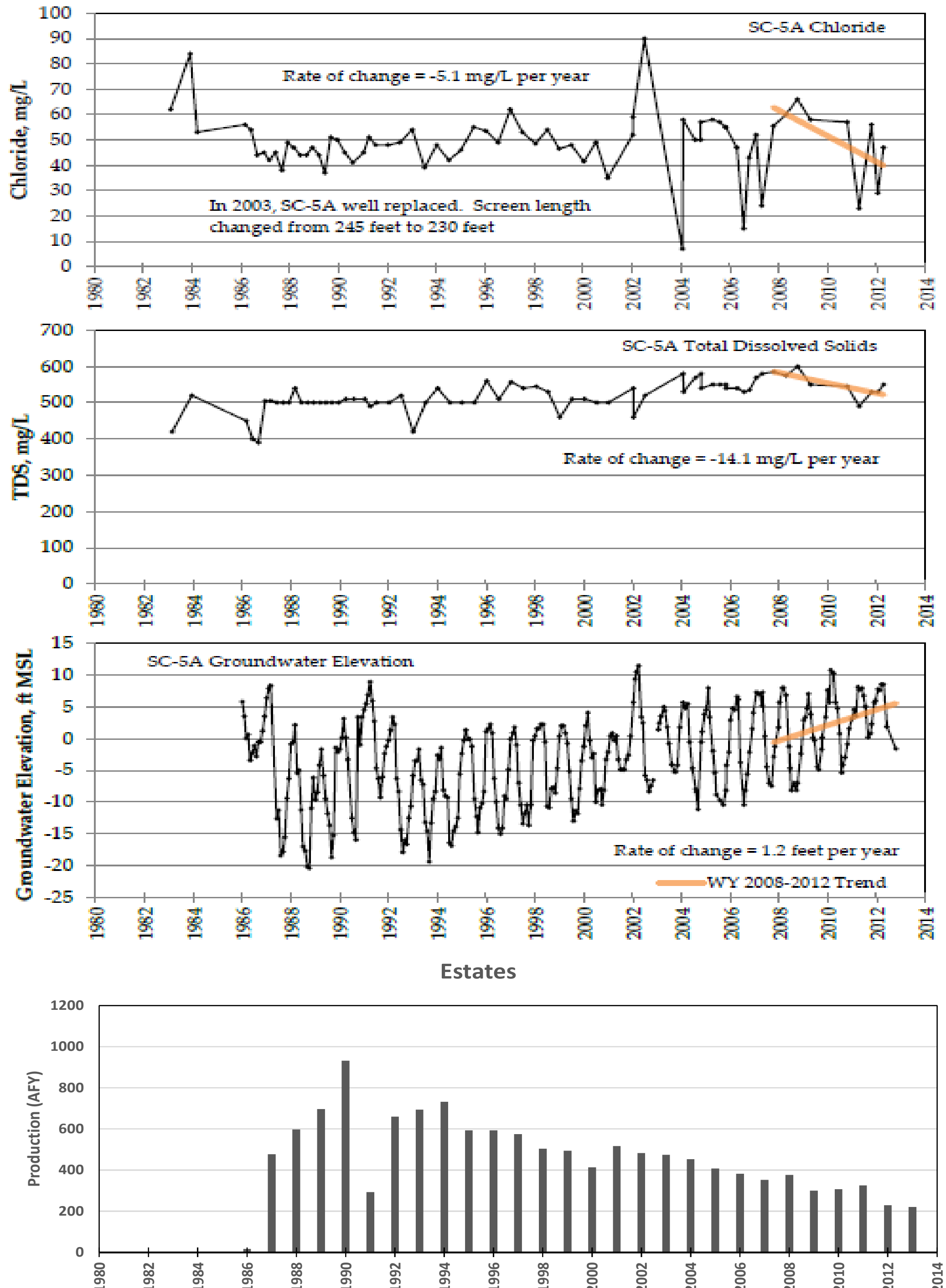


Source: Bedinger (1987)

May 2014

TODD GROUNDWATER

Figure 1
Rainfall Recharge in Semiarid Regions



Water levels and quality: SC-5A monitoring well
Groundwater pumping: Estates Well

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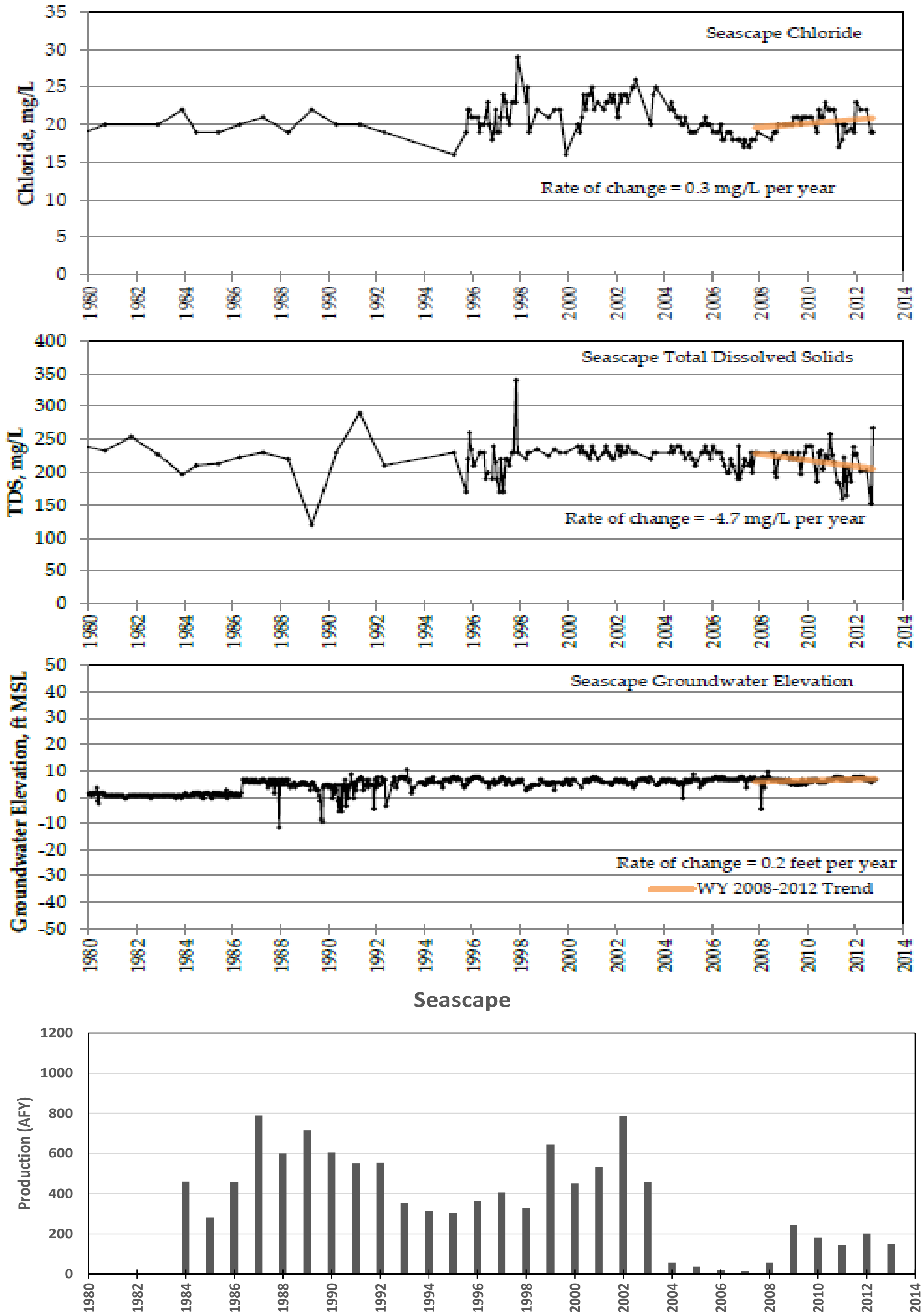
Figure 2

Pumping, Water Levels and Water Quality at Well SC-5A



Water levels and quality: Seascape Well
Groundwater pumping: Seascape Well

May 2013

TODD GROUNDWATER

Figure 3
Pumping, Water Levels and Water Quality at the Seascape Well

APPENDIX A. SEAWATER INTRUSION CASE STUDIES

The history of seawater intrusion in other coastal basins in California was compiled from published studies. The purpose of this review was to address the following questions related to intrusion risk in the Soquel-Aptos basin and the reasonableness of the HydroMetrics WRI analysis:

- What was the history of coastal water levels prior to the detection of intrusion? Has intrusion ever occurred due to density alone, or has it only occurred when onshore water levels dropped below sea level?
- What methods were used to estimate protective groundwater levels and the outflow associated with maintaining those levels?
- What management measures were implemented to prevent or minimize intrusion?

1. Salinas Valley

References: California Division of Water Resources (1946); Geoscience Support Services (2013)

Geology: Layered alluvial deposits: Shallow aquifer; Salinas Valley Aquitard; 180-Foot aquifer; 400-Foot aquifer; 900-Ft aquifer.

History of intrusion: Intrusion first noticed in 1938 in the 180-Foot aquifer and averaged approximately 6,000 AFY during 1939-1945. It has continued ever since.

Rate of water-level decline in 0-5 ft msl range: I tabulated all pre-1939 WL measurements in data report in quadrants 1B (Castroville to coast) and 1C (lower end of Salinas River). Almost all data were 1931-1938. In the 1-B region, only 23% of measured elevations were above sea level. 32% were 0-5 ft blw msl, 18% were 5-10 ft blw msl, and 12% were >10 ft blw msl (n=60). In the 1-C region, 70% of elevations were above msl. All but one of the others were in the 0-5 ft blw msl range.

Therefore, water levels had been frequently below sea level in many wells for 8 years leading up to the detection of intrusion.

Management response: Residents and agencies in the Salinas Valley have implemented a series of measures over the past 60 years to reduce or adapt to seawater intrusion:

- Drilling deeper wells. First to the 400-Foot aquifer (which also became intruded) and then to the 900-Foot or “deep” aquifer.
- Construction of Nacimiento and San Antonio Reservoirs in 1950s and 1960s to store water for increased groundwater recharge in the Salinas Valley.

- Construction of a regional wastewater treatment plant and use of recycled water for irrigation near the coast, beginning in the 1980s.
- Construction of the Salinas Valley Water Project which conveys upstream reservoir releases to coastal irrigators by means of a diversion dam near the coast, beginning in 2010.
- Identification of protective groundwater elevations for the 180-Foot and 400-Foot aquifers, in 2013. These were based on a Ghyben-Herzberg equivalent freshwater head at the coastline, plus a seaward gradient of 1 ft/mile near the coast (Geoscience Support Services, 2013).

2. Oxnard Plain, Ventura County

<u>Reference:</u> California Department of Water Resources (DWR), Bulletin 63 (1965)

<u>Geology:</u> layered alluvial deposits. Intrusion first occurred at the head of Hueneme Canyon (offshore feature).

<u>History of intrusion:</u> High salinity detected in two wells at the coast during 1931-32 drought, when WLs "were as much as 5 ft below sea level". pp. 6-7

1937-45: high WL's, no intrusion.

1950: first reported intrusion. Head of Hueneme Cyn. Also in a well at Pt. Mugu. Plate 2 shows 500 mg/L chloride just coming onshore at Port Hueneme in 1950.

1958: more definitive intrusion.

Plate 3: time series plot of WL in one well and area impacted by intrusion. The area curve is projected back (dashed lines) to zero acres in the year the WLs dropped below sea level.

<u>Rate of water-level decline in 0-5 ft msl range:</u> 10 ft/yr (spring-to-spring WLs)

<u>Management response:</u>

1950: United Water Conservation District formed

1955: Lake Piru reservoir built to supply water for groundwater recharge

1986: Direct pipeline delivery of Lake Piru water to growers in Oxnard Plain

1991: Freeman diversion to capture stormwater for groundwater recharge

1996: Expanded spreading grounds.

3. Santa Maria Basin, Arroyo Grande Area, San Luis Obispo County

Reference: DWR Bulletin 63-3 (1970). Todd Engineers (2010)

Geology: Well 30N2 is completed in the "B zone" aquifer, which is overlain by several sand and clay layers including one extensive clay layer 25 feet thick and three smaller clay layers 5-10 ft thick, according to a DWR (1970) cross section fortuitously located in the immediate vicinity.

History of intrusion: DWR investigated reports of elevated groundwater salinity in the 1960s but found that with two minor exceptions the source of the salinity was not seawater intrusion. One exception was the shallowest aquifer in direct contact with the ocean. Groundwater salinity in shallow coastal wells was high in spite of water levels above the level needed to repel intrusion. The salinity was attributed to other mechanisms such as wave overwash, lagoon leakage, etc. A deeper well 32S/13E-30P2 was flagged as having "possible intrusion". It was screened at 79-93 ft bgs and had water levels that had been stable at around +20 ft msl during 1951-58, fairly stable at 10-18 ft during 1959-1964, then declining to -1 to 18 ft during 1965-67. The summer low water levels were all between -1 and +3 ft msl during those last three years, when elevated chloride was detected.

A similar pattern appeared 50 years later. Seawater intrusion sentry well cluster 32S/13E-30N1, N2 and N3—located next to the lagoon near the site of 30P2—exhibited signs of incipient intrusion in 2009. The deepest well (30N2, screened 175-255 ft bgs) had experienced summer low water levels at 0 ft msl frequently during 1967-2008 (average water level about +4 ft msl) without signs of intrusion. In 2009, the water level dropped to -2.5 ft in summer, and TDS concurrently increased from 1,300 mg/L to 2,050 mg/L. A Schoeller plot of ion ratios confirmed a shift toward sodium-chloride composition (Todd Engineers, 2010). By the following winter, water levels were at +7 ft msl and TDS had declined to 950 mg/L.

Rate of water-level decline in 0-5 ft range: 2.5 ft/yr (1965-67); 0.8 ft/yr (2004-09)

Conclusion: density alone did not cause intrusion when water levels were between sea level and the G-H protective level of approximately +6 ft for 40 years. Rapid and reversible intrusion occurred as soon as water levels dropped below sea level in 2009.

Management response: no response intended to directly affect intrusion? Adjudication of basin groundwater rights in 2000s.

4. West Coast Basin, Los Angeles County

Reference: Johnson and Whitaker, 2004

Geology: layered Pliocene to Holocene alluvial deposits. Up to 12 named sand and gravel aquifers separated by fine-grained confining layers.

History of intrusion: Intrusion first reported in 1912, and cumulative total reached approximately 600,000 AF by the late 1950s.

Rate of water-level decline in 0-5 ft msl range: one example hydrograph showed water levels declining from +70 to -105 ft msl in 43 years, taking 2 years to pass through the 0 to +5 ft msl range (2.5 ft/yr). Too fast to detect density effects.

Management responses:

- Adjudicate the basin and create an agency to manage pumping
- Replenish the basin with active recharge of imported and recycled water
- Create an injection barrier along the coast (now 16 miles long).

5. Los Osos Basin, San Luis Obispo County

Reference: Cleath & Associates (2005)

Geology: This small, triangular basin deepens and widens toward the coast. The western part of the basin is overlain by Morro Bay (saltwater), which is separated from the Pacific Ocean by a narrow sand spit. Surficial dune sand deposits extend inland 1-2 miles from Morro Bay and are underlain by the Paso Robles Formation. Basin stratigraphy consists of relatively thin and discontinuous layers of sands, silts and clays. However, one laterally extensive clay layer noticeably impedes vertical groundwater flow over and separates the basin into “upper” and “lower” zones.

History of intrusion: Groundwater use was small prior until the 1970s, when residential development began increasing rapidly. Groundwater is the sole source of water supply. Test wells drilled on the sandspit in 1977 had chloride concentrations greater than 2,500 mg/L. Sandspit well 14B1 is screened at -170 to -190 ft msl and has had water levels 3-4 feet above sea level since the 1970s. This would counterbalance seawater only down to -120 to -160 ft msl. Salinity has not increased since the 1970s. This appears to be a case where saltwater has intruded onshore even while onshore water levels remained above sea level. It also means there was no lag in landward movement of the saltwater-freshwater interface due to sea level rise and therefore indicates a relatively permeable, near-shore connection between the groundwater basin and the ocean.

Well 13M2 located 3,000 feet inland is screened to -251 ft msl and has had water levels between 0 and -3 ft msl fairly continuously since 1989. Salinity increased during 1977-2005. The furthest inland advance to date is at municipal well 18J6, located 1.9 miles from the coast. It is located near the center of a pumping trough where water levels have been below sea level since at least 1980, averaging about -10 ft msl during that period.

Rate of water-level decline in 0-5 ft msl range: Few data are available. Most wells in the intruded areas had water levels at or below sea level when monitoring commenced. Levels have generally been fairly steady.

Management response:

- An adjudication proceeding that included only the large municipal pumpers was initiated in 2004. Private domestic and agricultural users represent one-third of total basin pumping, but they are not parties to the adjudication and are not required to participate in implementation of the basin plan. Within a few years, the adjudication proceedings shifted to a collaborative mode by means of an interlocutory stipulated judgment. Progress in implementing solutions has been slow, however. As of 2014, the sewer system and recycling projects have not been constructed, and a basin plan with probably-inadequate measures is still under review.
- A draft basin management plan was completed in 2013. It calls for shifting pumping inland and upward, water conservation, wastewater recycling, recycled water recharge, and encouragement of greywater, rainwater and stormwater capture systems.
- Overall, the physical measures proposed in the basin plan do not appear to solve the fundamental imbalance between recharge and withdrawals.
- The basin plan includes three metrics to guide adaptive management:
    - **Water level metric.** The management target is an average elevation of +8 ft msl at several key monitoring wells. Note that this would counterbalance sea water only down to -320 ft msl, whereas numerous municipal wells have screens that extend to -400 ft msl or deeper.
    - **Chloride metric.** The management target is an average chloride concentration of 100 mg/L in selected monitoring wells. Most of those wells had chloride concentrations around 60 mg/L in the 1970s, but the drinking water standard is 250 mg/L.
    - **Basin yield metric.** To hedge against uncertainty in the analysis, the target is to limit production to 80 percent of the basin yield, as calculated using an existing groundwater model. The yield changes as various water and wastewater projects are implemented.

6. Pajaro Valley, Santa Cruz and Monterey Counties

References: Hansen (2003); Johnson (1983); California State Water Resources Control Board (1953); Pajaro Valley Water Management Agency (2013)

Geology: Alluvial deposits overlie the Aromas Sand. No significant aquitards in the upper aquifer system, which extends to a depth of approximately 200 feet.

History of intrusion: Intrusion was first reported in 1943 at a time when coastal pumping troughs had water levels as much as 15 feet below sea level. In 1951, intrusion was present only south of the Pajaro River and extended at most 1 mile inland. By 2011 it was present along the entire coastline between La Selva Beach and Moss Landing, extending 1.5-4 miles inland. Studies have demonstrated that only saltwater in the upper aquifer system is from recent intrusion. Based on ion ratios, isotopes and age dating, saline groundwater in deeper units appears to be relict seawater from prior high stands of sea level or saline groundwater from onshore geologic materials of marine origin (Hansen, 2003).

Rate of water-level decline in 0-5 ft msl range: Because of confined aquifer conditions and large seasonal pumping stresses for irrigation, water levels began dropping below sea level in a pumping trough aproximately 1-2 miles inland in the Springfield Terrace area (just south of the Pajaro River) as early as 1940, before water levels were systematically monitored. Thus, it would be impossible to isolate density effects on intrusion from simple advective effects.

Management measures:

- A coastal distribution system was constructed to deliver surface water and recycled water to cropland near the coast, beginning in 2002.
- The Harkins Slough managed aquifer recharge project retains and percolates stormwater runoff that enters Harkins Slough. Some of the water is pumped back out of the aquifer and delivered to growers via the coastal distribution system.
- The Watsonville wastewater treatment plant was upgraded to produce recycled water for delivery via the coastal distribution system. Deliveries began in 2009.
- The 2012 basin management plan update identified and screened a large number of measures to balance the basin water balance and halt overdraft. A screening process identified several measures for implementation over the next 10 years:
    - Increased recycled water deliveries, facilitated by increased seasonal recycled water storage capacity.
    - Increased capture and percolation of stormwater, in Watsonville Slough and College Lake, plus a pipeline to connect College Lake to the coastal distribution system.
    - Water conservation.
    - An upgrade of the Harkins Slough recharge facilities.
    - Murphy crossing with recharge basins.

7. Santa Barbara

References: Martin (1984); City of Santa Barbara (2013)

Geology: The fault-bounded Storage Unit I basin consists of unconsolidated marine sand, silt and clay deposits up to 1,000 feet thick. These deposits are part of the Santa Barbara Formation, which is the same age as the Purisima Formation in the Soquel-Aptos basin. An offshore fault parallel to the shoreline was suspected of functioning as a barrier to seawater intrusion.

History of intrusion: Intrusion has been detected in this basin only during a controlled test of increased groundwater pumping rates accompanied by monitoring at coastal sentinal wells. Water use in the basin consists almost entirely of municipal use by the City of Santa Barbara, which is supplied primarily by imported surface water. In 1979, the City increased its use of local groundwater to more than double the average amount of pumping over the preceding five years. , partly to test the effectiveness of the offshore fault as a barrier against intrusion. Water levels declined by up to 100 feet over the two-year test period. Chloride concentrations at four of the six coastal monitoring wells increased during the 18-month test (on average by several hundred milligrams per liter), confirming that the offshore fault is not a barrier to intrusion.

Rate of water-level decline in 0-5 ft msl range: Water levels in the lower producing zone declined from +25 to -75 feet msl over an 18-month period (66 ft/yr) at the center of the pumping trough, 1 mile from the coast. This rate was far too fast to detect density effects on intrusion.

Management measures:

- State Water Project deliveries commenced in 1998.
- Construction of a seawater desalination plant, which is continuously available on a standby basis.
- Use of recycled water to serve parks, schools, golf courses, large landscaped areas and some public restrooms.
- Water conservation program that meets the requirements of the California Urban Water Conservation Council's best management practices, including rebates for turf conversion.

8. Westside Basin, San Francisco and San Mateo Counties

Reference: WRIME (2012); San Francisco Planning Department (2013)

Geology: The Westside basin covers the western part of San Francisco from Golden Gate Park to Daly City and continues across the peninsula to San Francisco Bay near San Bruno and Millbrae. Most of the basin fill is sandy material. Dune sands and the semi-consolidated Colma Formation are relatively thin surficial deposits. Most of the basin fill is Merced Formation, which consists of a fine sandstone with occasional moderately thick clay layers. Groundwater is connected to saltwater at both ends: the Pacific Ocean at the west end and San Francisco Bay at the east end.

The basin has not yet experienced seawater intrusion, but only because of unusual geologic features. Steep folding of the Merced Formation between Daly City and the coast has prevented intrusion in that area and extensive, continuous bay mud deposits plus a buried bedrock ridge have prevented intrusion at the east end of the basin.

History of intrusion: Seawater intrusion has not yet occurred in this basin. It is an example of the role geologic conditions can play in limiting the flow of seawater into onshore aquifers. Water levels in the Daly-City to San Bruno area have been consistently 150-200 feet below sea level since the 1970s. Intrusion has not occurred because of the unique geologic structures described above. San Francisco is actively planning to recommence use of its local groundwater resources using wells in the Sunset District. There is no known barrier between the basin and the ocean in that part of the basin. However, modeling of the proposed groundwater supply project produced simulated groundwater elevations in the primary production aquifer that were continuously below the Ghyben-Herzberg protective groundwater levels during the 47-year simulation period (San Francisco Planning Department, 2013).

Rate of water-level decline in 0-5 ft msl range: Most of the decline in water levels occurred during the 1950s and 1960s and was much too rapid to discern density-only intrusion, if intrusion had occurred.

Management response:

- Daly City and San Bruno have installed additional monitoring wells near the Pacific Ocean and San Francisco Bay to provide additional ability to detect incipient intrusion.
- A conjunctive use project in the Daly City-San Bruno part of the basin would store imported (Hetch-Hetchy) water by in-lieu recharge and allow San Francisco to pump the stored water back out during droughts. This project will raise long-term average groundwater elevations and thereby decrease the landward gradients that could eventually cause seawater intrusion.
- San Francisco plans to mitigate the low water levels expected to result from its groundwater supply project as follows:
    - Simulated movement of the interface was only 1 ft/yr. Therefore, sentinal wells will detect incipient intrusion before it reaches production wells.
    - Phase in the total amount of pumping from the network over a four-year period.
    - If incipient intrusion is detected, pumping will be shifted to other wells in the supply network.
    - If pumping redistribution does not appear to be sufficient to prevent the chloride concentration from reaching 250 mg/L at one or more production wells, total production will be decreased.

9. Seaside Basin, Monterey County.

Reference: Yates and others (2005); HydroMetrics, LLC (2009).

Geology: The basin includes two geologic formations tapped for groundwater. The upper one is the Paso Robles Formation consisting of relatively thin, discontinuous layers of sand, silt and clay. Water quality is generally good, but well yields are slightly low. This is underlain by the Santa Margarita Formation, which is a marine sandstone with higher yields but somewhat poorer quality. Because of folding and faulting, the depths of the two formations are variable, with the shallowest depths toward the southern end of the basin. There, the Paso Robles Formation is present at 0-500 ft below sea level (depending on location) and the Santa Margarita is at 300-600 ft below sea level.

<u>History of intrusion:</u> This is another basin where intrusion has not yet been detected. However, coastal water levels are commonly below sea level and there is no know geologic separation between the two main aquifers and the ocean. A pumping trough is present in the Paso Robles aquifer approximately 1-2 miles inland. Fall water levels are as much as 20 ft below sea level at the center of the trough but usually a few feet above sea level between the trough and the coastline. Multi-depth sentinel well clusters installed in 2007 revealed that spring water levels in the Santa Margarita aquifer are 10-15 feet below sea level along most of the coastline, and they drop to 20-25 ft below sea level in fall.

<u>Rate of water-level decline in 0-5 ft msl range:</u> 2-5 ft per year in inland monitoring wells in the Santa Margarita aquifer. Fluctuating water levels in the Paso Robles aquifer.

<u>Management response:</u> Water balance calculations in the early 2000's indicated that the basin was in overdraft. An adjudication was initiated shortly thereafter. The court-appointed watermaster initiated programs to install sentinel wells, develop a three-dimensional freshwater groundwater flow model of the entire basin, and estimate protective elevations using vertical cross-section SEAWAT models at four locations along the coastline.

Appendix B. Relationships between Pumping, Water Levels and Water Quality

The governing equations for groundwater flow predict that an increase in pumping at a well will decrease water levels in and near the well. Also, for coastal wells in or near the saltwater-freshwater transition zone, lower water levels would tend to increase concentrations of TDS and chloride. Finally, TDS and chloride should follow similar patterns over time because they are both relatively conservative water quality constituents that do not decay or react with the aquifer matrix. To test these relationships, water-level hydrographs for 85 SqCWD and City of Santa Cruz monitoring and production wells were compared with annual amounts of pumping in or near the well. Water-level trends were also compared with water-quality trends, and the trends for chloride were compared with the trends for TDS. The correlations were evaluated qualitatively by visual inspection of hydrographs and time-concentration plots. The degree of correlation was assigned to three categories: strong, weak or intermittent, and non-existent or counterintuitive. The results of this comparison for all 85 wells are listed in **Table B-1**.

Table B-1. Correlations among Pumping, Water Levels and Water Quality

Well	Correlation of Water Levels with Pumping[1]	Water-Quality Response to Water Levels[1]	Chloride and TDS Consistent[1]	Correlated Pumping Well
Coastal Monitoring Wells				
Corcoran Lagoon Shallow	✓	✗	✓	Beltz #9
Corcoran Lagoon Medium	✓	✓	✓	Beltz #9
Corcoran Lagoon Deep	✓	✓	✓	Beltz #9
Moran Lake Shallow	●	✗	✓	Beltz #9
Moran Lake Medium	●	✗	✓	Beltz #9
Moran Lake Deep	●	✓	✓	Beltz #9
Beltz #2 (2004-2012)	✓	✗	✓	Beltz #9
Beltz #6 (2004-2012)	✗	✗	✓	
Pleasure Point Shallow	●	✗	✓	Beltz #1, #2, #9
Pleasure Point Deep	●	✗	✓	Beltz #1, #2, #9
Soquel Point Shallow	✓	✓	✓	Total Live Oak
Soquel Point Medium	✓	●	✗	Total Live Oak
Soquel Point Deep	✓	✓	✓	Total Live Oak
SC-1A	✓	✗	✓	Garnet - Opal
SC-1B	●	--	--	Garnet - Opal
SC-3A	✓	●	✓	Monterey
SC-3B	●	✗	✓	Rosedale
SC-3C	✗	✗	✓	
SC-5A	✓	✓	✓	Estates
SC-5B	●	✓	✓	Estates
SC-5C	✗	✗	●	
SC-9A	✓	✗	✗	Estates, T. Hopkins
SC-9B	✓	✗	✓	Ledyard
SC-9C	✓	✗	✓	Ledyard
SC-9D	✗	✗	✗	
SC-9E	✗	✗	✗	
SC-8A	✓	●	●	Estates
SC-8B	●	✓	✓	Ledyard
SC-8C	●	✓	✓	Ledyard
SC-8D	●	✗	✓	Ledyard
SC-8E	✗	✓	✓	
SC-8F	✗	✓	✓	
SC-A1B	●	✓	✓	Country Club
SC-A1C	✗	●	●	
SC-A1D	●	✓	✓	Bonita
SC-A8A	●	✓	✓	Country Club
SC-A8A	●	✓	✓	Country Club, Bonita
SC-A8C	●	●	●	Country Club
SC-A2A	●	✓	✓	Seascape, Altivo + Sells
SC-A2B	●	●	✓	Seascape
SC-A2C	✗	✓	✓	
SC-A3A	✗	✓	✗	
SC-A3B	●	●	✓	Altivo, Sells
SC-A3C	✓	✗	✗	Altivo, Sells
SC-A4A	✗	●	✓	
SC-A4B	✗	●	✗	
SC-A4C	✗	✗	✗	
SC-A4C	✗	●	●	

Table B-1: Continued

Well	Correlation of Water Levels with Pumping	Water-Quality Response to Water Levels	Chloride and TDS Consistent	Correlated Pumping Well
Inland Monitoring Wells				
SC-10AA	✖	n.a.	●	
SC-10A	✖	n.a.	●	
SC-18AA	✓	n.a.	--	Main Street
SC-18A	✓	n.a.	--	Main Street
SC-16A	●	n.a.	--	Estates
SC-16B	●	n.a.	--	Estates
SC-14A	✓	n.a.	--	Estates
SC-14A	✓	n.a.	--	Estates
SC-14C	✖	n.a.	--	
SC-19	--	n.a.	--	
SC-17A	✖	n.a.	--	
SC-17B	✓	n.a.	--	Ledyard
SC-17C	✓	n.a.	--	Ledyard
SC-A6A	--	n.a.	--	
SC-A6B	--	n.a.	--	
SC-A6C	--	n.a.	--	
SC-A5A	✖	n.a.	✓	
SC-A5B	✖	n.a.	●	
SC-A5C	●	n.a.	✓	Seascape
SC-A5D	●	n.a.	✖	Seascape
Production Wells				
Garnet	●	✓	✓	Garnet
Main Street	●	n.a.	●	Main Street
Rosedale	●	n.a.	✓	Rosedale
Monterey	●	✖	✖	Monterey
Tannery II	✖	n.a.	✓	
Estates	●	✓	✓	Estates
Madeline	●	✓	✓	T. Hopkins
Ledyard	✓	✓	✓	Ledyard
T. Hopkins	✖	✓	✓	
Aptos Creek	✓	✓	✓	Aptos Creek
Aptos Jr. High	--	n.a.	--	
Country Club	✖	●	●	
Bonita	✖	n.a.	✓	
San Andreas	✖	n.a.	✓	
Seascape	✖	✖	✖	
Altivo	✖	✖	✓	
Sells	✖	✖	✓	

n.a. = not applicable. Water quality resonse only evaluated for wells near the coast.

[1] **Key to Symbols**

Symbol	Correlation of Water Levels with Pumping	Water-Quality Response to Water Levels	Chloride and TDS Consistent
✓	Strong	Intuitive	Consistent
●	Weak	Mixed	Mixed
✖	None	Counterintuitive	Inconsistent
--	Insufficient data	Insufficient data	No data