RELATIONSHIP OF CLIMATE CHANGE TO

SEAWATER INTRUSION IN COASTAL AQUIFERS

By

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TITLE OF STUDY: RELATIONSHIP OF CLIMATE CHANGE TO SEAWATER INTRUSION IN COASTAL AQUIFERS

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ABSTRACT: SCIENTIFIC CONSENSUS HAS ESTABLISHED THAT CLIMATE CHANGE OVER THE NEXT CENTURY WILL CAUSE A SIGNIFICANT RISE IN GLOBAL MEAN SEA LEVEL. A CONFLUENCE OF FACTORS PLACES THIS RISE TO BE BETWEEN 0.25 METERS AND 0.95 METERS, WITH A 95% CONFIDENCE INTERVAL. ALONG WITH COMPOUNDING ISSUES LIKE CHANGES IN THE PRECIPITATION CYCLE, THIS RISE IN SEA LEVEL WILL IMPACT GROUNDWATER RESOURCES, PARTICULARLY IN SENSITIVE AREAS SUCH AS COASTAL AQUIFERS. AS A REASONABLE UNDERSTANDING OF THE DYNAMICS OF AQUIFER SYSTEMS HAS BEEN DEVELOPED, THE ACTUAL IMPACT ON THESE GROUNDWATER RESOURCES CAN BE ESTIMATED. MOREOVER, THEY SHOULD BE ESTIMATED IN ORDER TO HELP PREPARE ROBUST WATER MANAGEMENT STRATEGIES FOR COASTAL COMMUNITIES. A PRELIMINARY INVESTIGATION IS CONDUCTED WITHIN THIS WORK, FOR THE CASE STUDY OF THE CALIFORNIAN OXNARD-MUGU AQUIFER, EMPLOYING THE HYDROSTATIC BALANCE RELATIONSHIPS ESTABLISHED BY GHYBEN AND HERZBERG, AND BY GLOVER, IN THEIR NOW STANDARD WORKS ON GROUNDWATER HYDROLOGY.

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CHAPTER 1

I.I INTRODUCTION

Although approximately 70% of the Earth's surface is covered by water; freshwater makes up only 3% of the total water on the planet. Moreover, the majority of freshwater is stored as ice, in glaciers and polar ice sheets. Although humans rely heavily on freshwater from rivers and lakes, this surface water amounts to only 0.02% of all water on Earth. Most liquid freshwater is stored in aquifers as groundwater. Still, groundwater makes up only 1% of all water on the planet (Douglas, 1997). Groundwater storage can be viewed as a product of climate. This is because the groundwater available for use is deposited primarily by atmospheric precipitation. Changes in climate then inevitably affect groundwater, both its quantity and quality.

Despite a growing consensus among climate scientists, readily available publications on the specific effects of climate change are numerous, dissimilar, and contradictory. The effects of climate changes on groundwater have also only been discussed in a limited manner. Geological science has demonstrated continuous climate change throughout the history of Earth. Changes developed both slowly and relatively quickly in the geological time scale. Past climatic changes have been caused by changes in solar activity, meteorite showers, variations in Earth axis position, volcanic activity, and a wide array of other natural activities, which caused changes in the Earth's albedo and the greenhouse effect of the atmosphere (Douglas, 1997). Figure 1.1 on the following page presents a schematic flowchart showing a relationship between climate change and loss of fresh groundwater in coastal aquifers, and the basic process of understanding that change. Of greatest concern herein is the step after abstract comprehension, analysis and modeling.

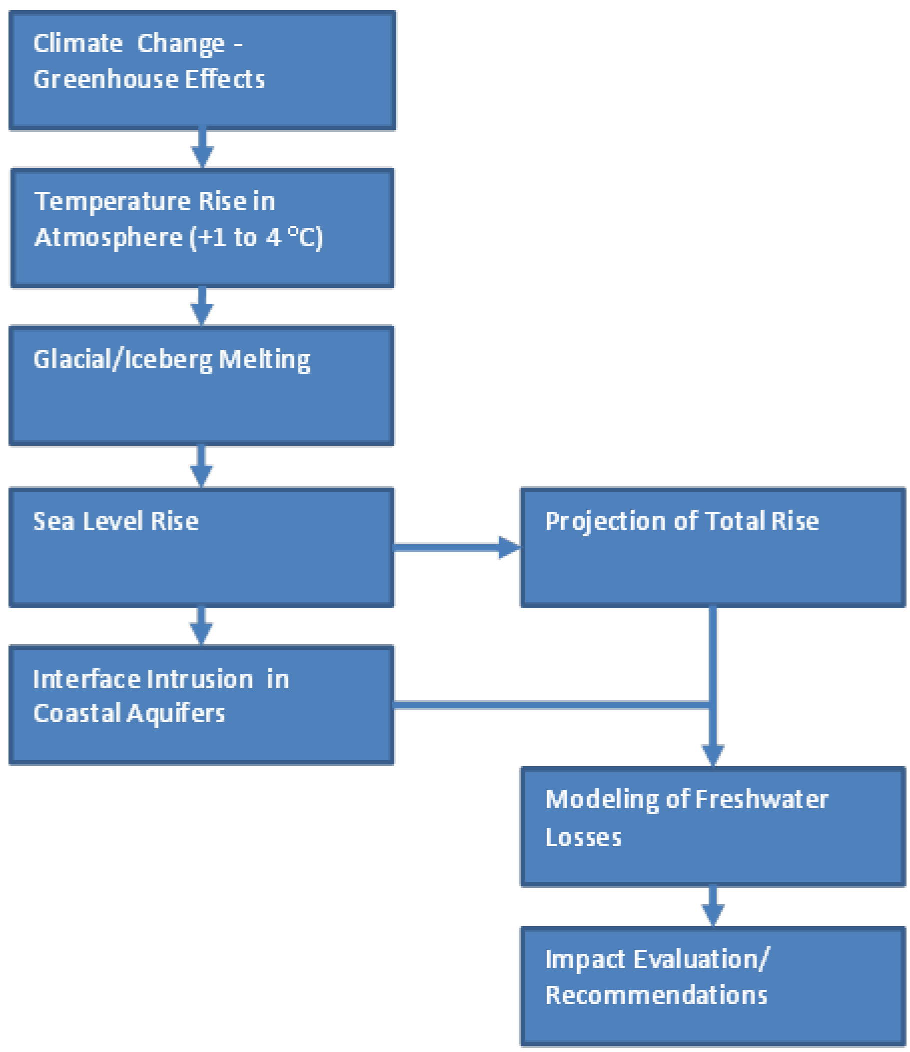

Figure 1 -- Process of climate change impacts on fresh groundwater in coastal aquifers

I.II CLIMATE CHANGE

Paleo-climates of the past allow the development of an analogue of the probable future climate. An example of how these relationships can be made can be seen by comparing temperatures today with the recorded temperatures found in ice cores such as the Vostok Ice Core temperature graph in figure 1.2. Global warming by 1° C can be the climate of the Holocene Optimum; by 2° C the climate of the Mikulian Interglacial Period; and warming by 3-4° C, the Pliocene Optimum (Kovalevskii, 2007). These time periods can be used to characterize the likely future climate.

These estimates of potential global warming are based on an extrapolated relationship between the air temperature and chemical content of the atmosphere (Tucker, 2008). Current predictions are commonly referred to as wide time intervals in the future. The global warming by 1° C is most often believed to occur in the first quarter of the 21st Century; 2° C in the mid-21st Century; and 3° C at the beginning of the next century (Kovalevskii, 2007). This determines possible hydrogeological forecasts.

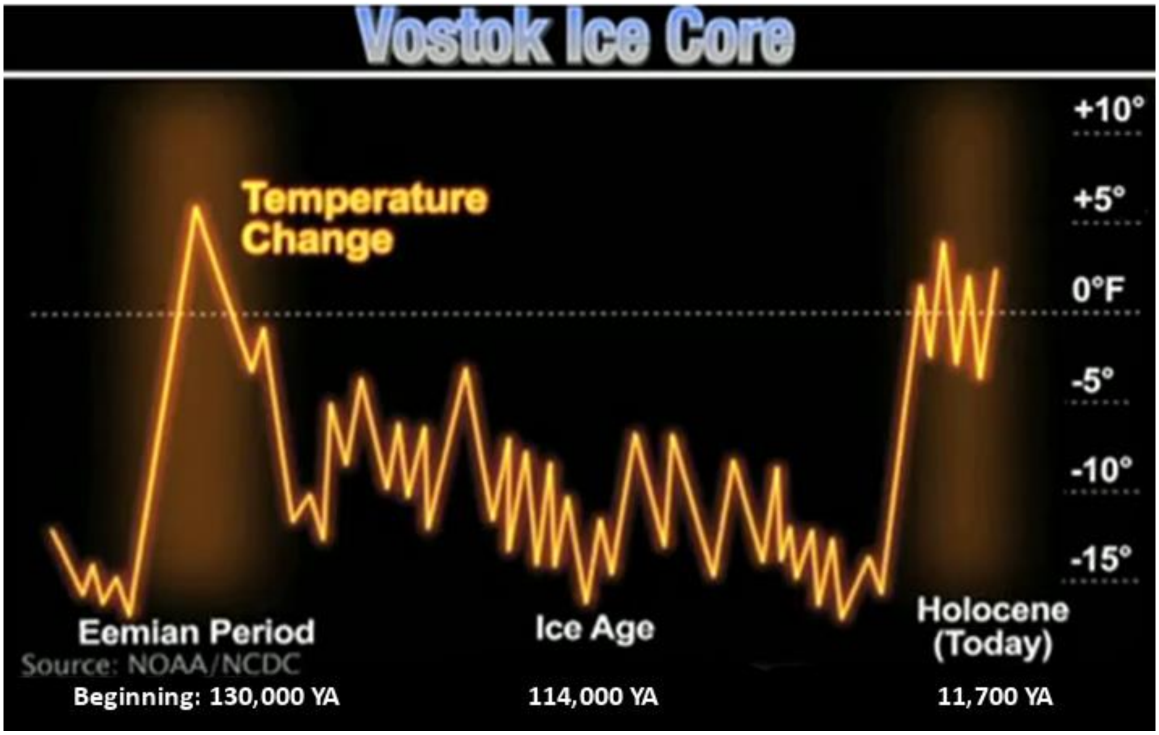

Figure 1.2 -- Average temperature over different epochs (Kovalevskii, 2007)

Based on the forecasts by Kovalevskii et al (2007) in "Effect of Climate Changes on Goundwater," there will be a regular and gradual growth of the air temperature increments from the south to the north. Some temperature changes have already been observed and can be seen in the two figures (figure 1.3 and figure 1.4) showing NOAA average sea surface temperatures in 1985 and 2006. These two figures can be compared with the Annual Mean Temperature figure following them. Predicted precipitation increases in the middle latitudes are many times smaller than those in the low and high latitudes. Model forecasts show even a likely decrease in precipitation in the middle latitudes (Joigneaux, 2011). Precipitation decrease is shown to spread from the western boundaries of Russia to the Urals, the primary area of concern for Kovalevskii's research, including the central and southern regions of Russia.

Around the world, the anticipated changes in climatic conditions will entail changes in the entire complex of hydrogeological conditions; in the water, heat, and salt balances of groundwater, as well as in the environment interconnected with groundwater. Taking into account the highest importance of hydrodynamic forecasts, it is practical to consider, first of all, the potential changes in groundwater resources (Kovalevskii, 2007).

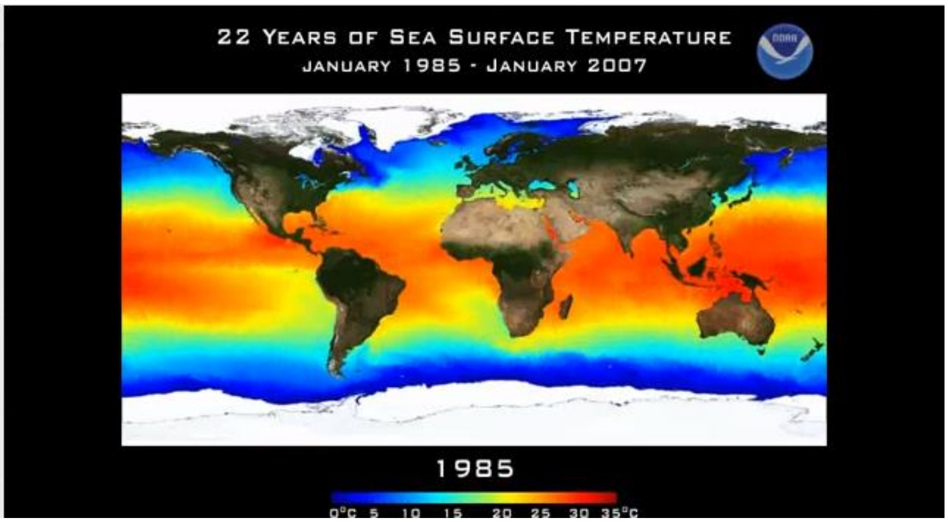

Figure 1.3 -- NOAA average sea surface temperature in 1985 (National Oceanic & Atmospheric Administration, 2008)

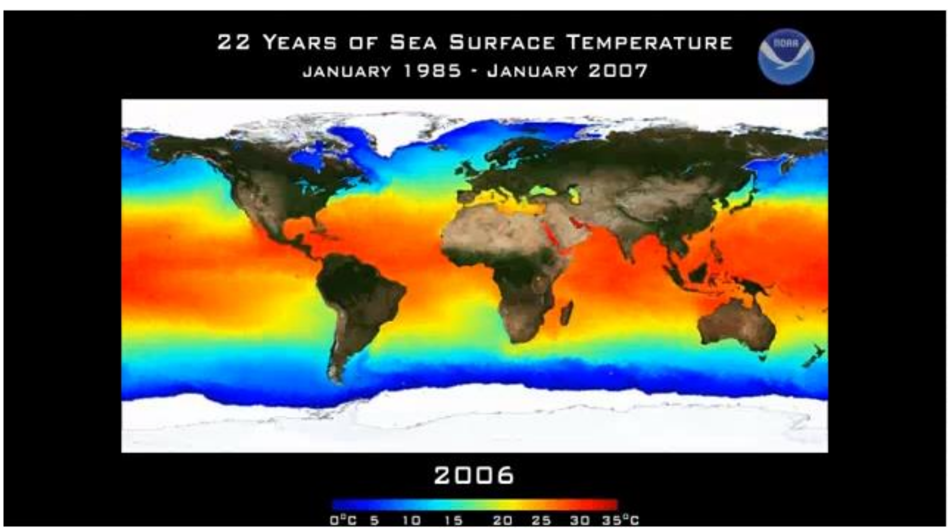

Figure 1.4 -- NOAA average sea surface temperature in 2006 (National Oceanic & Atmospheric Administration, 2008)

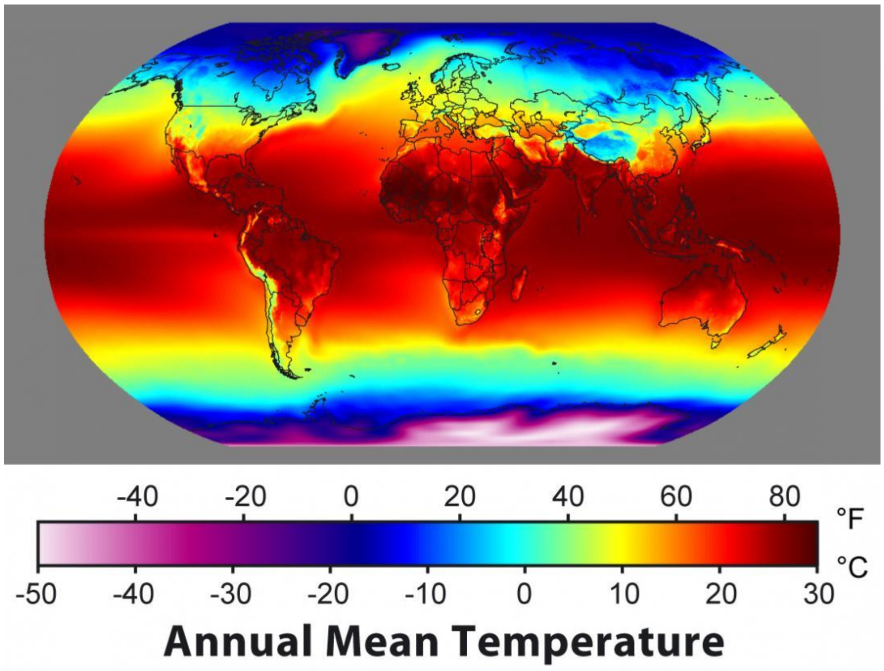

Figure 1.5 -- Annual mean temperature (National Oceanic & Atmospheric Administration, 2008)

Significant climate change is expected to alter India's hydro-climate regime over the course of the 21st Century. Wide agreement has been reached that the Indo-Gangetic basin is likely to experience increased water availability from increasing snow-melt up until around 2030 but face gradual reductions thereafter. Most parts of the Indo-Gangetic basin will probably also receive less rain than in the past; however all the rest of India is likely to benefit from greater precipitation.

According to the Intergovernmental Panel on Climate Change, most Indian landmass south of the Ganges Plain is likely to experience a 0.5-1° C rise in average temperature by 2029 and 3.5-4.5° C rise by 2099. Many parts of peninsular India, especially the Western Ghats, are likely to experience a 5-10% increase in total precipitation; however, this increase is likely to be accompanied by a greater variance in temperature (Shah, 2009). Throughout the sub-continent, it is expected that very wet days are likely to contribute more and more total precipitation, suggesting that most of India's precipitation may be received in fewer than 100 hours of thunderstorms.

This will generate more flooding events, and may reduce total infiltration as a matter of more concentrated run-off. The higher precipitation intensity and larger number of dry days in a year will also increase evapotranspiration. Increased frequency of extremely wet rainy seasons is also likely to mean increased run-off. In Shah's "Climate Change and Groundwater," a comparison of the 1900-1970 period and 2041-2060, most of India is likely to experience 5-20% increase in annual run-off. India can expect to receive more of its water via rain than via snow. Snow-melt will occur faster and earlier. Less soil moisture in summer and higher crop evapotranspirative demand can also be expected as a consequence. As climate change results in spatial and temporal changes in precipitation, it will significantly influence natural recharge.

Moreover, as much of natural aquifer recharge occurs in areas with vegetative cover, such as forests, changing evapotranspiration rates resulting from rising temperatures may reduce infiltration rates from natural precipitation and therefore reduce recharge. Recharge clearly has a strong response to the temporal pattern on precipitation as well as soil cover and soil properties. In the African context, Shah cites arguments that replacing natural vegetation by crops can increase natural recharge by nearly a factor of 10. If climate change results in changes in natural vegetation in forests or savanna, these too may influence natural recharge; however, the direction of the net effect will depend upon the pattern of changes in the vegetative cover (McCallum, 2010).

Simulations developed by Australian scientists have shown that changes in temperatures and rainfall may influence the growth rates and the leaf size of plants that have an effect on groundwater recharge. The direction of change is contextually sensitive. In some places, the vegetation response to climate change might cause the average recharge to decrease, but in other areas, groundwater recharge is likely to more than double (McCallum, 2010). We have an inadequate understanding of how exactly rainfall patterns will change, but increased variability seems almost guaranteed. This will lead to intense and large rainfall events in brief monsoons followed by longer dry spells. While evidence suggests that groundwater recharge through natural infiltration occurs only beyond a certain threshold level of precipitation, it also demonstrates that the run-off coefficient increases with increased rainfall intensity.

Increased variability in precipitation will negatively impact natural recharge in general. The Indo-Gangetic aquifer system has been getting a significant portion of its natural recharge from Himalayan snow-melt (Shah, 2009). As snow –melt-based run-off continues to increase during the coming decades, their contribution to potential recharge will likely increase; however, a great deal of this may end up as a form of "rejected recharge," enhancing river flows and intensifying the flood proneness of eastern India and Bangladesh. As the snow-melt-based run-off begins declining, one should expect a decline in run-off as well as groundwater recharge in that vast basin.

I.III MELTING GLACIERS

Glaciers are an important part of the current global ecosystem. They are found in the lower, mid, and upper latitudes. These glaciers generally have a melt and replenish cycle that coincides with the local seasons. However most of the regularly observed glaciers have been receding over the past years. In Greenland portions of the country have gone from completely covered by glaciers to rocky and without a continuous ice sheet, as seen in the figures following this page.

Figure 1.6 -- Greenland melting

In Alaska, coastal glaciers have been melting and shedding icebergs at an increasing rate. The figures below show a glacier going through a melt/erosion cycle with a dramatic collapse into the ocean. The following figures help to demonstrate an observed incident of glacier shelf face collapse.

Figure 1.7 -- Pine Island Glacier calving collapse (Antarcticglaciers.org, 2008)

The Gangotri Glacier in India is the main source for the Ganges river system. This glacier has been responsible for providing freshwater to a main river across southeastern Asia and is receding at continually increasing rates. The figure on the following page demonstrates, in a series of contours, this process of recession. The reduction of this glacier will greatly impact the flow of the Ganges and the ecosystem it supplies.

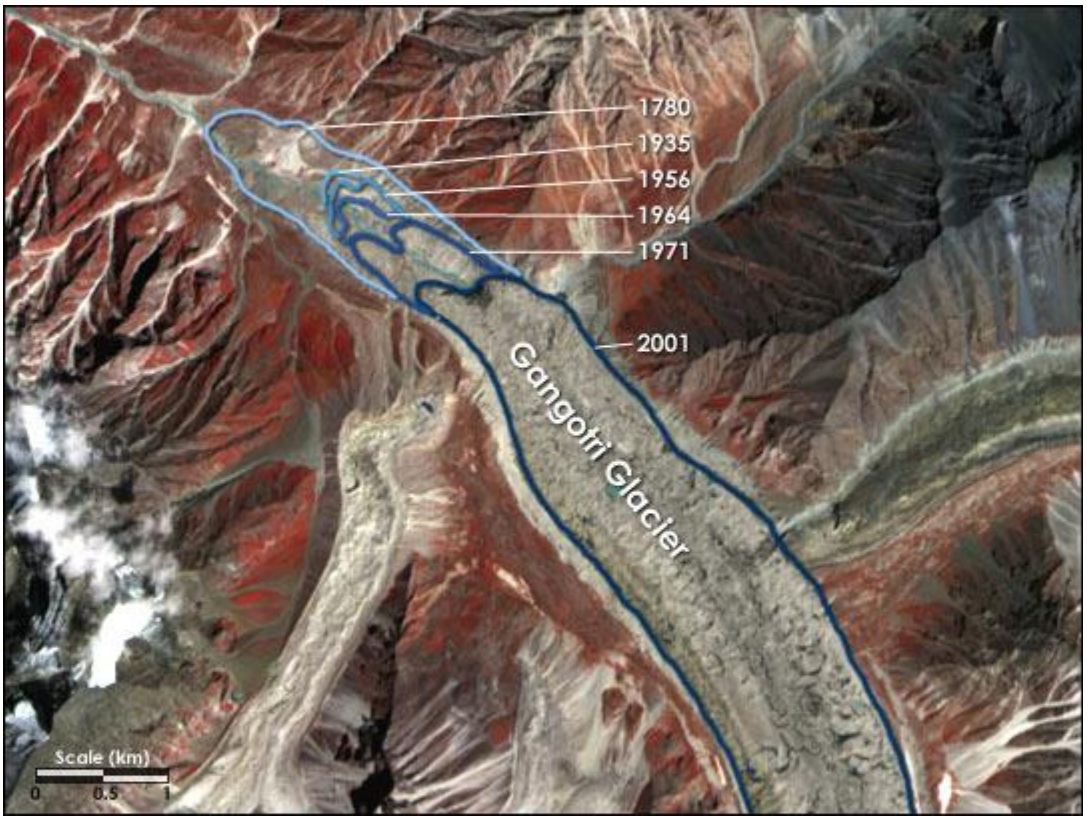

Figure 1.8 -- Gangotri glacier recession due to ice melt (Antarcticglaciers.org, 2008)

I.IV SEAWATER RISE AND INTRUSION

Climate change and groundwater will show some of their most drastic interrelation in coastal areas. Data from coastal tidal gauges in the north Indian Ocean are readily available for more than the last 40 years; in Tushaar Shah’s “Climate Change and Groundwater: India’s Opportunities for Mitigation and Adaptation,” estimates are presented for a sea level rise between 1.06 and 1.75 mm per year. This is consistent with a 1-2 mm per year global sea level rise which has been estimated by the IPCC. Rising sea levels will of course present a threat to coastal aquifers. Many of India's coastal aquifers are already increasing in saline intrusion. The problem is especially acute in the Saurashtra Coast in Gujarat and the Minjur Aquifer in Tamil Nadu. In coastal West Bengal, mangrove forests are threatened by saline intrusion overland (Shah, 2009). This will affect the aquifers supplying these ecosystems.

The sea-level rise that accompanies climate change will reduce the freshwater supply in many coastal communities, by infiltrating groundwater and rendering it brackish and undrinkable without excessive treatment (McCallum, 2010). "Most people are probably aware of the damage that rising sea levels can do above ground, but not underground, which is where the fresh water is," says Motomu Ibaraki, associate professor of earth sciences at Ohio State University.

According to Ibaraki, coastlines are made of many different layers and kinds of sand. Coarse sands let water through to aquifers and can lead to contaminated, brackish water. Ibaraki plans to create a world salinity hazard map showing areas which have the potential for the most groundwater loss due to sea-level rise. An example of the extensive and sever problems of water sufficiency and quality, Florida has the largest concentration of desalination plants in the United States. Ninety-three percent of Florida's 16 million residents rely on groundwater as their drinking water supply, via desalination of deep brackish aquifers (Meyland, 2008).

The saline/freshwater interface location and behavior can be approximated by several model types. The first is a U-Tube manometer. In the manometer the hydrostatic balance between fresh and saline water can be seen. The freshwater is less dense than the saline water and will therefore float on one side of the manometer. This shows that in an aquifer there will be an interface with freshwater on top and denser saline water intruding to the bottom of the aquifer (Todd & Mays, 2004). While somewhat simplistic, this model generates effective and useful approximations with little investigative data. Within most industrialized and preindustrial nations, the information required to apply this model is readily and freely available, having been collected by governments over decades of infrastructure development in coastal areas. Within the United States, this data has been made available through the U.S. Geological Survey (USGS), and has proven reliable and accurate over decades of study (U.S. Geological Survey, 2012).

The Glover model is another approach designed to address the issue of irregular interface shapes within a coastal aquifer system. This is a conceptual model that relies on some basic simplifying assumptions about the aquifer involved, but still gives good approximations of saline and freshwater interface (Todd & Mays, 2004). The greatest difficulty in application of the model derives from inaccuracies created by complex, multi-layered aquifer systems.

With variable hydraulic conductivities, predicting the interface shape as it crosses boundary layers becomes an exercise in non-continuous functions. In many aquifers, the layers can be simplified into a composite layer, as this maintains an accurate prediction of both volumetric changes and changes in the water table surface, but can result in accumulating errors in the prediction of interface locations as the aquifer layers become more varied and insular.

I.V EFFECTS ON GROUNDWATER

Scientists have suggested that climate change may alter the physical characteristics of aquifers. Higher CO_2 concentrations in the atmosphere are influencing carbonate dissolution and promote the formation of karstified soils which in turn may have a negative effect on the infiltration properties of top soils. This effect may derive from pH reduction in top soil exposed to post climate change precipitation (McCallum, 2010).

Others have argued the opposite; that increasing carbon dioxide levels will increase infiltration rates. From experimental data, some scientists have claimed that elevated atmospheric CO_2 levels may affect plants and the vadose zone in ways that may hasten infiltration from precipitation by up to 119% in a Mediterranean climate to up to 500% in a sub-tropical climate (Shah, 2009).

Diffusive groundwater recharge is the most important process in the restoration of groundwater resources. Changes to any of the variables that have an effect on diffuse recharge may have an impact on the amounts of water entering aquifers (Shah, 2009). Some efforts have been made to model changes predicted in diffuse aquifer recharge. To determine the impacts of climate change on the Edwards Aquifer in central Texas, USA a doubled atmospheric concentration of carbon dioxide was modeled for precipitation adjustments (McCallum, 2010). Changes to rainfall and streamflow were scaled based on this model, and by using a water-balance technique, the impact on recharge was determined. McCallum's review in "Impacts of Climate Change on Groundwater in

Australia" observed that changes to rainfall and streamflow under such scenarios would yield reduced groundwater levels in the aquifer even if groundwater extraction was not increased. The reduction in groundwater levels might allow for additional seawater intrusion, impacting groundwater quality. This is inferred from the simple relationships between recharge and climate change.

Saltwater intrusion is not the only issue changing climates can create in groundwater systems. Certain hydrological conditions allow for spring flow in karst systems to be reversed. The resulting back flooding represents a significant threat to groundwater quality. The surface water could be contaminated and carry unsafe compounds back into the aquifer system (Joigneaux, 2011). Joigneaux and his team examined the possible impacts of future climate change on the frequency and occurrences of back flooding in a specific karst system in their article "Impact of Climate Change on Groundwater Point Discharge." They first established the occurrence of such events in the study area over the past 40 years.

Preliminary investigations showed that back flooding in this Loiret, France karst has become more frequent since the 1980s. Adopting a downscaled algorithm relating large-scale atmospheric circulation to local precipitation special patterns, they viewed large-scale atmospheric circulation as a set of quasi-stationary and recurrent states, called weather types, and its variability as the transition between them (Joigneaux, 2011). Based on a set of climate model projections, simulated changes in weather type occurrence for the end of the century suggests that back flooding events can be expected to increase until 2075, at which point the event frequency will decrease.

As Joigneaux explains, alluvial systems and karst hydrogeological systems are very sensitive to small changes in hydrological components. Stream back flooding and the subsequent appearance of sink holes can occur because of relative changes between surface and underground drainage, which are controlled by both precipitation and discharge (Joigneaux, 2011). Consequently this type of system is sensitive to small climate variations, even at temperate mid-latitudes.

Dry weather streamflow is closely related to the rise and fall of groundwater tables. Since the 1980s, streamflow has deleted rapidly, owing to limited precipitation during the dry period and immoderate groundwater pumping for agricultural, domestic, and industrial uses. Ecologic and environmental disasters such as decreased number of species and population sizes, water quality deterioration, and interference with navigable waterways, have resulted from these changes. Kil Seong Lee and Eun-Sung Chung, in "Hydrological Effects of Climate Change, Groundwater Withdrawal, and Land Use in a Small Korean Watershed," analyze the influences on total runoff during the dry periods and simulate its variability (2007).

Understanding these factors is very important for the watershed-level planning and management of water resources, especially in tropical climate areas. Chung particularly investigated how changing dry-weather climate would affect the use and withdrawal of water from stream and groundwater systems. By using surface waters as a set of boundary conditions, models like Chung's help demonstrate the effects of climate change on groundwater resources.

I.VI LOSS OF FRESHWATER

The use of freshwater supplies will have a growing impact in a variety of issues. Desalination might be used to ensure supplies of drinkable water, but it's an energy-intensive process. "Our energy use now could reduce the availability of freshwater and groundwater through the climate change process," Ibaraki says in summation of research he is undertaking at Ohio State University. "These resources are decreasing due to human activities and population increase." Another approach to protecting water supplies is to transfer water from regions that have it in abundance to regions that face water shortage. Unfortunately, both approaches require much energy (Tucker, 2008).

In the U.S., much of the agricultural land depends on irrigating crops using water from aquifers. This is true around much of the world, more or less, as the following figure depicts. However, these aquifers are being "mined" for agriculture at rates that exceed the recharge rate, thus depleting them. The Ogallala Aquifer stretches across the U.S Great Plains region, running from South Dakota, down to New Mexico and Texas; it is being pumped faster than the natural replacement rate, leading to a significant drop in the water table, possibly by hundreds of feet. When fossil aquifers like the Ogallala and the North China Plain are depleted, pumping will become impossible (Meyland, 2008). This will make the existing agricultural system unfeasible.

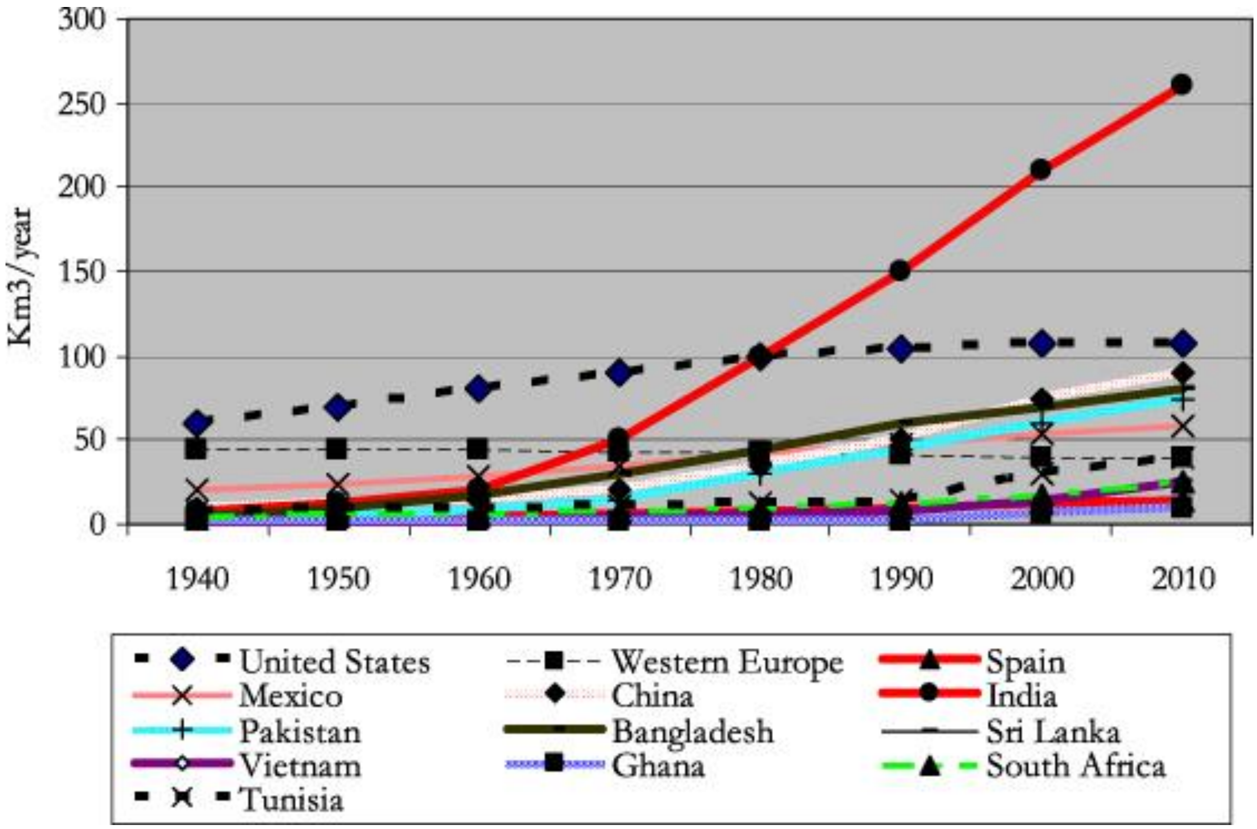

Figure 1.9 -- Increasing use of groundwater in agriculture (IPCC, 2007)

Groundwater is harder to manage and protect than surface water since it is difficult to monitor and model. Large efforts are needed to put groundwater systems under the management and protection of agencies dedicated to the job. Managing authorities could equitably administrate intrastate, interstate and international aquifer basins using scientific research and management plans, implemented by educated professionals. The management agencies can conduct studies, prepare management strategies, quantify the resources, determine equitable distributions of the water, and establish safety margins for allocations, anticipating climate swings such as severe drought. Groundwater will only become more important as a resource in the future. Effective management and protection of groundwater sources will become critical as the U.S. and the rest of the world work toward sustainable use of the Earth's water resources.

I.VII SUMMARY

A scientific consensus has been reached which states climate change is taking place around the globe. The expected temperature rise may range between 1° C to 4° C (IPCC, 2007). This is going to result in melting of icebergs, no matter how slow or fast. Such an action will raise the seawater level as much as 1 meter (or 3 feet). This rise will drive seawater interfaces globally inland, leading to loss of freshwater in coastal areas. In terms of the Ghyben-Herzberg approach, this can be examined as a shift upward in both the top of the water table and the saline-freshwater interface zone. This shift also reduces the total depth of freshwater in the aquifer in achieving a new equilibrium state.

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CHAPTER 2

LITERATURE REVIEW

Anderson, Miliken, and Wallace, review the consensus effects of accelerated sea level rise. Making note of inundation likely to occur in lowland coastal regions, together with some of the world's most populous cities, and relying on the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), this work suggests with some confidence that the global mean sea level may rise by as much as 0.6 meter by 2100. Specifically, Anderson addresses uncertainty projections of the melting of the Greenland and Antarctic ice sheets and their contribution to sea level rise, as well as the issues of coastal subsidence (Anderson, Miliken, & Wallace, 2010).

Prepared for the Groundwater Resources Association of California, the handbook, “California Groundwater Management” provides a launching point for those not previously familiar with the specifics of groundwater data and policy in California (Bachman, et al., 2005). This second edition builds on the work already established, in order to make the information accessible to readers of diverse backgrounds and understanding. As such, it can help to provide a general contextual framework for investigations in the groundwater resources of the state.

In their technical paper for the International Panel on Climate Change, Bates, Kundzewics, Wu, and Palutikof consider sea level rise as a tertiary issue (Bates, Kundzewics, Wu, & Palutikof, 2008). Instead, this paper focuses on the interconnection and following impacts on systems of freshwater, biophysics, and socioeconomics.

Bear leads a collaboration to assemble a complete introductory work on the interaction of seawater in coastal aquifers (Bear, Cheng, Sorek, Ouzar, & Herrera, 2008). Notably, the work includes a broad look at the chemical interactions which can compromise the geophysical properties of any coastal aquifer.

J. Anderson, et al, assembled a review of the preliminary efforts of California's water management agencies to incorporate climate change research into their practices (California Department of Water Resources, 2006). Historical observations, preliminary modeling, and potential impact studies are included, and placed in the context of projects such as the Central Valley Project.

In their Geophysical Research letter, Church and White indicate that a reconstruction of global sea level using tide-gauge data from 1950 to 2000 indicates a larger rate of rise after 1993 (Church & White, 2006). A relative comparison of sea level rise rates bridges 1870 to 2005. If this acceleration remained constant then the 1990 to 2100 rise would range from 280 to 340 mm, consistent with projections in the IPCC Third Assessment Report, although the state of consensus has shifted with the Fourth Report's release.

Assembled by A&N Technical Services, Inc., the city management for Oxnard, California has published a master plan for water conservation, including overviews of usage, supply, and relevant ordinances (City of Oxnard, 2010). Being the primary authority of withdrawal from the Oxnard-Mugu sub-basin, the city of Oxnard institutes and enacts much of the policy for the groundwater resource's usage going forward.

As part of the Coastal Trends Report Series, Crossett and other authors prepared a practical reconnoiter of human practices in coastal areas of the United States (Crossett, Culliton, Wiley, & Goodspeed, 2004). Herein, the balancing practice of maximum utilization and environmental concern and protection is addressed.

In order to facilitate discussion of the modern trends of global sea level rise, Jeffrey Donnelly has published a study of the same trends in the most recent geological era (Donnelly, 2006). By implementing accelerator mass spectrometry (AMS) radiocarbon dating, a revised record of sea level rise has been prepared dating to 3300 years before the present.

Undertaking a study of many varied series of data for sea level available for the previous century and beyond, Bruce Douglas has attempted to reconcile possible causes of identifiable inconsistency across multiple studies of sea level rise (Douglas, 1997). In doing so, Douglas confirms the sudden order of magnitude increase in mean sea level rise from previous millennia, but cannot identify a consistent acceleration of the rate over the past century.

Duncan Fitzgerald of Boston University, and his associates, discussed not only the expectations of sea level rise inundating coastal areas, but the possible impact of geometric changes on coast lines (Fitzgerald, Fenster, Argow, & Ilya, 2008). In "Coastal Impacts due to Sea Level Rise," Fitzgerald, et al., addresses both solids transport and accruing effects of sea level rise, with regards to mass transport. Therein, a notable discussion of tidal effects on the geometry of coastal regions is discussed.

Based on measurements from an approximately global distribution of 177 tidal gauges, Holgate & Woodworth establish that sea level rise from 1950 to 2004 has been 1.7 ± 0.2 millimeters per year (Holgate & Woodworth, 2004). Using altimetry, the supposition is then made that the rise of sea levels around global coastline was significantly greater than the average over all ocean surfaces. Holgate & Woodworth go on to review some models which predict this trend as a precursor to significant increases in global sea level rise.

The International Panel on Climate Change has now released four reports assessing the past, present and future state of the global climate and human effects thereon. With each assessment report, a team of international scientists and engineers has been tasked with establishing and reviewing the scientific foundations of any claims to be made (Intergovernmental Panel on Climate Change (IPCC), 2007). Published separately, their efforts are referred to as "The Physical Science Basis." Of particular concern to this work are chapters 8, 10, and 11 of that document. Respectively, these sections discuss climate models and their evaluation, global climate projections, and regional climate projections.

Loaiciga presents a method to assess the contributions of 21st-century sea-level rise and groundwater extraction to sea water intrusion in coastal aquifers in "Sea Water Intrusion by Sea-Level Rise: Scenarios for the 21st Century." Simulations of sea water intrusion in the Seaside Area sub-basin near the City of Monterey, California illustrate this methodology (Loaiciga, Pingel, & Garcia, 2012). The method presented in this work is also suggested to be applicable to coastal aquifers under a variety of other scenarios of change not considered in this work.

In “The Rising Tide,” Gordon McGrahan undertakes an examination of global populations in relation to coastal habitation (McGrahan, Balk, & Anderson, 2007). By defining low coastal areas as the continuous regions extending from coast lines at an elevation of less than 10 meters, McGrahan determined that 10% percent of the world’s human population (13% of the urban population) lives within this at risk region.

Nerem and Mitchum discuss in their chapter of “Sea Level Rise,” that while the long term standard for the measurement of sea level data has been tidal gauges, two fundamental issues can point out the preference for additional data collection. First, the gauges can only measure sea level relative to a crustal point, and this point may move at a rate similar to average sea level change. Second, it has been established that tide gauges have limited spatial distribution and suboptimal placement as a matter of convenience. Starting with the project TOPEX/POSEIDON, data has been collected from space for two decades, providing both a greater granularity and flexibility in determination in changes in sea level (Nerem & Mitchum, 2001).

Robert Nicholls and Anny Cazenave prepared “Sea-level Rise and its Impact on Coastal Zones” in order to address what they found to be an understated matter in the field of climate change. Effectively, they discuss the presence of data suggesting significant regional variation in the effects of climate change on sea level rise, independent of latitude (Nicholls & Cazenave, 2010). While inadequate research has been made to establish a defined trend for at risk regions, recent satellite telemetry can be shown to demonstrate the need for further investigation.

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The USGS prepared a calibrated ground-water flow model to analyze the distribution and magnitude of ground-water flow within the entire Santa Clara–Calleguas Basin, including the Oxnard-Mugu sub-basin (U.S. Geological Survey, 2012). The flow analysis includes a summary of flow under predevelopment and historical conditions, the reported pumpage, projected future groundwater flow conditions in relation to planned water-supply projects, and projected future groundwater flow conditions for possible alternative water-supply projects.

Webster and associates examined the number of tropical cyclones and cyclone days as well as tropical cyclone intensity over the past 35 years, in an environment of increasing sea surface temperature (Webster, Holland, Curry, & Chang, 2005). They observed a large increase in the number and proportion of hurricanes reaching categories 4 and 5.

William Yeh and Ben bray of the University of California, los Angeles attempted to develop and calibrate a conceptual model of seawater intrusion in southern California. The model was investigated for this work in order to gain a greater understanding of the state of the art approaches to the same problems investigated herein. A genetic algorithm linked to the simulation of hydraulic conductivity and well head was implemented to examine problems of optimizing well locations and optimizing pump scheduling (Yeh & Bray, 2006).

CHAPTER 3

TECHNICAL BACKGROUND FOR THE OXNARD-MUGU BASIN

III.I - INTRODUCTION

In order to prepare a case study of the Oxnard-Mugu basin, its physical properties must be more adequately understood. The U.S. Geological Survey has performed extensive investigations on this aquifer in collaboration with Californian water research agencies. Adequate geophysical data has been made available to engage in preliminary studies of the aquifer's susceptibility to saline intrusion. The usage history and physical information will be expanded upon in following sections, in order to provide the technical underpinnings and context for this case.

III.II - LITERATURE REVIEW

Anderson, Miliken, and Wallace, review the consensus effects of accelerated sea level rise. Making note of inundation likely to occur in lowland coastal regions, together with some of the world's most populous cities, and relying on the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), this work suggests with some confidence that the global mean sea level may rise by as much as 0.6 meter by 2100. Specifically, Anderson addresses uncertainty projections of the melting of the Greenland and Antarctic ice sheets and their contribution to sea level rise, as well as the issues of coastal subsidence (2010).

Prepared for the Groundwater Resources Association of California, the handbook, “California Groundwater Management” provides a launching point for those not previously familiar with the specifics of groundwater data and policy in California (Bachman, et al., 2005). This second edition builds on the work already established, in order to make the information accessible to readers of diverse backgrounds and understanding. As such, it can help to provide a general contextual framework for investigations in the groundwater resources of the state.

Bear leads a collaboration to assemble a complete introductory work on the interaction of seawater in coastal aquifers (Bear, Cheng, Sorek, Ouzar, & Herrera, 2008). Notably, the work includes a broad look at the chemical interactions which can compromise the geophysical properties of any coastal aquifer.

J. Anderson, et al, assembled a review of the preliminary efforts of California’s water management agencies to incorporate climate change research into their practices (California Department of Water Resources, 2006). Historical observations, preliminary modeling, and potential impact studies are included, and placed in the context of projects such as the Central Valley Project.

Assembled by A&N Technical Services, Inc., the city management for Oxnard, California has published a master plan for water conservation, including overviews of usage, supply, and relevant ordinances (City of Oxnard, 2010). Being the primary authority of withdrawal from the Oxnard-Mugu sub-basin, the city of Oxnard institutes and enacts much of the policy for the groundwater resource's usage going forward.

Undertaking a study of many varied series of data for sea level available for the previous century and beyond, Bruce Douglas has attempted to reconcile possible causes of identifiable inconsistency across multiple studies of sea level rise (1997). In doing so, Douglas confirms the sudden order of magnitude increase in mean sea level rise from previous millennia, but cannot identify a consistent acceleration of the rate over the past century.

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III.III - HISTORICAL USAGE

Little information exists on predevelopment water levels in the upper- or lower-aquifer system during the periods of early ground-water development. In the 1870s, wells near the coast on the Oxnard Plain sub-basin were reported to deliver water to the second floor of homes under the natural artesian pressures of the Oxnard aquifer. Several early ground-water-level maps were constructed for parts of the basin, but the first map of the entire basin was completed for fall, which was during a period of agricultural development and a severe drought.

As the surface-water resources became fully used in the early 1930s, ground-water development began to provide a significant part of the water resources. If the conditions in 1931 represent, in part, conditions prior to major ground-water development, then ground water in all the aquifers initially moved from the landward recharge areas toward the west or southwest to the discharge areas along the submarine outcrops offshore in the Pacific Ocean. By the 1930s, water levels had declined as a result of the 1927–1936 drought, changing from artesian-flowing conditions of the late 1800s to below or near land surface in most wells completed in the upper-aquifer system in the Oxnard Plain subbasin (Muir, 1982). The effects of ground-water development and overdraft first appeared in 1931 when water levels in wells in parts of the Oxnard Plain declined below sea level. In the 1930s, the first deep wells were drilled in the Pleasant Valley and Las Posas Valley subbasins. Well owners in coastal areas began to recognize the connection between the ground-water reservoirs and the ocean when they observed that water-level changes in wells corresponded with the rising and falling phases of the ocean tides. The Santa Clara Water Conservation District officially recognized the linkage between overdraft and seawater intrusion in their annual report of 1931 (U.S. Geological Survey, 1996).

Ground-water development continued to spread in the ground-water basin during the severe drought period of 1923–1936, tapping deeper aquifers for agricultural supplies. As the surface-water resources became fully developed in the early 1930s, new ground-water development began to provide a significant proportion of the water resources. In the 1930s, the first deep wells were drilled in the Pleasant Valley and Las Posas Valley subbasins. Calculated agricultural pumpage, estimated from the 1927 land-use map, yields a basinwide average rate of withdrawal of about 128,400 acre-ft/yr for 1927 and an estimated total withdrawal of about 513,500 acre-ft for 1927–30. Calculated pumpage estimated from the 1932 land-use map is at about 174,000 acre-ft/yr, yielding an estimated total withdrawal of about 2,610,000 acre-ft for 1931–45. Estimates of agricultural pumpage, based on the 1950 land-use map, yield a basinwide average rate of pumpage of 180,000 acre-ft/yr and a total withdrawal of about 2,880,000 acre-ft for 1946–61 (California Department of Water Resources, 2006).

Ground-water pumpage increased during the 1940s with the widespread use of the deep turbine pump. The effects of permanent overdraft were exemplified by the lack of recovery of water levels to historical levels after the spring of 1944, which marked the end of the wettest climatic period in the 103 years of historical rainfall record at Port Hueneme. The effects of overdraft also were recognized landward in the Santa Clara

River Valley when ground-water levels declined about 20 ft in the Fillmore subbasin. Water levels in the southern Oxnard Plain and Pleasant Valley were below sea level by 1946 (Muir, 1982). In 1949, water-level altitudes were 30 ft below sea level in parts of the Oxnard Plain subbasin, and one of the first wells intruded by seawater was identified along the coast in the Silver Strand well field (north of Port Hueneme). The direction of subsurface flow within the upper aquifers near the coast has been landward since approximately 1947 (California Department of Water Resources, 2006).

By 1967, about 800 wells equipped with deep-well turbine pumps provided more than 90 percent of the water demand in the basin (Muir, 1982). On the basis of 1969 land use, estimates of agricultural pumpage yield a basinwide average rate of withdrawal of about 201,700 acre-ft/yr, yielding an estimated total pumpage of 3,227,200 acre-ft for 1962–77.

Reported pumpage was compiled from the technical files of the Fox County Groundwater Management Agency (FGMA) and Underground Water Conservation District (UWCD) for July 1979–December 1993. These data generally were semiannual totals of user-reported agricultural, nonagricultural, and total pumpage. Early pumpage data were incomplete for the Las Posas Valley, Pleasant Valley, and Santa Rosa Valley subbasins. For these areas, 1984 FGMA reported pumpage was used to represent pumpage for 1978 through 1983. Estimated and reported total annual pumpage were combined for the entire Santa Clara–Calleguas Basin and range from 760 acre-ft for 1912 to as much as 301,400 acre-ft for 1990, which was during the last sustained drought (City of Oxnard, 2010).

III.IV - PRESENT DEMANDS

The largest source of discharge from the ground-water flow system in the Santa Clara–Calleguas Basin is pumpage. Pumpage has caused water-levels to decline below sea level which has resulted in seawater intrusion and changes in ground-water quality, altered ground-water vertical-hydraulic gradients, reduced streamflow, reduced evapotranspiration, and caused land subsidence. Long-term hydrographs of water levels in production wells and in the multiple-zone observation wells show fluctuations driven by multiple-year to decadal changes in recharge and seasonal to multiple-year changes in pumpage (California Department of Water Resources, 2006).

Reporting of metered pumpage began in the 1980s; the total reported basinwide pumpage was 2,468,610 acre-ft during the 10-year period 1984–93. Of this reported total pumpage, 37 percent was from the Oxnard Plain subbasin, 37 percent from the upper Santa Clara River Valley subbasins, 13 percent from the Las Posas Valley subbasin, 9 percent from Pleasant Valley subbasin, 3 percent from the Mound subbasin, and 1 percent from the Santa Rosa Valley subbasin (California Department of Water Resources, 2006).

III.V - HYDRAULIC PROPERTIES OF THE AQUIFER

The Oxnard plain, 60 miles northwest of Los Angeles, has an area of 120 sq. mi. and is underlain by a complex system of aquifers more than 1400 feet thick. This system contains two aquifers that have been developed for water supply-the Oxnard and Mugu aquifers. The Oxnard aquifer is about 180 feet below land surface. The Oxnard aquifer is underlain by the Mugu aquifer and overlain by thick, but areally extensive clay deposit (U.S. Geological Survey, 1996). This clay deposit separates the Oxnard aquifer from a shallow unconfined aquifer that previous researchers have referred to as the “perched-on.”

The use of this name should not be taken to imply that perched conditions exist in the Oxnard plain.

Two submarine canyons less than one quarter-mile off-shore, the Mugu and Hueneme, are subject to outcroppings. The aquifer outcrops immediately offshore all along the coast in the area of study. The figure below illustrates the position and seaward conditions of the aquifer.

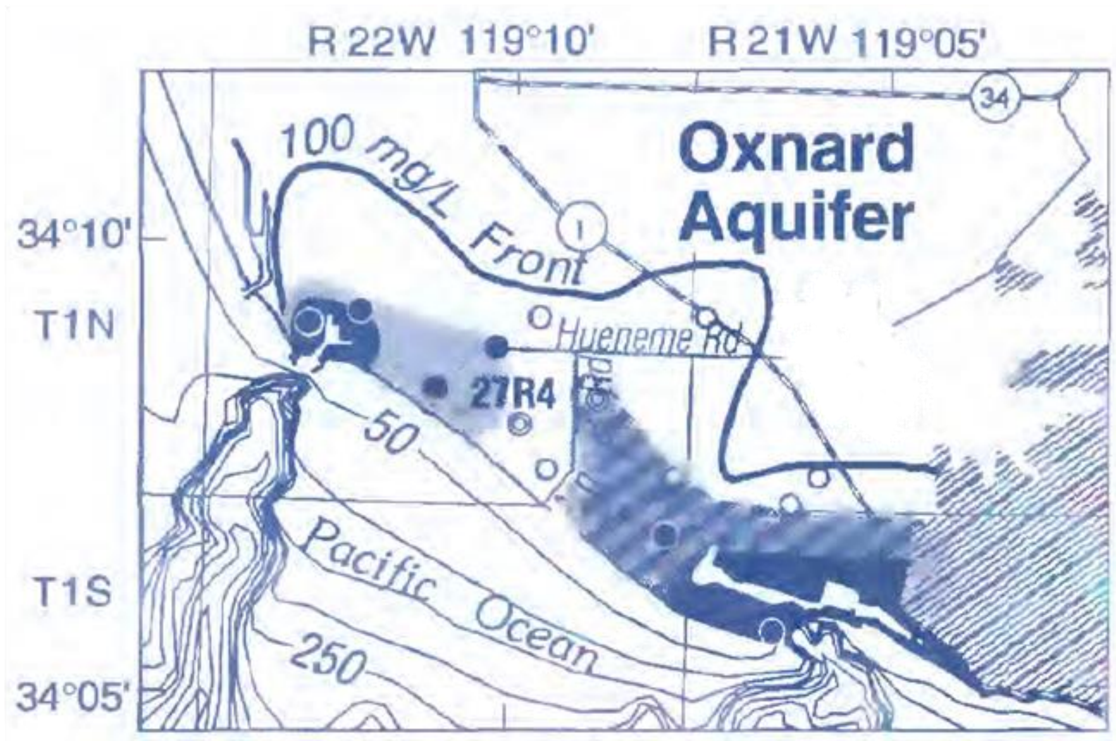

Figure 3.1 -- Aquifer system location (USGS, 1998)

Native water in the Oxnard and Mugu aquifers is generally fresh and tests for a saline concentration of about 40 mg/L. However this does not preclude that in some areas, especially near the Mugu submarine canyon, interbedded fine-grained deposits in the

Oxnard and Mugu aquifers contain saline water (California Department of Water Resources, 2006). Prior to the onset of seawater intrusion the Oxnard and Mugu aquifers were extensively pumped for local water supply.

The perched-on aquifer contains fresh and saline water, but is not used as source water supply. Saline water in the perched-on aquifer system results from the combination of seawater that has recharged the aquifer through offshore outcrops or infiltrated into the aquifer through coastal wetlands were during coastal flooding, or subsequent concentration of dissolved minerals resulting from the evaporative discharge of groundwater, or the infiltration of irrigation return water.

The lower aquifer system consists of alternating layers of alluvial sand and clay which varies from 5 to 50 feet thick. The deposits grade to Marine near the coast and overlie fine-grained marine sands that are more than 100 feet thick and are separated by marine silt and clay interbeds that are as much as 50 feet thick. The deposits of the lower aquifer system have been folded and faulted. Marine seismic reflection data and test drilling data show that the lower aquifer system outcrops in the Hueneme submarine canyon, but it does not prop out in the Mugu submarine canyon because of offshore faults and uplift of partly consolidated Marine and volcanic rock (U.S. Geological Survey, 2012).

The Oxnard aquifer lies at the base of the Holocene deposits and consists of sand and gravel deposited by the ancestral Santa Clara River and the Calleguas Creek and by their major tributaries. The coarser-grained basal deposits of the Holocene epoch are referred to as the “Oxnard aquifer”. The base of the aquifer ranges from about 150 to 250 ft. below land surface throughout most of the Oxnard Plain sub-basin. The basal deposits range in thickness from less than 10 to 200 ft. and are a major source of water to wells in the Piru, Fillmore, Santa Paula, Oxnard Plain Forebay, and Oxnard Plain subbasins. Hydraulic conductivity in the Oxnard aquifer is about 190 ft./d near Port Hueneme (Muir, 1982). The Oxnard aquifer is relatively fine grained in the Mound, Pleasant Valley, Santa Rosa Valley, and Las Posas Valley subbasins; this aquifer is not considered an important source of ground water in these subbasins. Throughout most of East and West Las Posas Valley subbasins, the Oxnard aquifer is unsaturated.

In the Piru and Fillmore subbasins, there are few if any clay layers separating the perched-on and Oxnard aquifers; therefore, ground water can move freely between the two. In the Santa Paula subbasin, the Santa Clara River has migrated south of the ancestral river that deposited the sediments of the Oxnard aquifer and mostly overlies non-water-bearing rocks of Tertiary age (Bachman, et al., 2005). As a result, the Santa Clara River does not overlie the Oxnard aquifer throughout most of the Santa Paula subbasin.

In the Oxnard Plain Forebay subbasin, there are relatively few clay layers separating the shallow and Oxnard aquifers. Alluvial fans derived from the mountains north of the Mound subbasin pushed the Santa Clara River south toward South Mountain. In the Oxnard Plain Forebay subbasin, clay layers were eroded by the Santa Clara River, and sand and gravel were deposited in their place; owing to the absence of clay. The Oxnard aquifer is considered to be unconfined in the Oxnard Plain Forebay subbasin.

Throughout the Oxnard Plain and Pleasant Valley subbasins, the perched-on and Oxnard aquifers are separated by clay layers. These clay layers confine or partly confine the

Oxnard aquifer throughout most of the Oxnard Plain and Pleasant Valley subbasins. Investigators reported that the clay layers separating the Shallow and Oxnard aquifers in the Point Mugu area are thin or absent, allowing free interchange of water in this part of the subbasin (U.S. Geological Survey, 2012). However, data, collected from several multiple-well monitoring sites constructed in the Point Mugu area as a part of this study, indicate that relatively thick clay layers separate the Shallow and Oxnard aquifers.

The Mugu aquifer is composed of the basal part of the unnamed upper Pleistocene deposits. In the Piru, Fillmore, Santa Paula, Mound, Oxnard Plain Forebay, and Oxnard Plain subbasins, these deposits are similar to those of the underlying lower-aquifer system because the Santa Clara River was the primary source of sediment for both aquifers. The Mugu aquifer is differentiated from the lower-aquifer system because it is less indurated and relatively undisturbed. However, because of the similarities between these deposits, many investigators include the upper Pleistocene deposits in the lower-aquifer system. In the Pleasant Valley, Santa Rosa Valley, East Las Posas Valley, and West Las Posas Valley subbasins, the Mugu aquifer sediments were derived from South Mountain and the surrounding hills and are finer grained than sediments derived from the Santa Clara River (Bachman, et al., 2005).

The following pages present a series of figures illustrating the differing compound layers of the aquifer system. These have been established by the USGS, using a series of test wells and state of the art soundings. The figures clearly demonstrate the boundaries of concern for the preliminary investigation, the upper aquifer system where the great majority of saline intrusion is allowed.

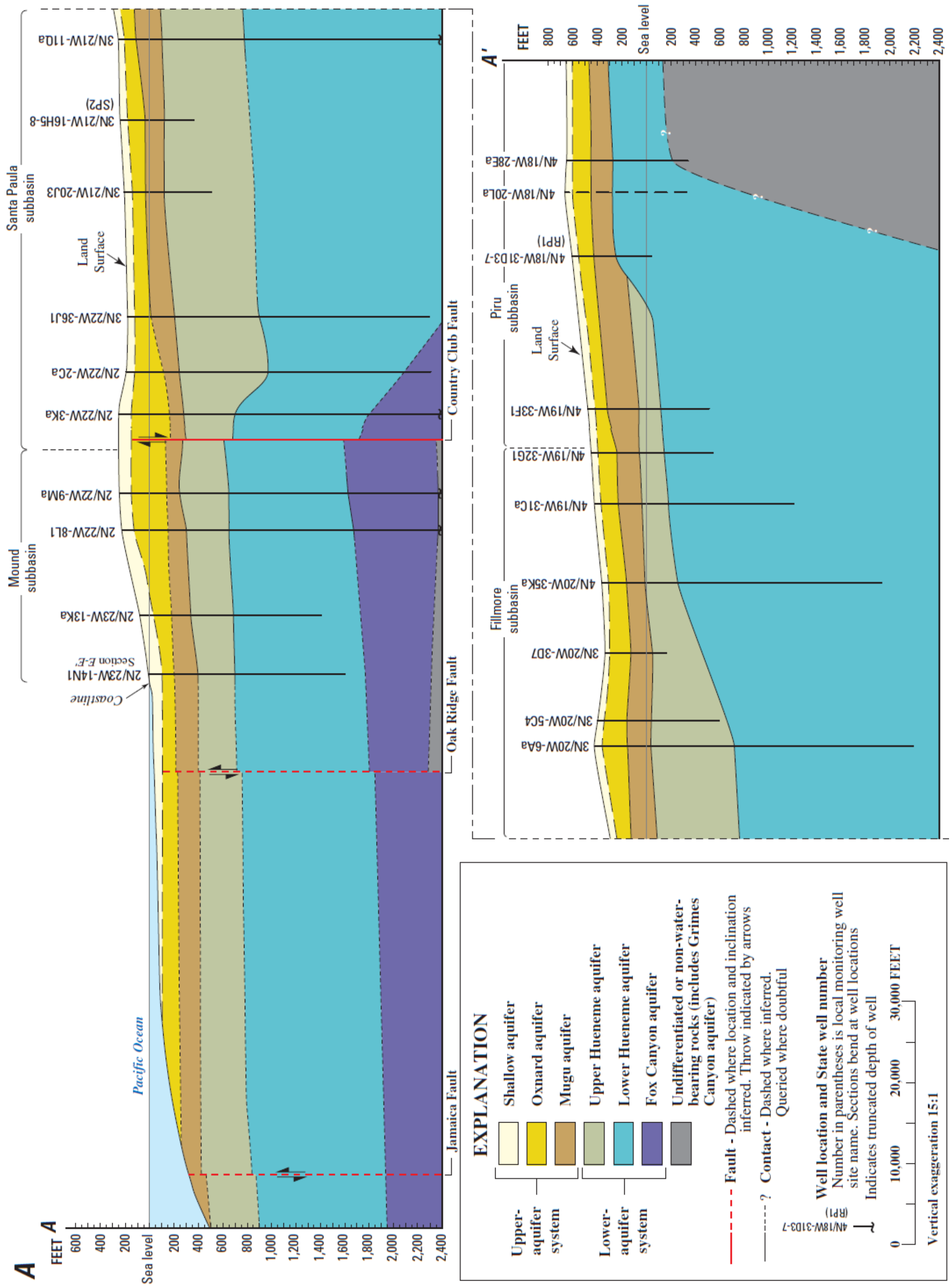

Figure 3.2 -- Geophysical structure of the Oxnard aquifer system, A section and key (USGS, 2012)

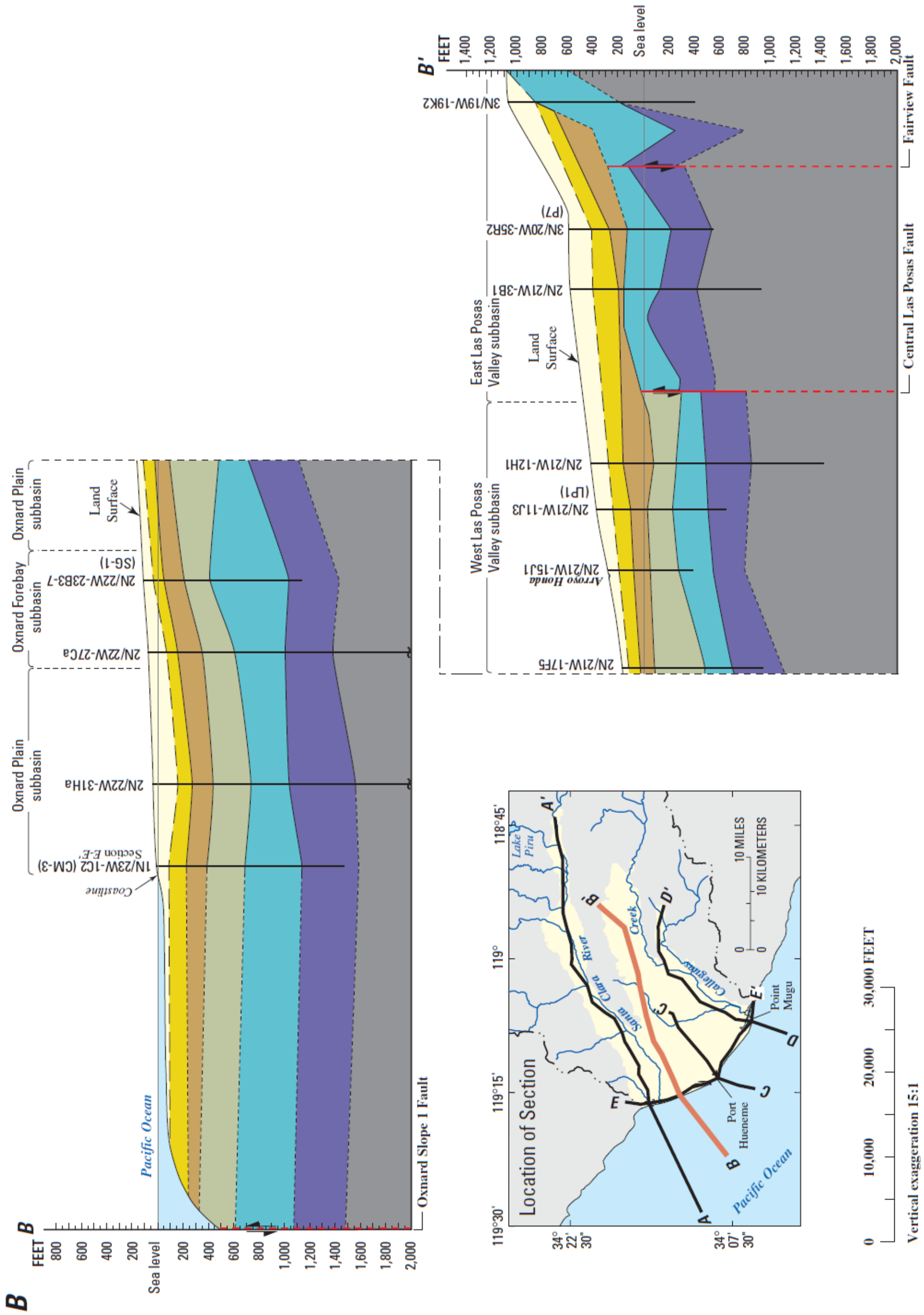

Figure 3.3 -- Geophysical structure of the Oxnard aquifer system, B section (USGS, 2012)

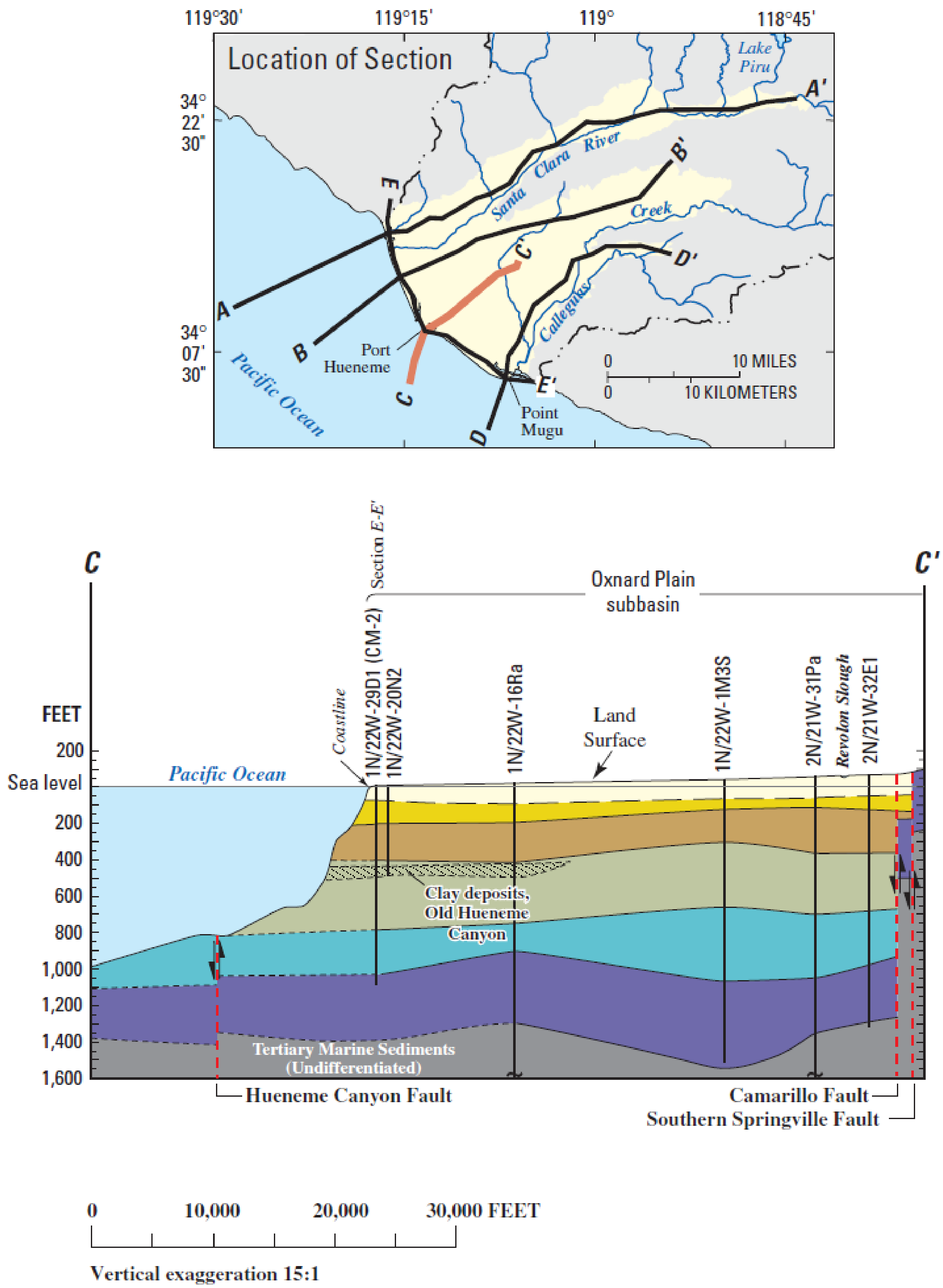

Figure 3.4 -- Geophysical structure of the Oxnard aquifer system, C section (USGS, 2012)

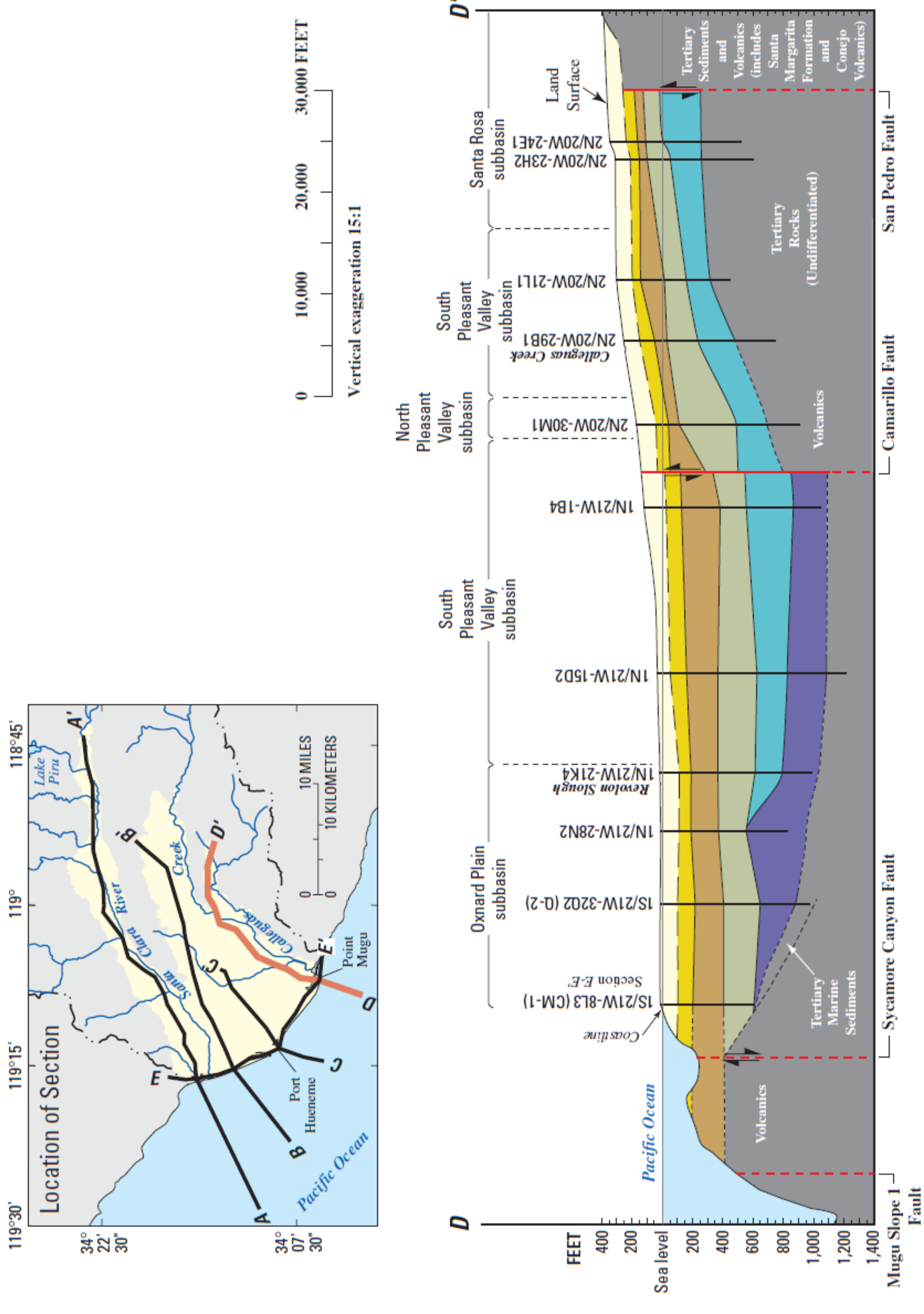

Figure 3.5 -- Geophysical structure of the Oxnard aquifer system, D section (USGS, 2012)

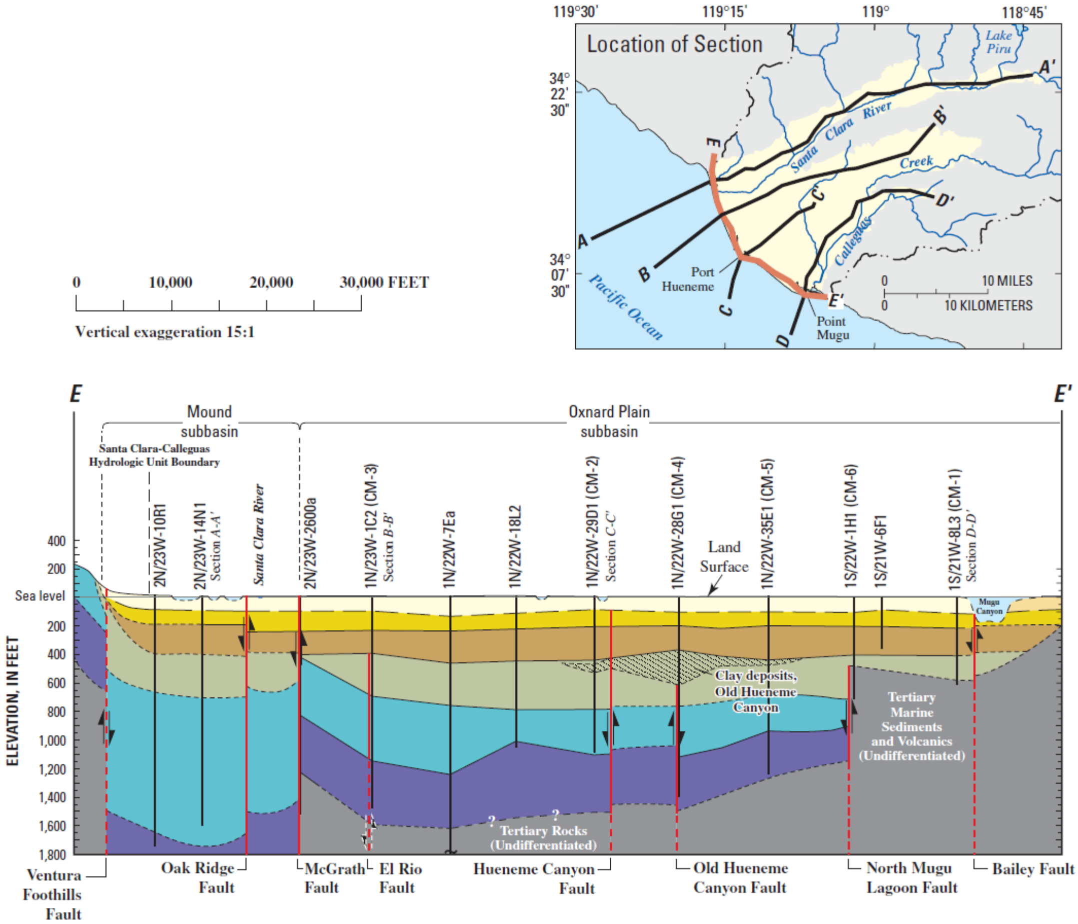

Figure 3.6 -- Geophysical structure of the Oxnard aquifer system, E section (USGS, 2012)

Throughout most of the ground-water basin, the Mugu aquifer extends from about 200 to 400 ft below land surface and consists of sand and gravel interbedded with silt and clay. The silt and clay layers retard the vertical movement of water through the Mugu aquifer and confine or partly confine the aquifer (U.S. Geological Survey, 2012). Over most of the ground-water basin, the top of the aquifer is relatively flat; however, the base of the aquifer has a more irregular surface owing to a regional uncomformity. This uncomformity, which is most pronounced in the Mound and the East Las Posas Valley subbasins, is due to deformation during deposition of older alluvium that contains the Mugu aquifer.

Few production wells are perforated solely in the Mugu aquifer; most are also perforated in the overlying Oxnard aquifer or in the underlying lower-aquifer system. In general, wells that are perforated opposite both the Oxnard and Mugu aquifers, which are similar in thickness, obtain most of their water from the Oxnard aquifer because it is significantly more permeable. Hydraulic conductivities estimated from slug tests at the multiple-well monitoring sites constructed for this study range from less than 1 to 98 ft/d; most, however, are less than 25 ft/d (City of Oxnard, 2010). When individual wells at the same multiple-well monitoring site were tested, the estimated hydraulic conductivity of the Oxnard aquifer was almost always higher than that estimated for the Mugu aquifer.

In subbasins in which the Mugu aquifer is predominantly coarse-grained (the Piru, Fillmore, and Santa Paula subbasins), wells perforated in both the Mugu aquifer and the underlying lower-aquifer system obtain most of their water from the Mugu aquifer. USGS researchers demonstrated this via a wellbore flow meter test completed on well 3N/21W–11J5 in the Santa Paula subbasin (U.S. Geological Survey, 1996). Although this well is perforated predominantly in the lower-aquifer system, almost all the water yielded by the well is derived from the Mugu aquifer. As stated previously, the Mugu aquifer is less indurated than the lower-aquifer system, which would account for its greater water-yielding capacity. In the subbasins where the Mugu aquifer is predominantly fine grained, wells yield significant quantities of water from the aquifer only if they are perforated opposite the basal coarse-grained zone. This laterally extensive basal zone, which, as noted earlier, is due to a regional unconformity, yields water readily to wells. Many wells are not perforated opposite this zone, however, because its thickness is 20 ft or less throughout many of the subbasins.

In the Oxnard Plain subbasin, the Upper Hueneme aquifer is predominantly fine grained in two areas along the coast line between Port Hueneme and Point Mugu. These fine-grained deposits are more than 200 ft thick near the coast, and they extend about 3.5 mi inland. Reports from the U.S. Geological Survey attributed these deposits to a lagoonal or embayment depositional environment throughout most of the San Pedro Formation deposition (2012). Inspection of lithologic and electrical logs collected during the drilling of the multiple-well monitoring sites constructed for this study indicates that these fine-grained deposits are ancestral submarine canyons that were backfilled during a rise in sea level. The submarine canyons were carved into the San Pedro Formation sometime prior to the deposition of the deposits of the upper Pleistocene (U.S. Geological Survey, 2012). These backfilled ancestral submarine canyons are important hydrologic features because they are low permeable barriers to ground-water flow and may contribute to coastal subsidence. The hydraulic conductivity of the fine-grained deposits in the ancestral submarine canyon, estimated from a slug test at the CM-5 multiple-well monitoring site, was 0.1 ft/d (U.S. Geological Survey, 1996). This testing can be used to establish idealized parameters for the aquifer, critical to the approximation of non-numerical methods of analysis. For the area of concern, the idealized aquifer can be pictured as having an average unconsolidated depth of 1400 ft, over an area of 120 square miles. Moreover, the hydraulic conductivity of the aquifer structure can be taken as 190 ft/d.

III.VI - SEA LEVEL RISE

Climate change and groundwater will show some of their most drastic interrelation in coastal areas. Some areas are already increasing in saline intrusion. The sea-level rise that accompanies climate change will reduce the freshwater supply in many coastal communities, by infiltrating groundwater and rendering it brackish and undrinkable without excessive treatment (McCallum, 2010). Coastlines are made of many different layers and kinds of sand. Coarse sands, usually located well below the shore surface let water through to aquifers and can lead to contaminated, brackish water, particularly in the lower regions of the aquifer. In order to highlight the risks of saline intrusion, a case study in an aquifer of interest can be conducted.

The California Department of Water Resources (CDWR) issued a landmark report in July 2006 that incorporated climate change predictions into management of California's water resources (California Department of Water Resources, 2006). The CDWR identified saline intrusion into coastal aquifers as one likely impact of modern-age climate change. Although sea level has been rising since the end of the last (Wisconsinan) Ice Age, the rate of increase might have been recently exacerbated by thermal expansion and ice melting caused by anthropogenic greenhouse gas (GHG) emissions to the atmosphere (Intergovernmental Panel on Climate Change (IPCC), 2007). Other effects of increased GHGs emissions, CO2, specifically, on sea water have been pondered in Lo´aiciga (2012). Global mean sea level (GMSL) increased by an average rate of 1.8 mm/year during the 20th century (Douglas, 1997). The IPCC reports a high confidence that this rate has been increasing. The IPCC estimated that GMSL increased 3.1 mm/year from1993 to 2003, although this change is not spatially uniform, worldwide. Nicholls and Cazenave estimated a GMSL rise of approximately 3.3 mm/year in the period 1992 to 2010 (2010). The rise of sea level poses exacerbated threats in coastal aquifers undergoing land subsidence and decreased riverine sediment output to estuaries, while its threat is diminished in pre-glaciated areas undergoing isostatic rebound (Anderson, Miliken, & Wallace, 2010). Eight long-term tidal records on the coast of California exhibit increases in mean sea level (MSL) ranging from 0.84 mm/year (Los Angeles) to 2.22 mm/year (La Jolla), while one station shows a decrease in MSL of−0.48 mm/year during the 20th century (California Department of Water Resources, 2006). The CDWR postulated an increase in sea level ranging from 0.10 to 0.90 m along California's coast during the 21st century, which is consistent with recent 21st-century predictions of GMSL by Nicholls and Cazenave (2010). One effect of such an increase in sea level rise is to induce sea water intrusion into coastal aquifers (Bear, et. al, 2008). Sea water intrusion caused by groundwater extraction has been noted in Monterey, Santa Cruz, and Ventura counties of California, and in lands surrounding the San Francisco Bay, dating back to the 1930s, as well as in many other parts of the world. Groundwater has a prominent role in water supply in California—accounting to about 40%of its urban and agricultural water use—thus the concern to address the threat posed by future sea-level rise to California's coastal aquifers (Bachman, et al., 2005). Similar concerns apply to coastal aquifers in other regions given that more than 60% of the world population lives within 30 km of oceanic shorelines.

III.VII - BASICS OF MODELING THE PROBLEM

In order to predict the saline/freshwater interface two basic model types will be implemented. As discussed in chapter 1, these two approximate models are the Ghyben-Herzberg (U-Tube) and Glover models. The U-Tube or manometer model, the hydrostatic balance between fresh and saline water can be estimated based on columnar pressures. The relative lower density of the fresh water leads it to float entirely on one side of the manometer. This shows that in an aquifer there will be an interface with freshwater on top and denser saline water intruding to the bottom of the aquifer (Todd & Mays, 2004). This model does not predict any intermixing at this boundary, which is a reasonable assumption in an aquifer, where low plume velocities will prevent the actual mixing region from extending to the bottom of the aquifer.

The Glover model is a conceptual model that relies on some basic simplifying assumptions about the aquifer involved, but still gives good approximations of saline/freshwater interface (Todd & Mays, 2004). The most important data to this model is easily and accurately obtained, that being the rate of seaward flow in the top layers of the aquifer. The data is easily obtained because the top layers are the most readily accessible. A simplified idealized version of the aquifer can be seen in Figure 3.7 below.

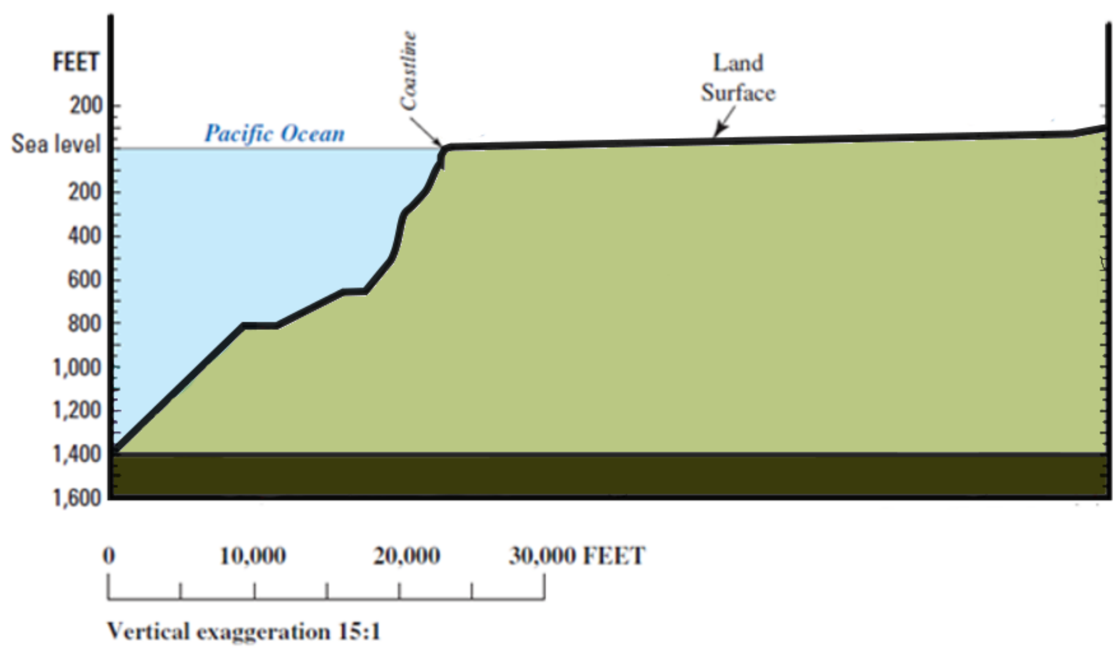

Figure 3.7 - Idealized Aquifer Section

In the following chapters, these elementary models will be applied, and the results generated will be used to highlight water management issues. Further, some preliminary recommendations for modified management can be made.

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CHAPTER 4

SALINE VULNERABILITY OF THE WATER TABLE ASSESSED BY THE GHYBEN-HERZBERG RELATIONSHIP

IV.I - INTRODUCTION

Near the beginning of the 20^{th} century two investigators, working independently along the European coast, found that saltwater occurred underground, not at sea level but at a depth below sea level of about 40 times the height of the freshwater above sea level. This distribution was attributed to a hydrostatic equilibrium existing between the two fluids of different densities. The equation derived to explain the phenomenon is generally referred to as the Ghyben-Herzberg relation after its originators.

IV.II - LITERATURE REVIEW

Prepared for the Groundwater Resources Association of California, the handbook, “California Groundwater Management” provides a launching point for those not previously familiar with the specifics of groundwater data and policy in California (Bachman, et al., 2005). This second edition builds on the work already established, in order to make the information accessible to readers of diverse backgrounds and understanding. As such, it can help to provide a general contextual framework for investigations in the groundwater resources of the state.

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Based on measurements from an approximately global distribution of 177 tidal gauges, Holgate & Woodworth establish that sea level rise from 1950 to 2004 has been 1.7 ± 0.2 millimeters per year (2004). Using altimetry, the supposition is then made that the rise of sea levels around global coastline was significantly greater than the average over all ocean surfaces. Holgate & Woodworth go on to review some models which predict this trend as a precursor to significant increases in global sea level rise.

The International Panel on Climate Change has now released four reports assessing the past, present and future state of the global climate and human effects thereon. With each assessment report, a team of international scientists and engineers has been tasked with establishing and reviewing the scientific foundations of any claims to be made (2007). Published separately, their efforts are referred to as “The Physical Science Basis.” Of particular concern to this work are chapters 8, 10, and 11 of that document. Respectively, these sections discuss climate models and their evaluation, global climate projections, and regional climate projections.

Loaiciga presents a method to assess the contributions of 21st-century sea-level rise and groundwater extraction to sea water intrusion in coastal aquifers in “Sea Water Intrusion by Sea-Level Rise: Scenarios for the 21st Century.” Simulations of sea water intrusion in the Seaside Area sub-basin near the City of Monterey, California illustrate this methodology (2012). The method presented in this work is also suggested to be applicable to coastal aquifers under a variety of other scenarios of change not considered in this work.

Nerem and Mitchum discuss in their chapter of “Sea Level Rise,” that while the long term standard for the measurement of sea level data has been tidal gauges, two fundamental issues can point out the preference for additional data collection. First, the gauges can only measure sea level relative to a crustal point, and this point may move at a rate similar to average sea level change. Second, it has been established that tide gauges have limited spatial distribution and suboptimal placement as a matter of convenience. Starting with the project TOPEX/POSEIDON, data has been collected from space for two decades, providing both a greater granularity and flexibility in determination in changes in sea level (2001).

One of the foundation texts for the field, David Keith Todd’s Groundwater Hydrology has received multiple updates since its initial printing. Of particular concern here are the explanations of equilibrium calculations for saline and freshwater interfaces (2004). These sections help establish a basis for the estimation of impacts from sea level rise.

Recent work on seawater intrusion in aquifers underlying the Oxnard Plain, Ventura County, California is reported by the USGS in "Seawater Intrusion in a Coastal California Aquifer." The geologic setting and hydrologic processes that affect seawater intrusion in aquifers underlying the Oxnard Plain are similar to those in other coastal basins in southern California (1996).

IV.III - GENERAL FORM OF THE MODEL

The hydrostatic balance between fresh and saline water can be illustrated by the "U-Tube" manometer as shown in the figure on the following page. Pressures on each side of the tube must be equal; therefore an equation hydrostatic balance is established. For typical seawater conditions, that equation may be simplified such that:

$$z = 40\, h_f$$

By translating the U-tube to a coastal situation, h_f becomes the elevation of the water table above sea level and *z* is the depth to the fresh-saline interface below sea level. This is a hydrodynamic rather hydrostatic balance because fresh waters flowing toward the sea. From density considerations alone, without flow, a horizontal interface would develop with fresh water everywhere floating above saline water. It can be shown that when the flow is nearly horizontal the relation provides satisfactory results. Only near the shoreline where vertical flow components become pronounced due significant errors in the position of the interface occur.

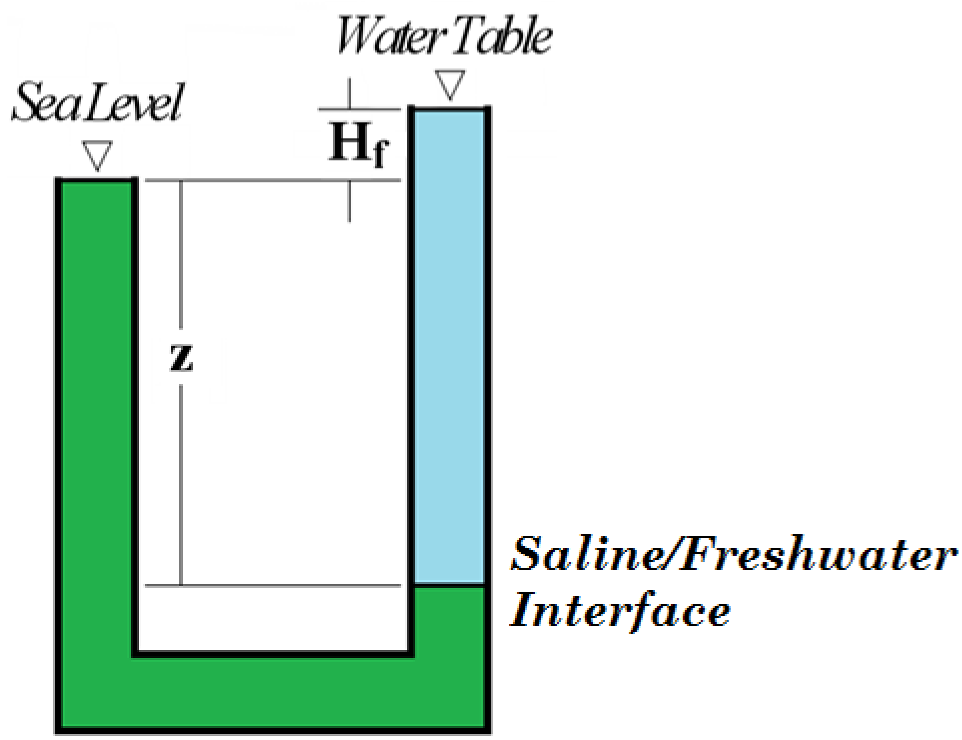

Figure 4.1 -- Manometer approximation of the saline/freshwater interface

IV.IV - BENEFITS OF THE APPROACH

The Ghyben-Herzberg relation simplifies the balance in freshwater-seawater equilibrium down to only its most direct components. The effects of relative density are critical to this calculation, and the value presented here is unlikely to be notably affected even by significant sea level rise, due to the nature of the volumetric contribution. The greatest advantage of this method is of course its simplicity and ease of use. It can provide a reasonably confident rough estimate of the effects of changing mean sea level. The equation can provide underestimated results, as it does not account for some factors of hydrogeology which may see exaggerated changes in the aquifer's saline interface with greater sea level rise.

IV.V - DRAWBACKS OF THE APPROACH

Although the results provided by this method are not extreme, they are transparently imprecise. The known factor of this conservative result can also be detrimental in policy modification. It discourages consideration of upper boundaries or excess change, beyond the most confident predictions.

What is perhaps the most obvious drawback of the method is its inability to account for the hydrodynamic properties of the geostructure in a groundwater basin of interest. The model considers a situation under which equilibrium between the fresh and saltwater reservoirs has been reached. This can be considered a minimal issue, since the sea level rise will occur over a long period, and allow adequate transmission through the interface. Further, the shape of the transition zone in the aquifer is not taken into account. The conservative nature of the estimates derives primarily from this fact. As the transition zone occupies a greater fraction of the aquifer depth when nearing the ocean boundary, the changing sea level reduces in impact.

IV.VI - REQUIRED DATA

As mentioned previously, the U-Tube model does not account for many physical properties of the aquifer being assessed. The only required information is the depth of the aquifer over which transmission occurs, the change in depth of either the saline or fresh water regions, and the known densities of the waters involved. The result can be expanded into something more useful by including the area of the aquifer, in order to obtain a resulting change in volume. Table 1 below illustrates this most basic information for this model in the Oxnard-Mugu aquifer, and the most simplified form of the function for the model.

Table 1 -- U-Tube parameters of the Oxnard-Mugu aquifer

$z = h_f \rho_f / (\rho_s - \rho_f)$		
$z = 40 h_f$		
A_{aqu} =	120	mi^2
ρ_f =	1.000	g/cm^3
ρ_s =	1.025	g/cm^3
D_{aqu} =	1400	ft

As seen in the table, the average depth of the aquifer has been previously established as approximately 1400 feet, below which the geostructure is consolidated and impermeable (U.S. Geological Survey, 1996). Simple surveying methods have established the boundaries and total area of the aquifer. The densities used in these calculations are based on standard values for fresh and saline waters, as there are no exceptional particulates in the constraints of the Oxnard-Mugu aquifer (Muir, 1982). Additional confirmation of this data has been obtained by non-governmental private interest groups, such as the California Groundwater Resource Management Association (Bachman, et al., 2005).

IV.VII - MEAN SEA LEVEL RISE

Based on proxy data, the magnitude of centennial-scale global mean sea level variations did not exceed 0.25 m over the past few millennia. This prediction can be made with medium confidence (Donnelly, 2006). The current rate of global mean sea level change, starting in the late 19th-early 20th century, is, with medium confidence, unusually high in the context of centennial-scale variations of the last two millennia. Tide gauge data also indicate a likely acceleration during the last two centuries (Douglas, 1997). Based on proxy and instrumental data, it is virtually certain that the rate of global mean sea level rise has accelerated during the last two centuries, marking the transition from relatively low rates of change during the late Holocene, order tenths of mm yr^{-1}, to modern rates, of the order mm yr^{-1} (Holgate & Woodworth, 2004).

Global mean sea level has risen by 0.19 [0.17 to 0.21] m, estimated from a linear trend over the period 1901– 2010, based on tide gauge records and additionally on satellite data since 1993. It is very likely that the mean rate of sea level rise was 1.7 [1.5 to 1.9] mm yr^{-1} between 1901 and 2010. Between 1993 and 2010, the rate was very likely higher at 3.2 [2.8 to 3.6] mm yr^{-1}; similarly high rates likely occurred between 1930 and 1950.The rate of global mean sea level rise has likely increased since the early 1900 with estimates ranging from 0.000 to 0.013 [–0.002 to 0.019] mm yr^{-2} (Intergovernmental Panel on Climate Change (IPCC), 2007). The figures on the following pages condense this information and demonstrated the scenarios most likely to occur in sea level rise. By most likely, it is meant that the scenario is within two standard deviations of current predictive information.

These figures, 4.3, 4.4, and 4.5, are built upon data collected via traditional methods and modern methods. The most recent predictors for sea level rise are established through satellite altimetry and the components of this data have significantly greater granularity than previous estimates (Nerem & Mitchum, 2001). The figures present a range scenarios within these bounds, and with 95% confidence it can be assumed sea level rise will be between 0.20 meters and 0.95 meters by 2100 (Bates, Kundzewics, Wu, & Palutikof, 2008).

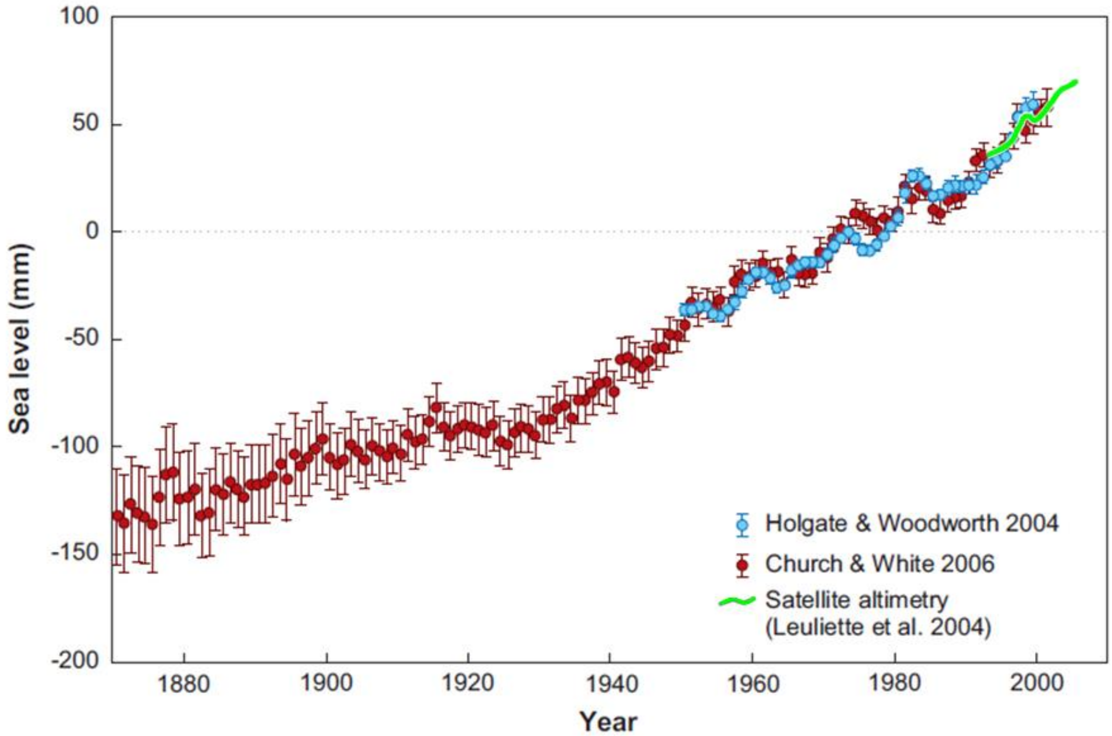

Figure 4.2 -- Global sea levels by tide gauges, altimetry, and satellite reading (IPCC, 2011)

Please note that Figure 4.3 is reproduced as originally presented in the IPCC Fourth Assessment Report by the International Panel on Climate Change, per that organization's reference and publication requirements, and as such, requires some additional explanation. The predicted seal level rise shows a range both of scenarios and SLR changes within those cases, in order to produce a prediction with a much higher confidence interval. The 4 cases demonstrated in this figure are based on human emission patterns. RCP2.6 represents a significant reduction in human emissions and resulting global mean temperature increase of approximately 1 degree Celsius by 2100; RCP 2.6 represents a continuance of current emission growth and yields a likely global mean temperature increase of 3.7 degrees Celsius. RCP 4.5 and RCP 6.0 are intermediate scenarios for those two extremes. Figure 4.4 then demonstrates the combined observed data and predicted trend, in order to graphically demonstrate the confidence of the curve fit.

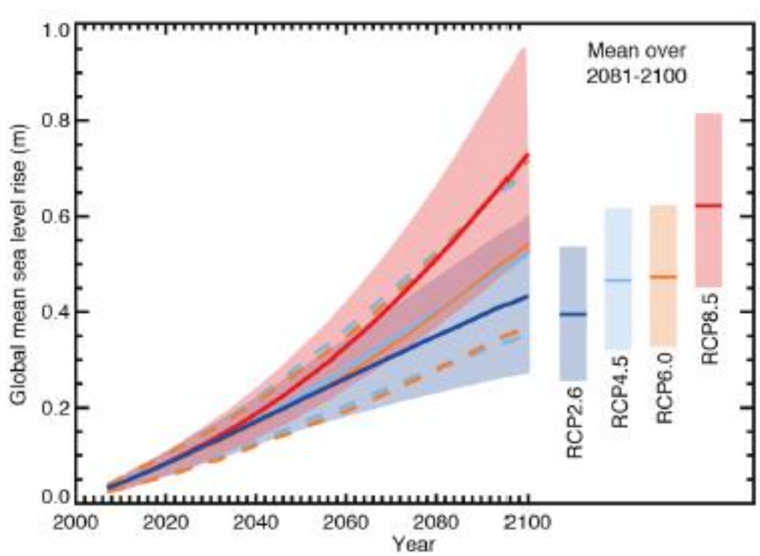

Figure 4.3 -- Predicted sea level rise per the IPCC fourth assessment report (IPCC, 2011)

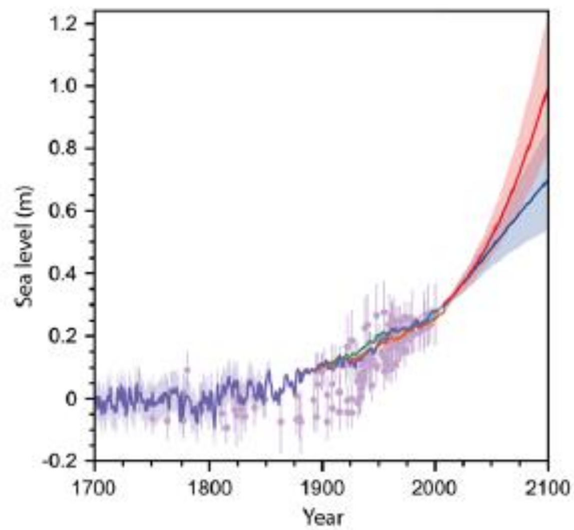

Figure 4.4 -- Past and future global sea level estimates

IV.VIII - RESULTING DATA

By inserting a range of values for sea level rise, a spectrum of changes can be anticipated. The results illustrated in Table 2 following this page estimate a volumetric change based on the changes in elevation for the top and bottom of the freshwater zone, ΔV. Of course, this model represents a linear progression of losses. Therefore, a total loss of potable groundwater per centimeter of sea level rise can also be established. This value of 20.5 acre-feet may be more valuable than any other result, as a method of simplifying and condensing the results of the analysis. This is consistent with values typically generated by the model in established past studies (Bear, et. al, 2008).

Table 2 -- U-Tube estimates of water table changes in the Oxnard-Mugu aquifer

ΔD_{sea} Meters of sea level rise	ΔD_{aqu} Meters of lost aquifer depth	ΔV Thousands of cubic meters lost	ΔV Acre-feet lost
0.1	0.10	253	205
0.59	0.58	1490	1208
1	0.98	2530	2047
2	1.95	5050	4095
3	2.93	7580	6142

Further, these calculations can also produce a prediction for the landward advance of the saline-freshwater interface in the aquifer. Using a graphic area method with the equation:

$$\Delta\overline{L_\iota} = (A_{SLR} - A_0)/d_2 - d_1$$

A satisfactory estimate of the average intrusion of the interface inland can be found. In this calculation, $\Delta\overline{L_\iota}$ equals the average intrusion across a vertical region from a depth, d_2, up to a depth closer to ground surface, d_1. A_0 is the cross sectional area occupied by seawater in the aquifer, from the coastal structure to the interface, across the depth specified d_1 and d_2, under current environmental conditions; while A_{SLR} is the same region with the interface boundary position relocated after sea level rise. Considering the primary regions of water extraction to be the Oxnard-Mugu (30m to 122m) and the upper Hueneme (122m to 225m), Table 3, following this, has been prepared to show interface intrusion in the elected SLR cases, with both average intrusion and predicted actual intrusion at the nominal depths.

Table 3 - Saline-Freshwater Interface Landward Intrusion Due to SLR, U-Tube Method

Region of Concern	Oxnard-Mugu, Depth 30m to 122m (100 to 400 ft)				Upper Hueneme, Depth 122m to 225m (400 to 738 ft)			
Sea Level Rise, SLR (m)	0.59	1.00	2.00	3.00	0.59	1.00	2.00	3.00
Interface Intrusion, $\Delta\overline{L_i}$ (m)	11.1	18.9	37.8	56.6	17.7	30.0	60.1	90.1
Interface Intrusion, ΔL_{30} (m)	8.3	14.0	28.0	42.1	--	--	--	--
Interface Intrusion, ΔL_{122} (m)	9.5	16.1	32.2	48.3	9.5	16.1	32.2	48.3
Interface Intrusion, ΔL_{225} (m)	--	--	--	--	33.8	57.2	114.5	171.7

To further illustrate the effects of sea level rise on the water table, figure 4.5 on the following page demonstrates the visible difference in the interface boundary after the most likely change of 0.59 meters increase in mean sea level by 2040. This value was read from the IPCC predicted data, for the 95% confidence interval case. For context, the figure also includes a base line average of the current depth of the interface across the aquifer, at 426 meters (1400 feet). Note, the dimensions of the figure have been exaggerated and abbreviated, so as not to include the entire aquifer, in order to make the difference in interface profile more legible.

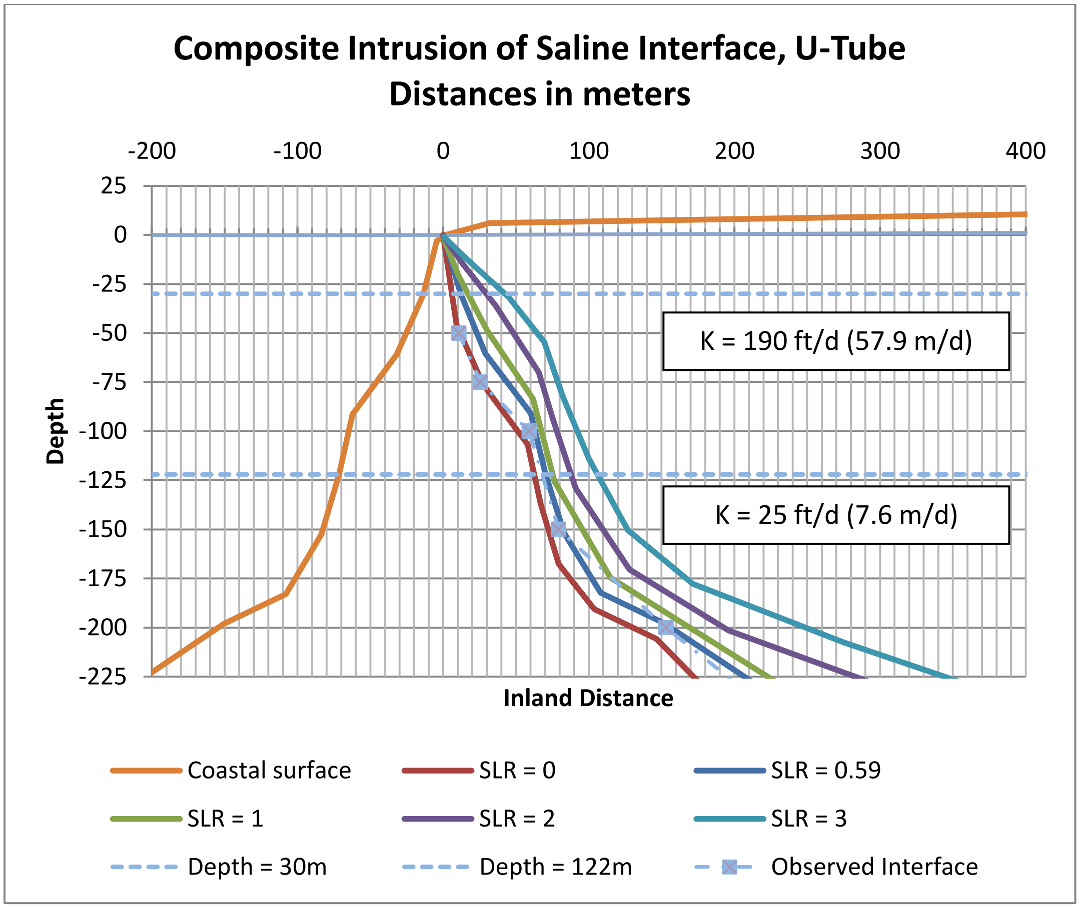

Figure 4.5 - Composite Intrusion of Saline Interface, U-Tube, Distances in meters

We can see reasonable agreement between the estimated interface location at the current level (2010) with sea level rise equal to 0, and the observed interface location data provided by the USGS (U.S. Geological Survey, 1996). Note that these locations are established by the saline concentration reaching a level of 100 mg/l. Figure 4.6 following this tightens then focus of in each region even more, in order to make the actual distances legible within a comfortable margin of visual error.

Now continuing from these estimates, some conclusions can be drawn about other levels of sea rise, including simplified equations to predict volumetric capacity losses from the

aquifer storage and intrusion distance predictors. The figures collating this data and fitting equations to these situations follow Figure 4.6 in Figures 4.7 and 4.8.

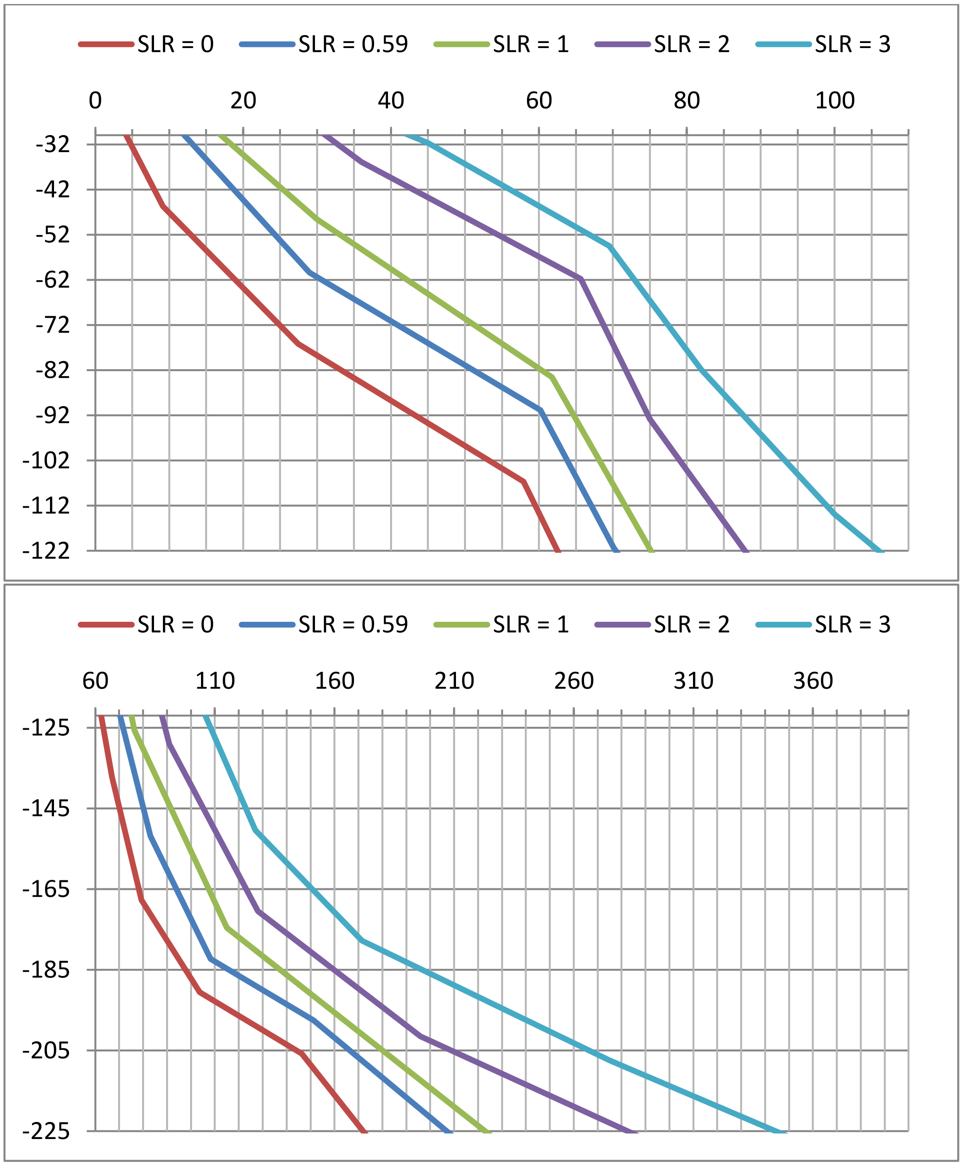

Figure 4.6 -- Saline/freshwater interface changes, post SLR, Ghyben-Herzberg, Aquifer depth versus distance inland in meters

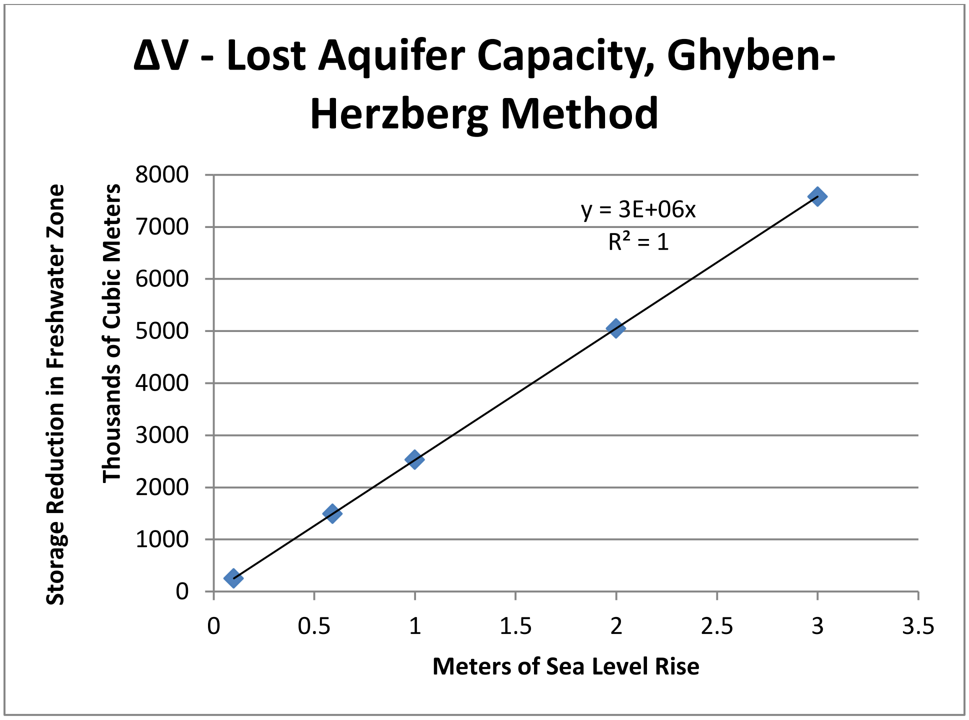

Figure 4.7 - ΔV - Lost Aquifer Capacity, Ghyben-Herzberg Method

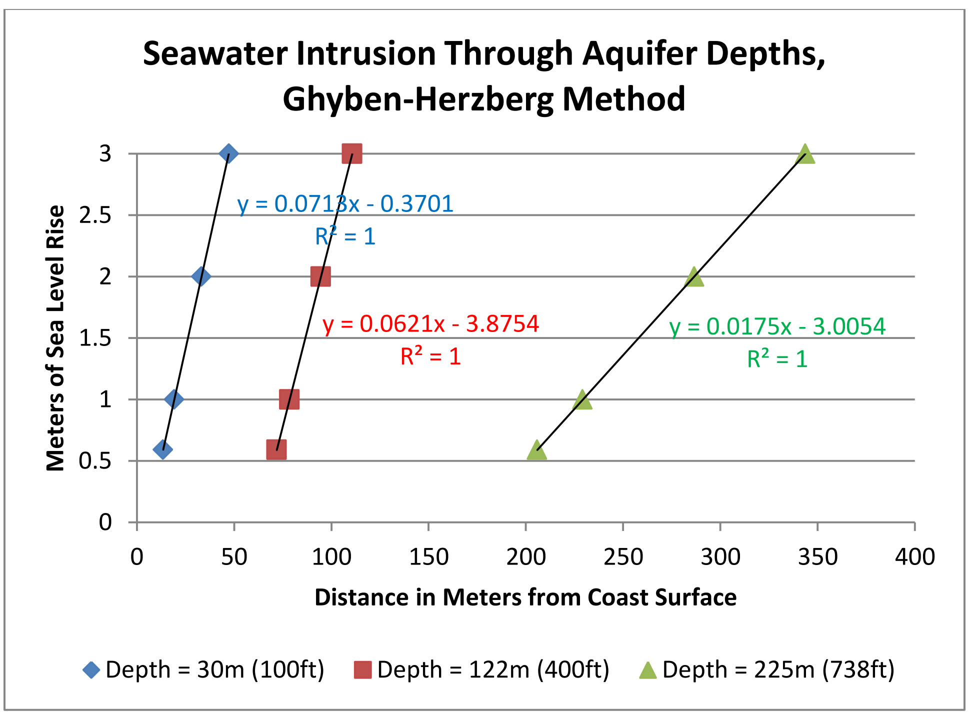

Figure 4.8 - Seawater Intrusion Through Aquifer Depths, Ghyben-Herzberg Method

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CHAPTER 5

SALINE VULNERABILITY OF THE WATER TABLE ASSESSED BY THE GLOVER INTERFACE METHOD

V.I - INTRODUCTION

By recognizing the approximations inherent in the previous relationship, more exact solutions for the shape of the interface have been developed from potential flow theory. The results from the commonly used Glover equation have the form:

$$z^2 = \frac{2\rho q x}{\Delta\rho K} + (\frac{\rho q}{\Delta\rho K})^2$$

In this equation, z represents the depth from the sea level at the coast to the saline interface in the aquifer. The components ρ and K are the water density of the saline region and transmissivity of the geostructure, respectively. The variable q is a calculated composite representing the rate of freshwater flow from the top of the aquifer toward the sea.

The sharp interface boundary described by the above equation between fresh and saline water does not normally occur under field conditions. Instead, the brackish transition zone of finite thickness separates the two fluids. This zone develops from dispersion by flow of the freshwater plus unsteady displacements of the interface by external influences such as tides, recharge, and pumping wells. In general, the greatest thickness of transition zones are found in highly permeable coastal aquifers subject to heavy pumping. Observed thicknesses vary from less than 1 m to more than 100 m.

Additional parameters in this model are taken from the equations:

$$h_f = \left(\frac{2\Delta\rho q x}{(\rho + \Delta\rho)K}\right)^2$$

And:

$$x_0 = -\frac{\rho q}{2\Delta\rho K}$$

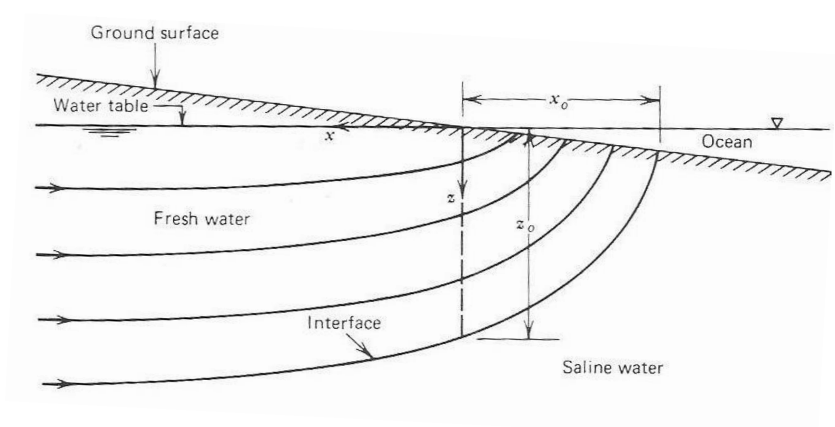

Figure 5.1 -- Abstract Glover interface (Todd & Mays, 2004)

While the figure above demonstrates the abstracted relationship of these dimensions, it should be noted that real world aquifers will rarely demonstrate such a smooth thransition zone, and often have properties which restrict dispersion in either the vertical or horizontal direction.

An important consequence of the transition zone ended seaward flow is the transport of saline water to the pumping locations. This water originates from underlying saline water; hence, some continuity considerations, there must exist a small landward flow in the saline water region. Field measurements and experimental studies have confirmed the landward movement of the saline water bath. Where tidal action is the predominant mixing mechanism, fluctuations of groundwater, and hence the thickness of the transition zone, become greatest near the shoreline.

V.II - LITERATURE REVIEW

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Based on measurements from an approximately global distribution of 177 tidal gauges, Holgate & Woodworth establish that sea level rise from 1950 to 2004 has been 1.7 ± 0.2

millimeters per year (2004). Using altimetry, the supposition is then made that the rise of sea levels around global coastline was significantly greater than the average over all ocean surfaces. Holgate & Woodworth go on to review some models which predict this trend as a precursor to significant increases in global sea level rise.

The International Panel on Climate Change has now released four reports assessing the past, present and future state of the global climate and human effects thereon. With each assessment report, a team of international scientists and engineers has been tasked with establishing and reviewing the scientific foundations of any claims to be made (2007). Published separately, their efforts are referred to as “The Physical Science Basis.” Of particular concern to this work are chapters 8, 10, and 11 of that document. Respectively, these sections discuss climate models and their evaluation, global climate projections, and regional climate projections.

Loaiciga presents a method to assess the contributions of 21st-century sea-level rise and groundwater extraction to sea water intrusion in coastal aquifers in “Sea Water Intrusion by Sea-Level Rise: Scenarios for the 21st Century.” Simulations of sea water intrusion in the Seaside Area sub-basin near the City of Monterey, California illustrate this methodology (2012). The method presented in this work is also suggested to be applicable to coastal aquifers under a variety of other scenarios of change not considered in this work.

Nerem and Mitchum discuss in their chapter of “Sea Level Rise,” that while the long term standard for the measurement of sea level data has been tidal gauges, two fundamental issues can point out the preference for additional data collection. First, the gauges can only measure sea level relative to a crustal point, and this point may move at a rate similar to average sea level change. Second, it has been established that tide gauges have limited spatial distribution and suboptimal placement as a matter of convenience. Starting with the project TOPEX/POSEIDON, data has been collected from space for two decades, providing both a greater granularity and flexibility in determination in changes in sea level (2001).

One of the foundation texts for the field, David Keith Todd's Groundwater Hydrology has received multiple updates since its initial printing. Of particular concern here are the explanations of equilibrium calculations for saline and freshwater interfaces (2004). These sections help establish a basis for the estimation of impacts from sea level rise.

Recent work on seawater intrusion in aquifers underlying the Oxnard Plain, Ventura County, California is reported by the USGS in "Seawater Intrusion in a Coastal California Aquifer." The geologic setting and hydrologic processes that affect seawater intrusion in aquifers underlying the Oxnard Plain are similar to those in other coastal basins in southern California (1996).

V.III - BENEFITS OF THE APPROACH

The Glover method for analysis is based on discovery of the freshwater-saltwater interface shape. Therefore, the method can be used to find the depth between the water table and the saline interface, and the changes in this depth in relation to sea level rise. This value is also more accurate than the same value found through the Ghyben-Herzberg relationship. This method can also approximate the location at which the transition zone becomes of minimal impact on the total available depth of water.

V.IV - DRAWBACKS OF THE APPROACH

Like the Ghyben-herzberg analysis, this method greatly simplifies the problem and thus ignores many factors which can affect the relationship of freshwater and saltwater in a coastal aquifer. It is less accurate than numerical modeling, though more accurate than the U-tube method. It requires more investigation of local conditions than the U-tube method, but significantly less than any numerical approach. Essentially, the greatest drawback is that this method is only slightly more responsive to in situ conditions than the U-tube method.

V.V - REQUIRED DATA

Like the U-tube analysis method, the Glover approach requires a known value for the densities of the waters in the problem situation. Similarly, it also requires a known value for the depth of fresh water in the aquifer. The table below includes both the idealized average depth of 1400 feet, and the approximate area of the aquifer, 120 square miles. Additionally, the method requires the Hydraulic conductivity, K, of the aquifer geostructure. The method also requires the unit flow of the aquifer interface. Most generally this is stated in terms of volumetric exchange per unit length of the shoreline. For the most accurate interface description, K and q must be adjusted for different layers of the aquifer. Table 3 on the following page summarizes the data collected for this analysis.

Table 4 -- Glover parameters for the Oxnard-Mugu aquifer

K =	190	ft/d
A_{aqu} =	120	mi^2
ρ_f =	1.000	g/cm^3
ρ_s =	1.025	g/cm^3
D_{aqu} =	1400	ft
$\Delta\rho$ =	0.025	g/cm^3

V.VI - MEAN SEA LEVEL RISE

Based on proxy data, the magnitude of centennial-scale global mean sea level variations did not exceed 0.25 m over the past few millennia. This prediction can be made with medium confidence (Donnelly, 2006). The current rate of global mean sea level change, starting in the late 19th-early 20th century, is, with medium confidence, unusually high in the context of centennial-scale variations of the last two millennia. Tide gauge data also indicate a likely acceleration during the last two centuries (Douglas, 1997). Based on proxy and instrumental data, it is virtually certain that the rate of global mean sea level rise has accelerated during the last two centuries, marking the transition from relatively low rates of change during the late Holocene, order tenths of mm yr–1, to modern rates, of the order mm yr–1 (Holgate & Woodworth, 2004).

Global mean sea level has risen by 0.19 [0.17 to 0.21] m, estimated from a linear trend over the period 1901– 2010, based on tide gauge records and additionally on satellite data since 1993. It is very likely that the mean rate of sea level rise was 1.7 [1.5 to 1.9] mm yr–1 between 1901 and 2010. Between 1993 and 2010, the rate was very likely higher at 3.2 [2.8 to 3.6] mm yr–1; similarly high rates likely occurred between 1930 and 1950.The rate of global mean sea level rise has likely increased since the early 1900 with estimates ranging from 0.000 to 0.013 [–0.002 to 0.019] mm yr–2 (IPCC, 2007). The figures on the following pages condense this information and demonstrated the scenarios most likely to occur in sea level rise. By most likely, it is meant that the scenario is within two standard deviations of current predictive information.

These figures are built upon data collected via traditional methods and modern methods. The most recent predictors for sea level rise are established through satellite altimetry and the components of this data have significantly greater granularity than previous estimates (Nerem & Mitchum, 2001). The figures present a range scenarios within these bounds, and with 95% confidence it can be assumed sea level rise will be between 0.20 meters and 0.95 meters by 2100 (Bates, et. al, 2008).

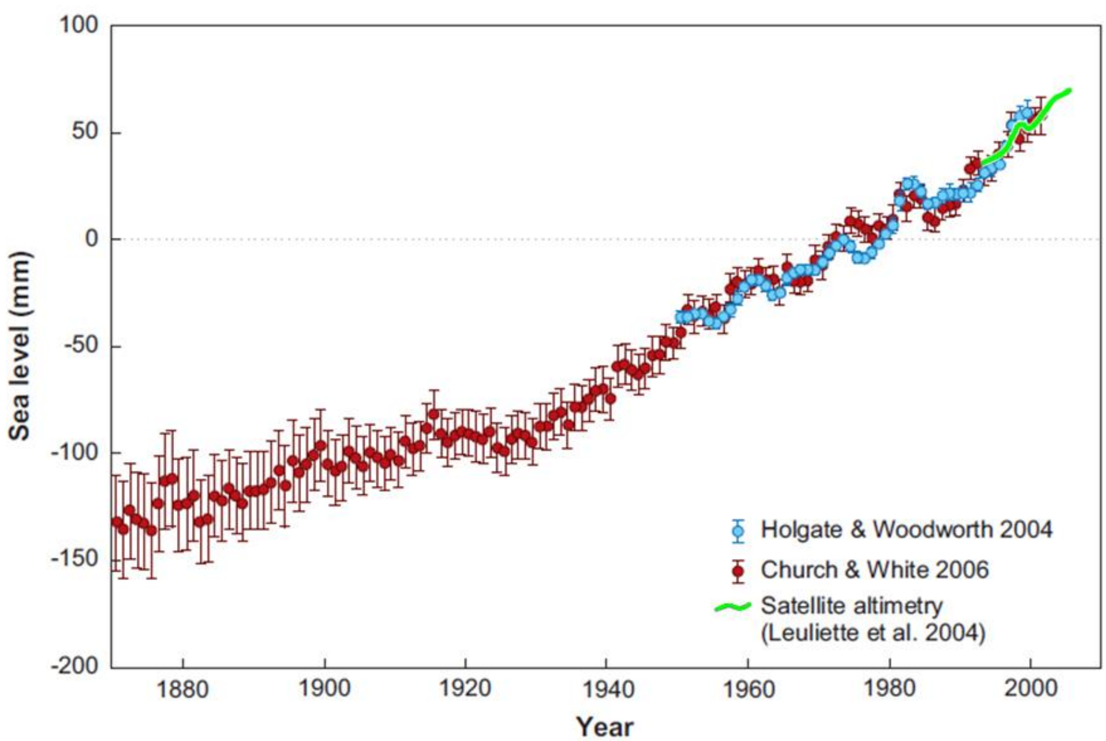

Figure 5.2 -- Global sea levels by tide gauges, altimetry, and satellite reading (IPCC, 2011)

Please note that Figure 5.3 is reproduced as originally presented in the IPCC Fourth Assessment Report by the IPCC, per that organization's reference and publication requirements, and as such, requires some additional explanation. The predicted seal level rise shows a range both of scenarios and SLR changes within those cases, in order to produce a prediction with a much higher confidence interval. The 4 cases demonstrated in this figure are based on human emission patterns. RCP2.6 represents a significant reduction in human emissions and resulting global mean temperature increase of approximately 1 degree Celsius by 2100; RCP 2.6 represents a continuance of current emission growth and yields a likely global mean temperature increase of 3.7 degrees Celsius. RCP 4.5 and RCP 6.0 are intermediate scenarios for those two extremes. Figure 4.4 then demonstrates the combined observed data and predicted trend, in order to graphically demonstrate the confidence of the curve fit.

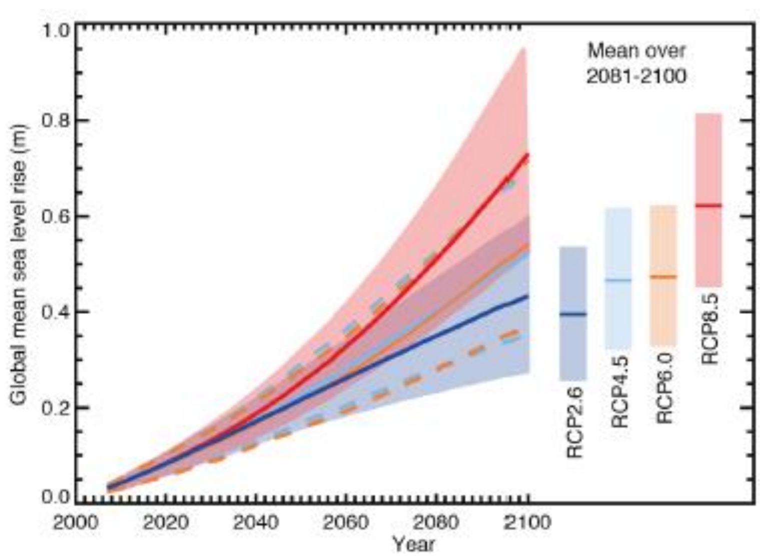

Figure 5.3 -- Predicted sea level rise per the IPCC fourth assessment report (IPCC, 2011)

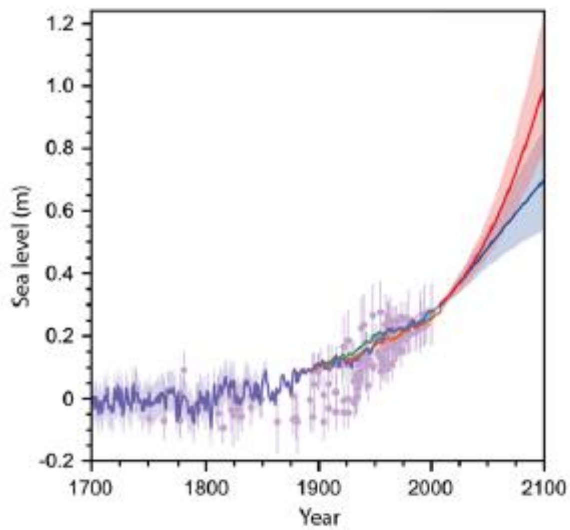

Figure 5.4 - Past and future global sea level estimates

V.VII - RESULTING DATA

By inserting a range of values for sea level rise, a spectrum of changes can be anticipated. Below is a summary table of results for the Glover analysis. The most important result is the loss of volume noted in the right columns, in metric and imperial units. In comparison to the results provided by the Ghyben-Herzberg method, it can be seen that the loss of volume is initially predicted to be smaller, but becomes greater as the rise in sea level increases. Since the method is nonlinear, this result makes qualitative sense. As the method is known to be more accurate, this result provides a valuable caution to policy makers.

Table 5 - Glover estimates for changes in the Oxnard-Mugu aquifer

ΔD_{sea} Meters of sea level rise	ΔV Thousands of cubic meters lost	ΔV Acre-feet lost
0.1	291	24
0.59	1010	820
1	2910	2356
2	11508	9436
3	26200	21241

Further, these calculations can also produce a prediction for the landward advance of the saline-freshwater interface in the aquifer. Using a graphic area method with the equation:

$$\overline{L_\iota} = (A_{SLR} - A_0)/d_2 - d_1$$

A satisfactory estimate of the average intrusion of the interface inland can be found. In this calculation, $\overline{L_\iota}$ equals the average intrusion across a vertical region from a depth, d_2, up to a depth closer to ground surface, d_1. A_0 is the cross sectional area occupied by seawater in the aquifer, from the coastal structure to the interface, across the depth specified d_1 and d_2, under current environmental conditions; while A_{SLR} is the same region with the interface boundary position relocated after sea level rise. Considering the primary regions of water extraction to be the Oxnard-Mugu (30m to 122m) and the upper Hueneme (122m to 225m), Table 3, following this, has been prepared to show interface intrusion in the elected SLR cases, with both average intrusion and predicted actual intrusion at the nominal depths. Also, observe that because the Glover method predicts in each case, that the band of seaward flow is deeper than 30 meters, the intrusion at that depth is effectively still zero.

Table 6 - Saline-Freshwater Interface Landward Intrusion Due to SLR, Glover Method

Region of Concern	Oxnard-Mugu, Depth 30m to 122m (100ft ~ 400ft)				Hueneme, Depth 122m to 225m (400ft ~ 738ft)			
Sea Level Rise, SLR (m)	0.59	1.00	2.00	3.00	0.59	1.00	2.00	3.00
Interface Intrusion, $\Delta\overline{L_i}$ (m)	3.4	8.8	37.2	95.7	14.0	24.5	86.9	191.4
Interface Intrusion, ΔL_{30} (m)	0	0	0	0	--	--	--	--
Interface Intrusion, ΔL_{122} (m)	5.6	16.1	64.4	144.9	5.6	16.1	64.4	144.9
Interface Intrusion, ΔL_{225} (m)	--	--	--	--	22.9	42.1	118.6	245.3

Following this table is figure 5.5 demonstrating these changes in terms of the water table interface position. Also note that this figure represents a stepwise examination of the transmission zones, in order to simplify calculation of the varying transmissivity in the regions of the aquifer.

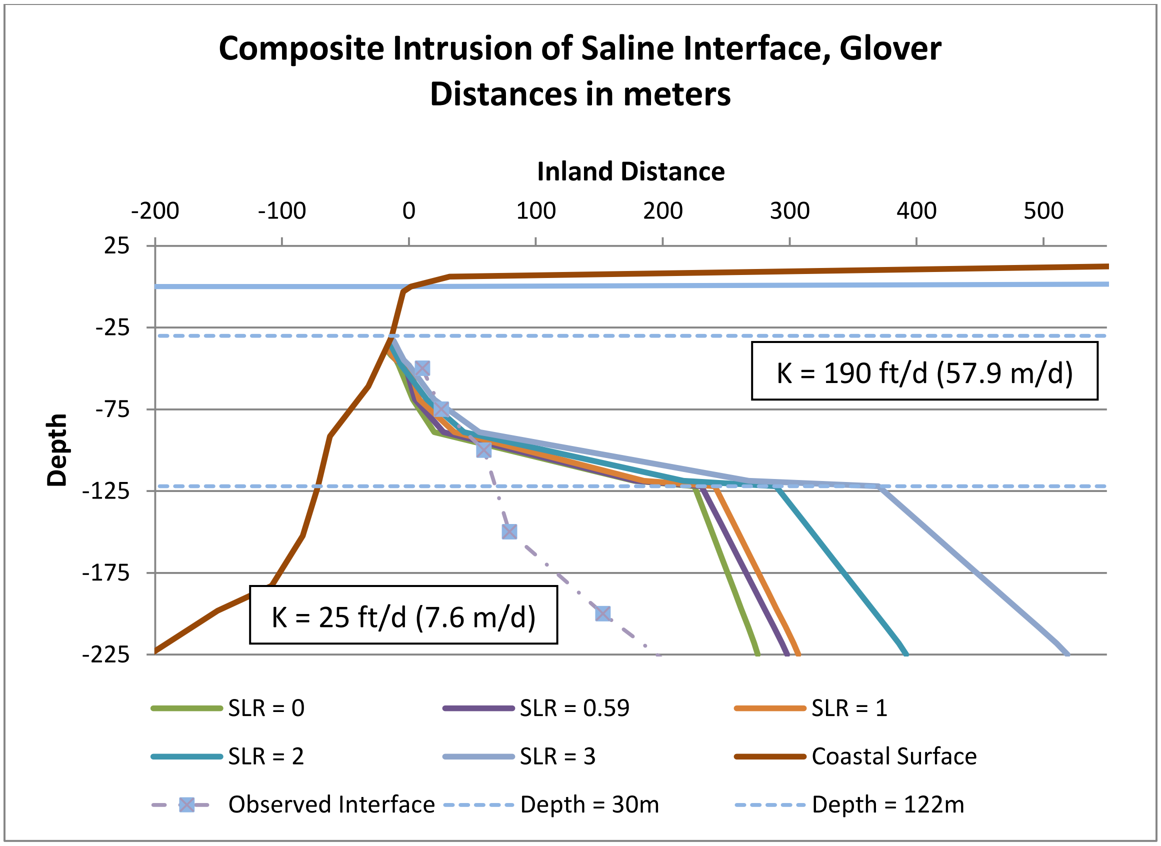

Figure 5.5 - Composite Intrusion of Saline Interface, Glover

We can see reasonable agreement between the estimated interface location at the current level (2010) with sea level rise equal to 0, and the observed interface location data provided by the USGS (U.S. Geological Survey, 1996). The agreement between prediction and observation do improve at greater depths. Note that these locations are established by the saline concentration reaching a level of 100 mg/l. Figure 5.6 following this tightens then focus of in each region even more, in order to make the actual distances legible within a comfortable margin of visual error.

Now continuing from these estimates, some conclusions can be drawn about other levels of sea rise, including simplified equations to predict volumetric capacity losses from the

aquifer storage and intrusion distance predictors. The figures collating this data and fitting equations to these situations follow Figure 5.6 in Figures 5.7 and 5.8.

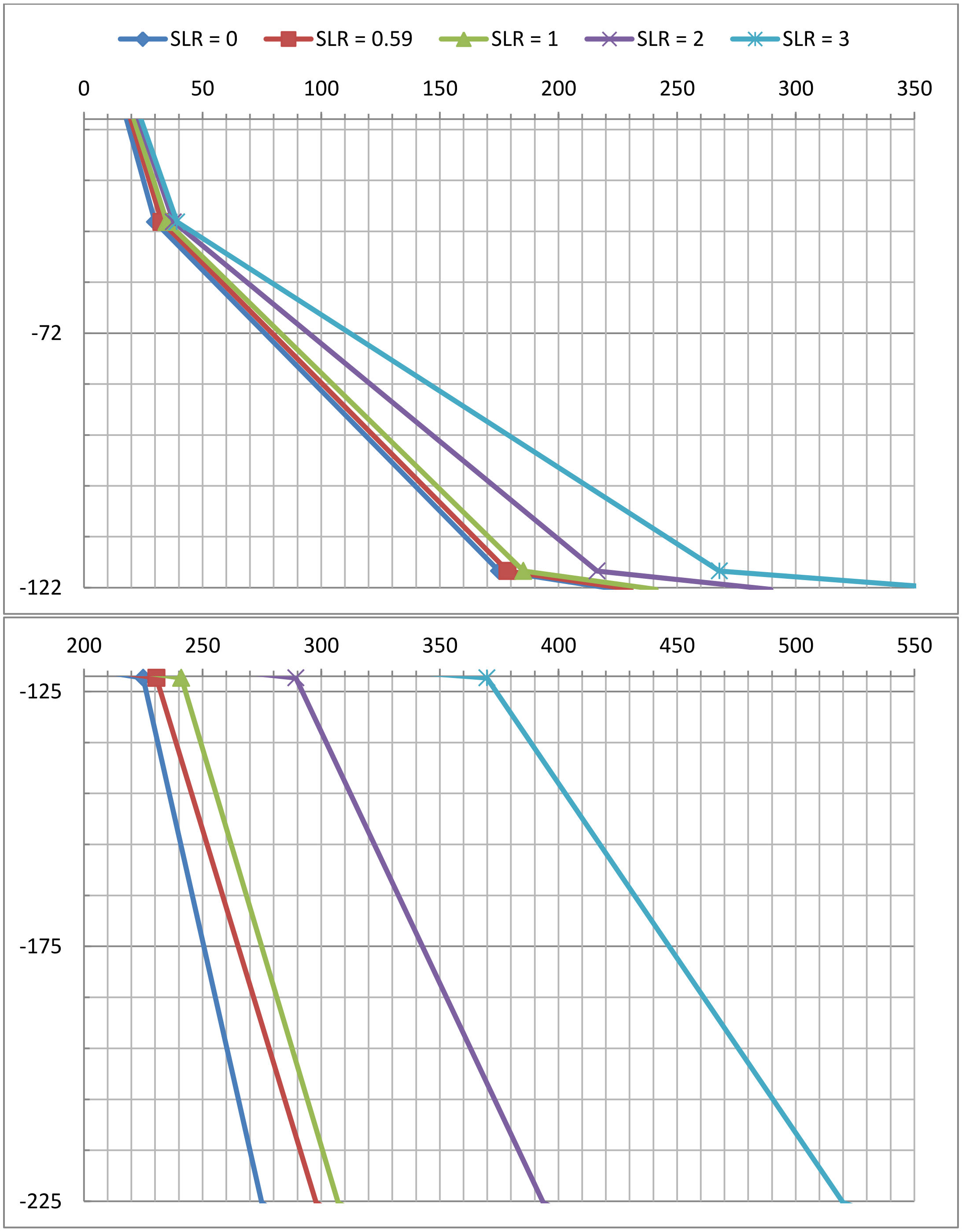

Figure 5.6 - Interface changes post sea level rise, Aquifer depth versus distance inland in meters

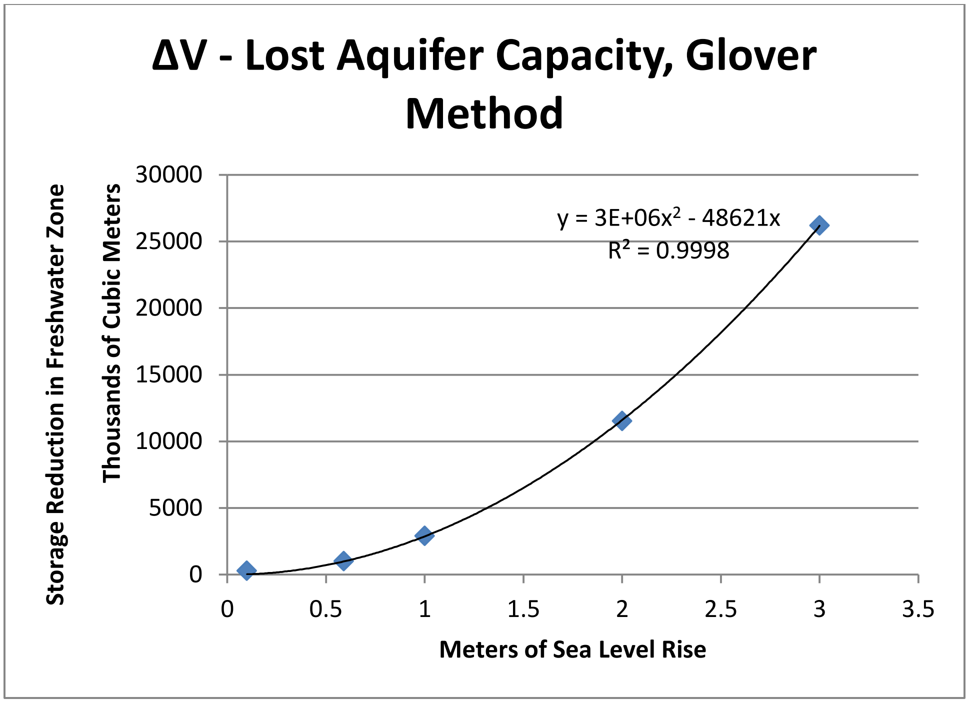

Figure 5.7 - ΔV - Lost Aquifer Capacity, Glover Method

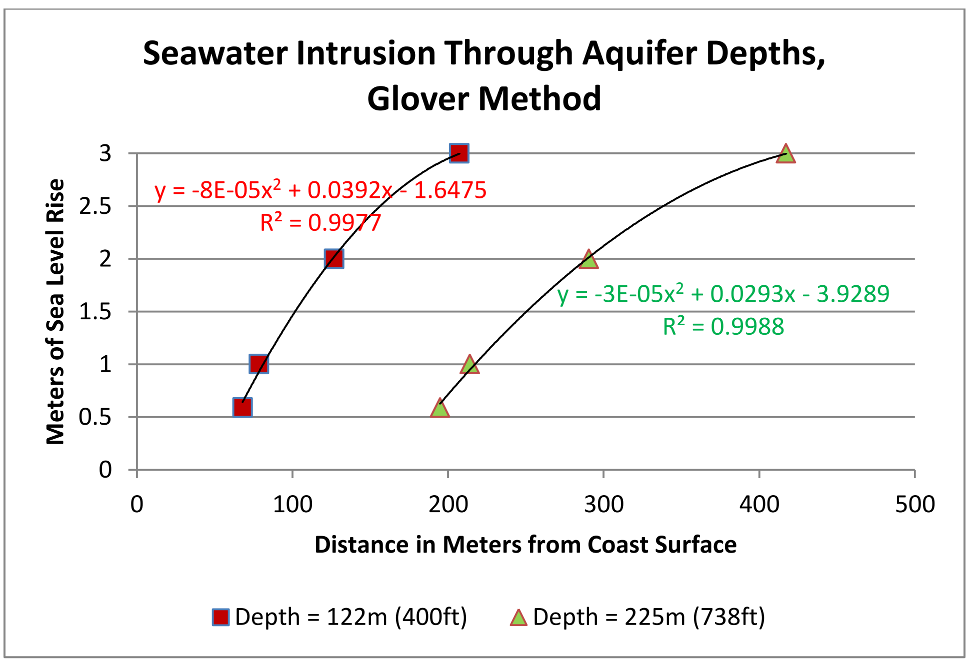

Figure 5.8 - Seawater Intrusion Through Aquifer Depths, Glover Method

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CHAPTER 6

CONCLUSIONS

Global climate change has posed a variety of problems for infrastructure and resource planning. While the methods presented here examine one issue, it is only part of a larger context, and is most useful when viewed within that framework. The water resource issue will certainly be key to developing effective coping techniques with all the aspects of climate change, and this is why even the narrower aspects of it merit consideration, as in this paper. Moving forward, the climate change problem in its relation to groundwater can be summed up by a confluence of three points.

- First, there will be a reduction in available groundwater resources. This arises both from sea level changes reducing storage capacity, and from greater average temperatures reducing aquifer recharge rates.
- Second, with high confidence an assumption can be made that population growth will continue to increase and continue to concentrate in urban and low-lying coastal areas, demanding more water resources, for the foreseeable future.
- Third, quality issues may arise with groundwater, at least in coastal areas, as climate change drives chemical change in sea water and groundwater, such as acidification lifting solids from aquifer boundaries.

VI.I - COLLATION OF DATA

To address these issues, the first step must be to accurately grasp the finite impacts, which has been attempted to a limited extent herein. These impacts can be most briefly summarized by the following:

- The Ghyben-Herzberg method predicts a loss of potable water reserves for the Oxnard basin area of California by 20.5 acre-feet per centimeter of sea level rise.
- The most likely scenario thus expects a loss of slightly more than 1200 acre-feet.
- For the Oxnard basin, which is already pumped at just less than a maximum capacity rate of 246, 800 acre-ft/yr, this represents a 0.5% reduction in the serviceable population.
- By the Glover method, the losses could be considered marginal for any sea level rise of less than 0.5 meters.
- It should be noted however, that even for the likely 0.59 scenario, a loss of more than 800 acre-feet still requires a reduction of 0.3% of the serviced population.
- In scenarios of greater increase in sea level, it is more conservative and accurate to estimate losses via the Glover method, and in the most extreme scenarios (3.0 m SLR), it predicts losses an order of magnitude greater than the Ghyben-Herzberg method.
- Note that a sharp drop in interface predicted by the Glover method is illustrated in figure 6.1, when the interface boundary interacts with the Hueneme aquifer layer. The discrepancy in these two methods occurs primarily in a small region that can appear exaggerated by figures which are designed primarily to demonstrate the changing interface.

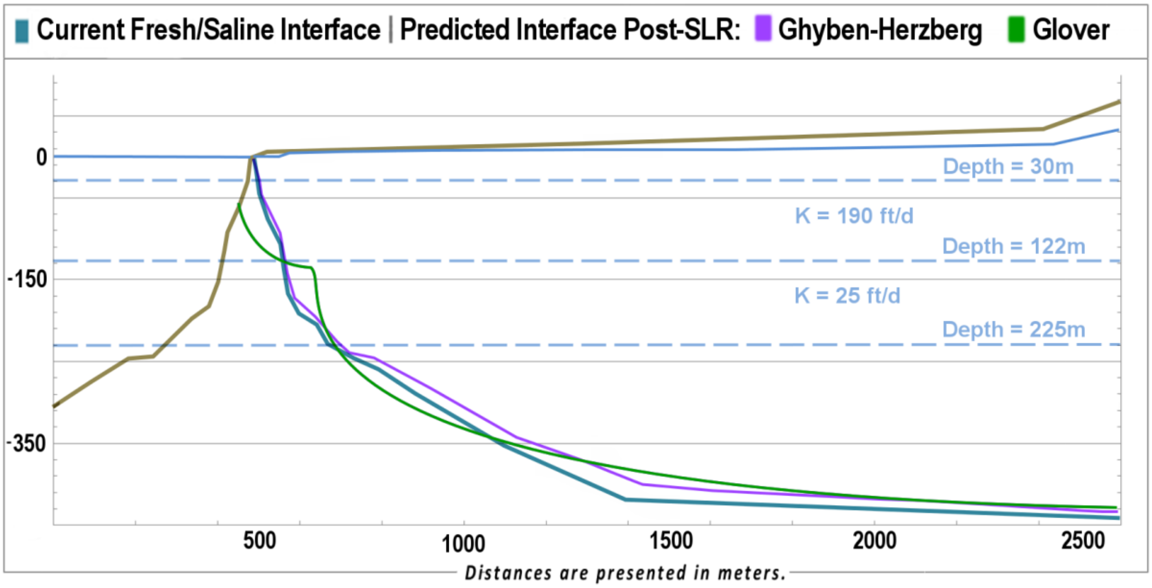

Figure 6.1 - Discrepancy Demonstration of U-Tube and Glover methods

- The landward intrusion of the saline interface for both methods is summarized Table 7 below.

Table 7 - Saline-Freshwater Interface Landward Intrusion Due to SLR, methods compared

Method	Region of Concern	Oxnard-Mugu, Depth 30m to 122m (100 to 400 ft)				Upper Hueneme, Depth 122m to 225m (400 to 738 ft)			
	Sea Level Rise, SLR (m)	0.59	1.00	2.00	3.00	0.59	1.00	2.00	3.00
Ghyben-Herzberg	Interface Intrusion, $\Delta\overline{L}_i$ (m)	11.1	18.9	37.8	56.6	17.7	30.0	60.1	90.1
	Interface Intrusion, ΔL_{30} (m)	8.3	14.0	28.0	42.1	--	--	--	--
	Interface Intrusion, ΔL_{122} (m)	7.5	12.7	25.5	38.2	7.5	12.7	25.5	38.2
	Interface Intrusion, ΔL_{225} (m)	--	--	--	--	33.8	57.2	114.5	171.7
Glover	Interface Intrusion, $\Delta\overline{L}_i$ (m)	3.4	8.8	37.2	95.7	14.0	24.5	86.9	191.4
	Interface Intrusion, ΔL_{30} (m)	0	0	0	0	--	--	--	--
	Interface Intrusion, ΔL_{122} (m)	5.6	16.1	64.4	144.9	5.6	16.1	64.4	144.9
	Interface Intrusion, ΔL_{225} (m)	--	--	--	--	22.9	32.1	118.6	245.3

- Since the population is unlikely to decrease and accommodate this capacity reduction, water management practices must be implemented to service additional people.
- The most easily implemented methods would include increased grey water utilization and treatment of waste streams to potable levels.

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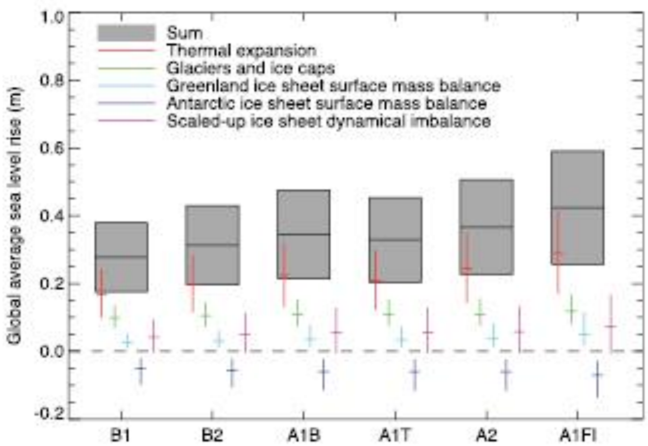
APPENDIX A

Raw component data for projection of sea level rise, via IPCC, as condensed in earlier figures.

		B1		**B2**		**A1B**		**A1T**		**A2**		**A1FI**	
Thermal expansion	m	0.10	0.24	0.12	0.28	0.13	0.32	0.12	0.30	0.14	0.35	0.17	0.41
	mm yr-1	1.1	2.6	1.6	4.0	1.7	4.2	1.3	3.2	2.6	6.3	2.8	6.8
G&IC	m	0.07	0.14	0.07	0.15	0.08	0.15	0.08	0.15	0.08	0.16	0.08	0.17
	mm yr-1	0.5	1.3	0.5	1.5	0.6	1.6	0.5	1.4	0.6	1.9	0.7	2.0
Greenland Ice Sheet SMB	m	0.01	0.05	0.01	0.06	0.01	0.08	0.01	0.07	0.01	0.08	0.02	0.12
	mm yr-1	0.2	1.0	0.2	1.5	0.3	1.9	0.2	1.5	0.3	2.8	0.4	3.9
Antarctic Ice Sheet SMB	m	-0.10	-0.02	-0.11	-0.02	-0.12	-0.02	-0.12	-0.02	-0.12	-0.03	-0.14	-0.03
	mm yr-1	-1.4	-0.3	-1.7	-0.3	-1.9	-0.4	-1.7	-0.3	-2.3	-0.4	-2.7	-0.5
Land ice sum	m	0.04	0.18	0.04	0.19	0.04	0.20	0.04	0.20	0.04	0.20	0.04	0.23
	mm yr-1	0.0	1.8	-0.1	2.2	-0.2	2.5	-0.1	2.1	-0.4	3.2	-0.8	4.0
Sea level rise	m	0.18	0.38	0.20	0.43	0.21	0.48	0.20	0.45	0.23	0.51	0.26	0.59
	mm yr-1	1.5	3.9	2.1	5.6	2.1	6.0	1.7	4.7	3.0	8.5	3.0	9.7
Scaled-up ice sheet discharge	m	0.00	0.09	0.00	0.11	-0.01	0.13	-0.01	0.13	-0.01	0.13	-0.01	0.17
	mm yr-1	0.0	1.7	0.0	2.3	0.0	2.6	0.0	2.3	-0.1	3.2	-0.1	3.9



From the IPCC Physical Science Basis: "Projections and uncertainties (5 to 95% ranges) of global average sea level rise and its components in 2090 to 2099 (relative to 1980 to 1999) for the six SRES marker scenarios. The projected sea level rise assumes that the part of the present-day ice sheet mass imbalance that is due to recent ice flow acceleration will persist unchanged. It does not include the contribution shown from scaled-up ice sheet discharge, which is an alternative possibility. It is also possible that the present imbalance might be transient, in which case the projected sea level rise is reduced by 0.02 m."

APPENDIX B

Basic equations and parameters for the Ghyben-Herzberg Method (U-Tube) analysis

$z = h_f \; \rho_f / (\rho_s - \rho_f)$				
$z = 40\, h_f$				
A_{aqu} =	120	mi^2	D_{aqu} =	1400 ft
ρ_f =	1.000	g/cm^3		
ρ_s =	1.025	g/cm^3		

$z_1 = 40\, h_{f1}$	$z_1 + h_{f1} = D_{aqu1} = 1400$ ft	
$z_2 = 40\, h_{f2}$	$z_2 = z_1 + \Delta D_{sea}$	
$h_{f2} - h_{f1} = \Delta D_{aqu}$		

h_{f1} =	35	z_1 =	1400

Displacement table for average depth of water table, saline/freshwater interface, and depth modification post-SLR, Oxnard-Mugu Aquifer

ΔD_{sea} (m)	z_2	H_{f-2}	Δz	ΔD_{aqu} (m)	ΔV (m^3)	ΔV (ac-ft)
0.1	426.82	10.6705	0.0025	-0.0975	-2.53E+05	-204.7
0.2	426.92	10.673	0.005	-0.195	-5.05E+05	-409.4
0.3	427.02	10.6755	0.0075	-0.2925	-7.58E+05	-614.2
0.59	427.31	10.68275	0.01475	-0.57525	-1.49E+06	-1207.9
1	427.72	10.693	0.025	-0.975	-2.53E+06	-2047.2
2	428.72	10.718	0.05	-1.95	-5.05E+06	-4094.5
3	429.72	10.743	0.075	-2.925	-7.58E+06	-6141.7

APPENDIX C

Basic equations and parameters for the Glover Method analysis, including the estimated values for transmissivity and hydraulic conductivity

$z^2 = 2\rho qx/\Delta\rho K + (\rho q/\Delta\rho K)^2$				
$h_f = (2\Delta\rho qx/(\rho+\Delta\rho)K)^{1/2}$				
$x_0 = -\rho q/2\Delta\rho K$				
$z_0 = \rho q/\Delta\rho K$		$q = K\,i\,z =$	8.063984	m^2/d
$K =$	13.2283	m/d		
$A_{aqu} =$	120	mi^2		
$\rho_f =$	1.000	g/cm^3		
$\rho_s =$	1.025	g/cm^3		
$D_{aqu} =$	60.96	m		
$\Delta\rho =$	0.025	g/cm^3		
$z_0 =$	24.384	m		

Table of calculated displacement of the landward front for saline/freshwater interface, Oxnard-Mugu Aquifer (All units' distances in meters)

	slope	0.023392					
	rise	0.1	0.59	1	3		
z	data	X0.1	X0.59	X1.0	X3.0	X	Inland progress
0	0	-7.917	13.0305	30.558	116.058	-12.192	0
15.61538	-15.61538	-2.917	18.0305	35.558	121.058	-7.192	5
22.08348	-22.08348	2.083	23.0305	40.558	126.058	-2.192	10
24.384	-24.384	4.275	25.2225	42.75	128.25	0	12.192
34.21158	-34.21158	16.083	37.0305	54.558	140.058	11.808	24
48.38248	-48.38248	40.083	61.0305	78.558	164.058	35.808	48
69.83409	-69.83409	92.083	113.0305	130.558	216.058	87.808	100
98.76032	-98.76032	192.083	213.0305	230.558	316.058	187.808	200
139.6682	-139.6682	392.083	413.0305	430.558	516.058	387.808	400
441.6696	-441.6696	3992.083	4013.031	4030.558	4116.058	3987.808	4000
624.6151	-624.6151	7992.083	8013.031	8030.558	8116.058	7987.808	8000
883.3391	-883.3391	15992.08	16013.03	16030.56	16116.06	15987.81	16000
1249.23	-1249.23	31992.08	32013.03	32030.56	32116.06	31987.81	32000
1766.678	-1766.678	63992.08	64013.03	64030.56	64116.06	63987.81	64000

Table of depth displacement for saline/freshwater interface, Oxnard-Mugu Aquifer (All units' distances in meters)

				z			
X	Inland progress	Coastal	d	X0.1	X0.59	X1.0	X3.0
-12.192	0	64000	742	0.1	0.59	1	3
-7.192	5	1008.888	12.192	-15.5154	-15.0254	-14.6154	-12.6154
-2.192	10	518.16	6.096	-21.9835	-21.4935	-21.0835	-19.0835
0	12.192	487.68	0	-24.284	-23.794	-23.384	-21.384
11.808	24	481.584	-3.048	-34.1116	-33.6216	-33.2116	-31.2116
35.808	48	472.44	-30.48	-48.2825	-47.7925	-47.3825	-45.3825
87.808	100	454.152	-60.96	-69.7341	-69.2441	-68.8341	-66.8341
187.808	200	423.672	-91.44	-98.6603	-98.1703	-97.7603	-95.7603
387.808	400	402.336	-152.4	-139.568	-139.078	-138.668	-136.668
3987.808	4000	377.952	-182.88	-441.57	-441.08	-440.67	-438.67
7987.808	8000	335.28	-198.12	-624.515	-624.025	-623.615	-621.615
15987.81	16000	304.8	-213.36	-883.239	-882.749	-882.339	-880.339
31987.81	32000	243.84	-243.84	-1249.13	-1248.64	-1248.23	-1246.23
63987.81	64000	182.88	-246.888	-1766.58	-1766.09	-1765.68	-1763.68

APPENDIX D

Paper 1

SEA LEVEL RISE AND THE IMPACT ON FRESHWATER RESOURCES

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May 2014

ABSTRACT

The threat posed to groundwater by climate change is discussed herein. The contributing factors are assessed in both sea level changes and water cycle changes. Global NPO groups such as the International Panel on Climate Change have examined the issue for years. That data is re-examined with an eye towards predicting future complications caused by human effects. In particular the possible methods for estimation of changes in ground water reserve are investigated.

Keywords: Climate Change, Groundwater, Indo-Gangetic Basin, Saltwater Intrusion, Sea level Rise, SLR

INTRODUCTION

Although approximately 70% of the Earth's surface is covered by water; freshwater makes up only 3% of the total water on the planet. Moreover, the majority of freshwater is stored as ice, in glaciers and polar ice sheets. Although humans rely heavily on freshwater from rivers and lakes, this surface water amounts to only 0.02% of all water on Earth. Most liquid freshwater is stored in aquifers as groundwater. Still, groundwater makes up only 1% of all water on the planet (Douglas, 1997). Groundwater storage can be viewed as a product of climate. This is because the groundwater available for use is deposited primarily by atmospheric precipitation. Changes in climate then inevitably affect groundwater, both its quantity and quality.

Despite a growing consensus among climate scientists, readily available publications on the specific effects of climate change are numerous, dissimilar, and contradictory. The effects of climate changes on groundwater have also only been discussed in a limited manner. Geological science has demonstrated continuous climate change throughout the history of Earth. Changes developed both slowly and relatively quickly in the geological time scale.

Past climatic changes have been caused by changes in solar activity, meteorite showers, variations in Earth axis position, volcanic activity, and a wide array of other natural activities, which caused changes in the Earth's albedo and the greenhouse effect of the atmosphere (Douglas, 1997). Figure 1.1 on the following page presents a schematic flowchart showing a relationship between climate change and loss of fresh groundwater in coastal aquifers, and the basic process of understanding that change. Of greatest concern herein is the step after abstract comprehension, analysis and modeling.

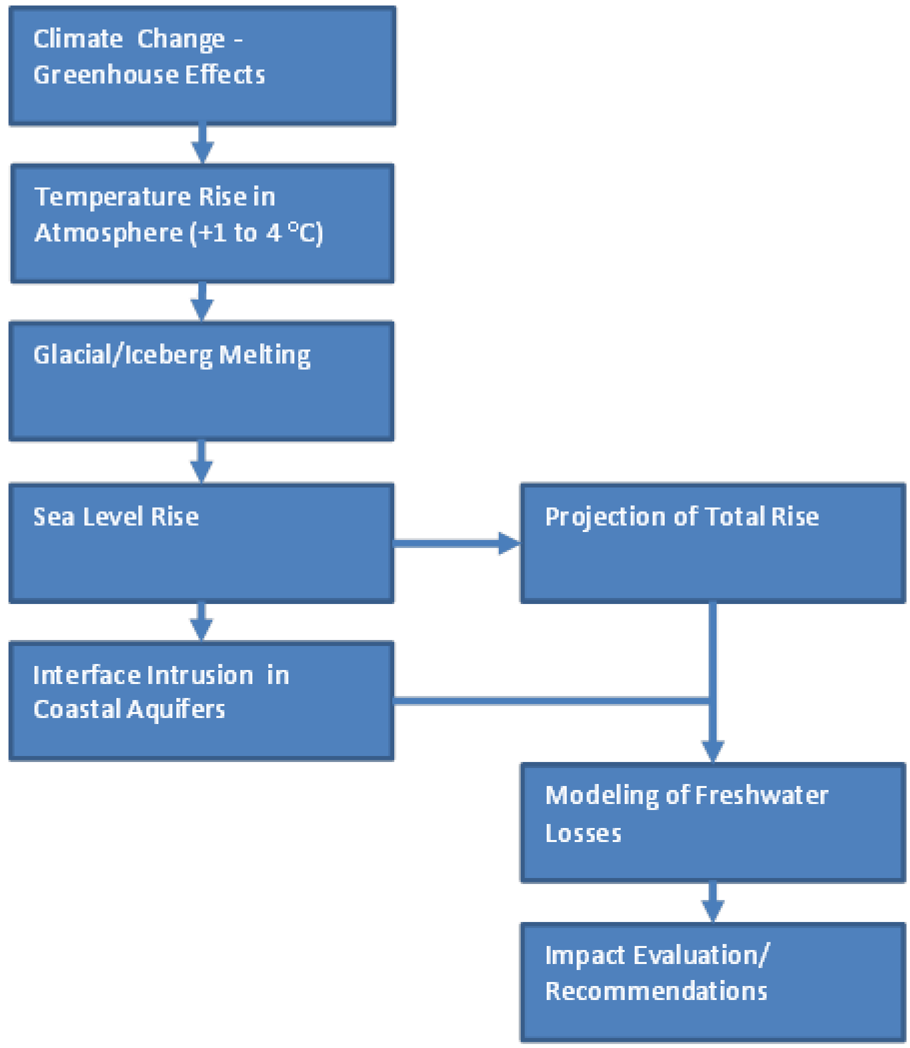

Figure 1 -- Relationship between climate change and fresh groundwater in coastal aquifers

CLIMATE CHANGE

Paleo-climates of the past allow the development of an analogue of the probable future climate. An example of how these relationships can be made can be seen by comparing temperatures today with the recorded temperatures found in ice cores such as the Vostok Ice Core temperature graph below. Global warming by 1° C can be the climate of the Holocene Optimum; by 2° C the climate of the Mikulian Interglacial Period; and warming by 3-4° C, the Pliocene Optimum (Kovalevskii, 2007). These time periods can be used to characterize the likely future climate.

These estimates of potential global warming are based on an extrapolated relationship between the air temperature and chemical content of the atmosphere (Tucker, 2008). Current predictions are commonly referred to as wide time intervals in the future. The global warming by 1° C is most often believed to occur in the first quarter of the 21st Century; 2° C in the mid-21st Century; and 3° C at the beginning of the next century (Kovalevskii, 2007). This determines possible hydrogeological forecasts.

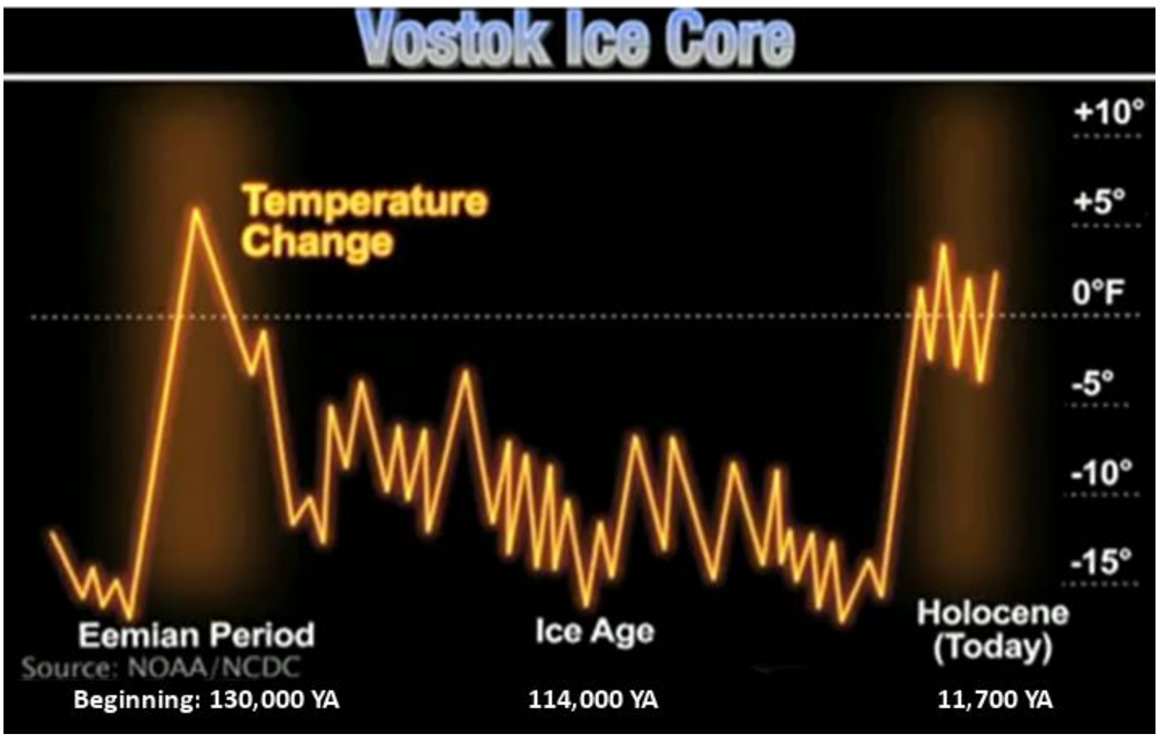

Figure 2 -- Average temperature over different epochs

Based on the forecasts by Kovalevskii et al in "Effect of Climate Changes on Goundwater," there will be a regular and gradual growth of the air temperature increments from the south to the north. Some temperature changes have already been observed and can be seen in the two figures showing NOAA average sea surface temperatures in 1985 and 2006 below. These two figures can be compared with the

Annual Mean Temperature figure following them. Predicted precipitation increases in the middle latitudes are many times smaller than those in the low and high latitudes. Model forecasts show even a likely decrease in precipitation in the middle latitudes (Joigneaux, 2011). Precipitation decrease is shown to spread from the western boundaries of Russia to the Urals, the primary area of concern for Kovalevskii's research, including the central and southern regions of Russia.

Around the world, the anticipated changes in climatic conditions will entail changes in the entire complex of hydrogeological conditions; in the water, heat, and salt balances of groundwater, as well as in the environment interconnected with groundwater. Taking into account the highest importance of hydrodynamic forecasts, it is practical to consider, first of all, the potential changes in groundwater resources (Kovalevskii, 2007).

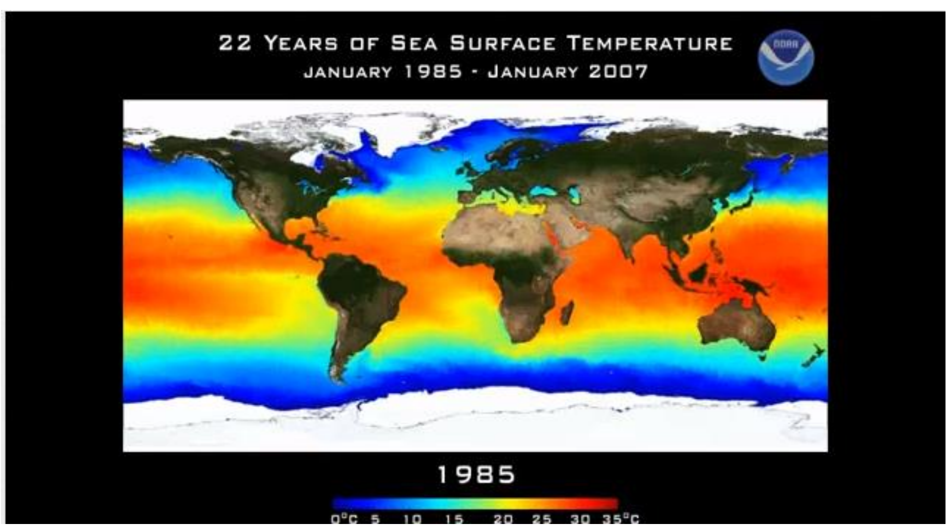

Figure 3.1 -- NOAA average sea surface temperature in 1985

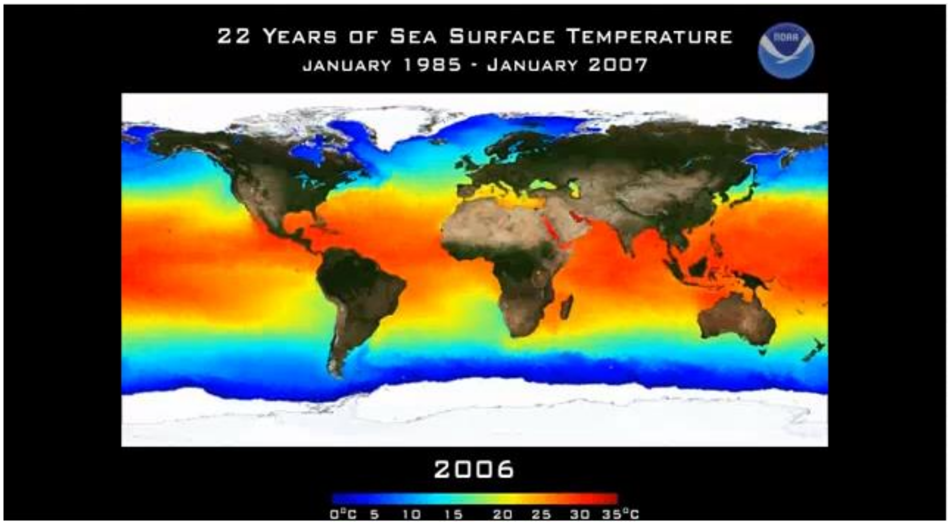

Figure 3.2 -- NOAA average sea surface temperature in 2006

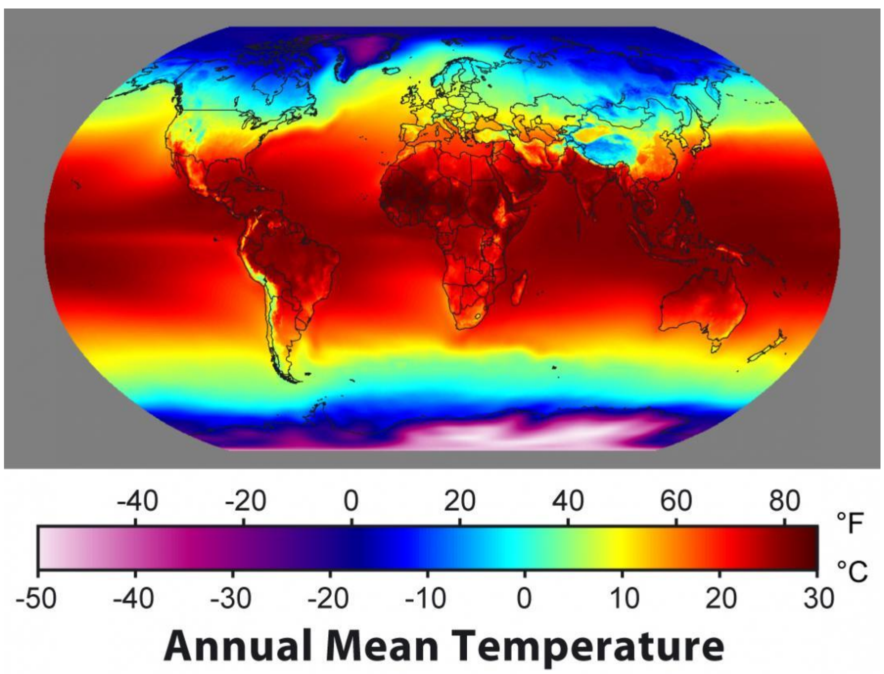

Figure 3.3 -- Annual mean temperature

To illustrate these potential changes, first narrow the lens to one particularly heavily populated water basin region. Significant climate change is expected to alter India's hydro-climate regime over the course of the 21st Century. Wide agreement has been reached that the Indo-Gangetic basin is likely to experience increased water availability from increasing snow-melt up until around 2030 but face gradual reductions thereafter. Most parts of the Indo-Gangetic basin will probably also receive less rain than in the past; however all the rest of India is likely to benefit from greater precipitation.

According to the Intergovernmental Panel on Climate Change, most Indian landmass south of the Ganges Plain is likely to experience a 0.5-1° C rise in average temperature by 2029 and 3.5-4.5° C rise by 2099. Many parts of peninsular India, especially the Western Ghats, are likely to experience a 5-10% increase in total precipitation; however, this increase is likely to be accompanied by a greater variance in temperature (Shah, 2009). Throughout the sub-continent, it is expected that very wet days are likely to contribute more and more total precipitation, suggesting that most of India's precipitation may be received in fewer than 100 hours of thunderstorms.

This will generate more flooding events, and may reduce total infiltration as a matter of more concentrated run-off. The higher precipitation intensity and larger number of dry days in a year will also increase evapotranspiration. Increased frequency of extremely wet rainy seasons is also likely to mean increased run-off. In Shah's "Climate Change and Groundwater," a comparison of the 1900-1970 period and 2041-2060, most of India is likely to experience 5-20% increase in annual run-off. India can expect to receive more of its water via rain than via snow. Snow-melt will occur faster and earlier. Less soil moisture in summer and higher crop evapotranspirative demand can also be expected as a consequence. As climate change results in spatial and temporal changes in precipitation, it will significantly influence natural recharge.

Moreover, as much of natural aquifer recharge occurs in areas with vegetative cover, such as forests, changing evapotranspiration rates resulting from rising temperatures may reduce infiltration rates form natural precipitation and therefore reduce recharge. Recharge clearly has a strong response to the temporal pattern on precipitation as well as soil cover and soil properties. In the African context, Shah cites arguments that replacing natural vegetation by crops can increase natural recharge by nearly a factor of 10. If climate change results in changes in natural vegetation in forests or savanna, these too may influence natural recharge; however, the direction of the net effect will depend upon the pattern of changes in the vegetative cover (McCallum, 2010).

Simulations developed by Australian scientists have shown that changes in temperatures and rainfall may influence the growth rates and the leaf size of plants that have an effect on groundwater recharge. The direction of change is contextually sensitive. In some places, the vegetation response to climate change might cause the average recharge to decrease, but in other areas, groundwater recharge is likely to more than double (McCallum, 2010). We have an inadequate understanding of how exactly rainfall patterns will change, but increased variability seems almost guaranteed. This will lead to intense and large rainfall events in brief monsoons followed by longer dry spells. While evidence suggests that groundwater recharge through natural infiltration occurs only beyond a certain threshold level of precipitation, it also demonstrates that the run-off coefficient increases with increased rainfall intensity.

Increased variability in precipitation will negatively impact natural recharge in general. The Indo-Gangetic aquifer system has been getting a significant portion of its natural recharge from Himalayan snow-melt (Shah, 2009). As snow –melt-based run-off continues to increase during the coming decades, their contribution to potential recharge will likely increase; however, a great deal of this may end up as a form of “rejected recharge,” enhancing river flows and intensifying the flood proneness of eastern India and Bangladesh. As the snow-melt-based run-off begins declining, one should expect a decline in run-off as well as groundwater recharge in that vast basin.

MELTING GLACIERS

Glaciers are an important part of the current global ecosystem. They are found in the lower, mid, and upper latitudes. These glaciers generally have a melt and replenish cycle that coincides with the local seasons. However most of the regularly observed glaciers have been receding over the past years. In Greenland portions of the country have gone from completely covered by glaciers to rocky and without a continuous ice sheet, as seen in the figures following this page.

Figure 4 -- Greenland melting

In Alaska, coastal glaciers have been melting and shedding icebergs at an increasing rate. The figures below show a glacier going through a melt/erosion cycle with a dramatic collapse into the ocean. The following figures help to demonstrate an observed incident of glacier shelf face collapse.

Figure 5 -- Pine Island Glacier calving collapse (Antarcticglaciers.org, 2008)

The Gangotri Glacier in India is the main source for the Ganges river system. This glacier has been responsible for providing freshwater to a main river across southeastern Asia and is receding at continually increasing rates. The figure on the following page demonstrates, in a series of contours, this process of recession. The reduction of this glacier will greatly impact the flow of the Ganges and the ecosystem it supplies.

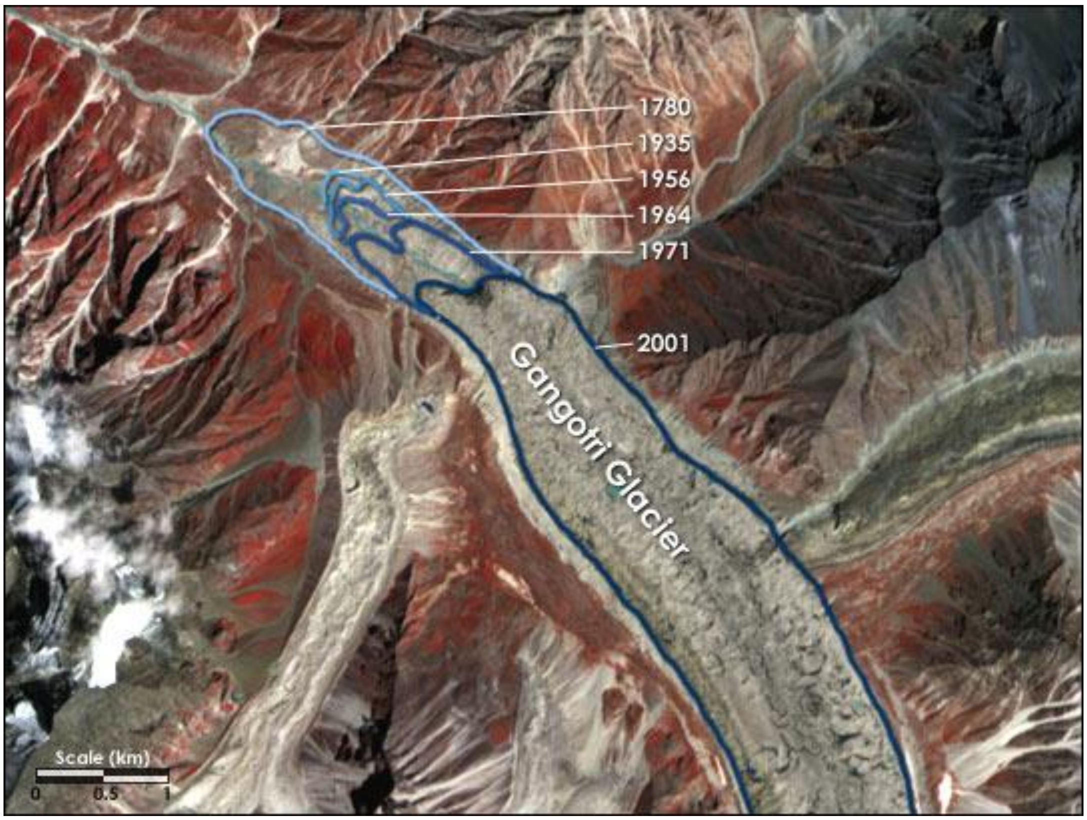

Figure 6 -- Gangotri glacier recession due to ice melt (Antarcticglaciers.org, 2008)

SEAWATER RISE AND INTRUSION

Climate change and groundwater will show some of their most drastic interrelation in coastal areas. Data from coastal tidal gauges in the north Indian Ocean are readily available for more than the last 40 years; in Tushaar Shah's "Climate Change and Groundwater: India's Opportunities for Mitigation and Adaptation," estimates are presented for a sea level rise between 1.06 and 1.75 mm per year. This is consistent with a 1-2 mm per year global sea level rise which has been estimated by the IPCC. Rising sea levels will of course present a threat to coastal aquifers. Many of India's coastal aquifers are already increasing in saline intrusion. The problem is especially acute in the Saurashtra Coast in Gujarat and the Minjur Aquifer in Tamil Nadu. In coastal West Bengal, mangrove forests are threatened by saline intrusion overland (Shah, 2009). This will affect the aquifers supplying these ecosystems.

The sea-level rise that accompanies climate change will reduce the freshwater supply in many coastal communities, by infiltrating groundwater and rendering it brackish and undrinkable without excessive treatment (McCallum, 2010). "Most people are probably aware of the damage that rising sea levels can do above ground, but not underground, which is where the fresh water is," says Motomu Ibaraki, associate professor of earth sciences at Ohio State University.

According to Ibaraki, coastlines are made of many different layers and kinds of sand. Coarse sands let water through to aquifers and can lead to contaminated, brackish water. Ibaraki plans to create a world salinity hazard map showing areas which have the potential for the most groundwater loss due to sea-level rise. An example of the extensive and sever problems of water sufficiency and quality, Florida has the largest concentration of desalination plants in the United States. Ninety-three percent of Florida's 16 million residents rely on groundwater as their drinking water supply, via desalination of deep brackish aquifers (Meyland, 2008).

The saline/freshwater interface location and behavior can be approximated by several model types. The first is a U-Tube manometer. In the manometer the hydrostatic balance between fresh and saline water can be seen. The freshwater is less dense than the saline water and will therefore float on one side of the manometer. This shows that in an aquifer there will be an interface with freshwater on top and denser saline water intruding to the bottom of the aquifer (Todd & Mays, 2004).

While somewhat simplistic, this model generates effective and useful approximations with little investigative data. Within most industrialized and preindustrial nations, the information required to apply this model is readily and freely available, having been collected by governments over decades of infrastructure development in coastal areas. Within the United States, this data has been made available through the U.S. Geological Survey (USGS), and has proven reliable and accurate over decades of study (U.S. Geological Survey, 2012).

Based on previously publicized data for the Oxnard-Mugu aquifer system in California, a preliminary application of this model can provide useful estimations of ocean rise based impacts. From the application of this simple method reasonable estimates have been provided for both the loss of freshwater storage capacity, and the intrusion of salt water further inland of the aquifer system. These data are available in Tables 1 and 2 respectively, on the following page.

Table 1 - Sea Level Rise versus Volumetric Aquifer Capacity Loss

ΔD_{sea} Meters of sea level rise	ΔV Thousands of cubic meters lost	ΔV Acre-feet lost
0.59	1010	820
1	2910	2356
2	11508	9436
3	26200	21241

Table 2 - Sea Level Rise versus Intrusion of Saline Inland

Region of Concern	Oxnard-Mugu, Depth 30m to 122m (100 to 400 ft)				Upper Hueneme, Depth 122m to 225m (400 to 738 ft)			
Sea Level Rise, SLR (m)	0.59	1.00	2.00	3.00	0.59	1.00	2.00	3.00
Interface Intrusion, $\Delta \overline{L_\iota}$ (m)	11.1	18.9	37.8	56.6	17.7	30.0	60.1	90.1
Interface Intrusion, ΔL_{30} (m)	8.3	14.0	28.0	42.1	--	--	--	--
Interface Intrusion, ΔL_{122} (m)	7.5	12.7	25.5	38.2	7.5	12.7	25.5	38.2
Interface Intrusion, ΔL_{225} (m)	--	--	--	--	33.8	57.2	114.5	171.7

The values for sea level rise used for these calculations are based on scenarios developed by the International Panel on Climate Change in their 2007, Fourth Assessment Report. In particular, the 0.59 meter case is the median case of 95% confidence interval, by the year 2040 (IPCC, 2007). This is an important milestone thanks to California's intention of enacting plans to deal with climate change based threats to potable water availability by that date. The other cases represent cases up to the 10% confidence interval prediction for sea level rise by 2100. Following these tables, Figure 7 illustrates a graphic interpretation of the infiltration data.

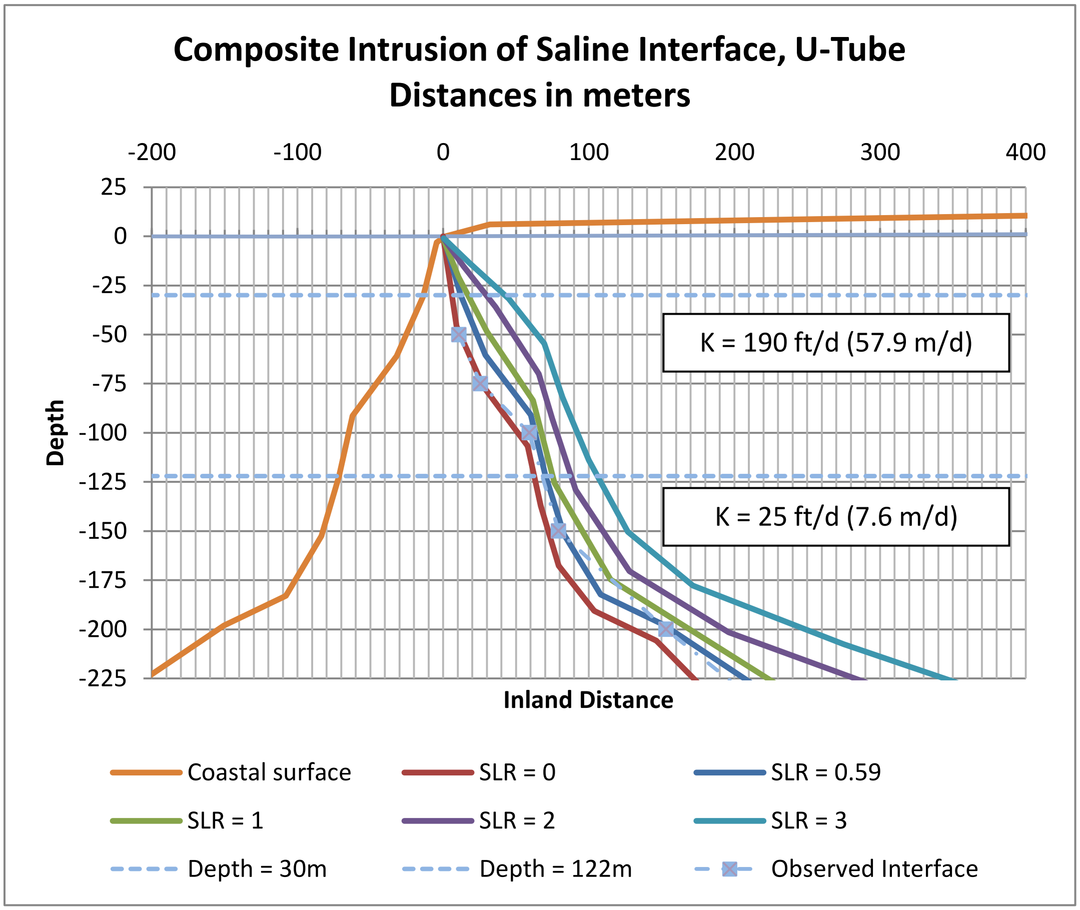

Figure 7 - Composite Intrusion of Saline Interface, U-Tube, Distances in meters

We can see reasonable agreement between the estimated interface location at the current level (2010) with sea level rise equal to 0, and the observed interface location data provided by the USGS (U.S. Geological Survey, 1996). Note that these locations are established by the saline concentration reaching a level of 100 mg/l. Figure 8 following this tightens then focus of in each region even more, in order to make the actual distances legible within a comfortable margin of visual error.

Now continuing from these estimates, some conclusions can be drawn about other levels of sea rise, including simplified equations to predict volumetric capacity losses from the

aquifer storage and intrusion distance predictors. The figures collating this data and fitting equations to these situations follow Figure 8 in Figures 9 and 10.

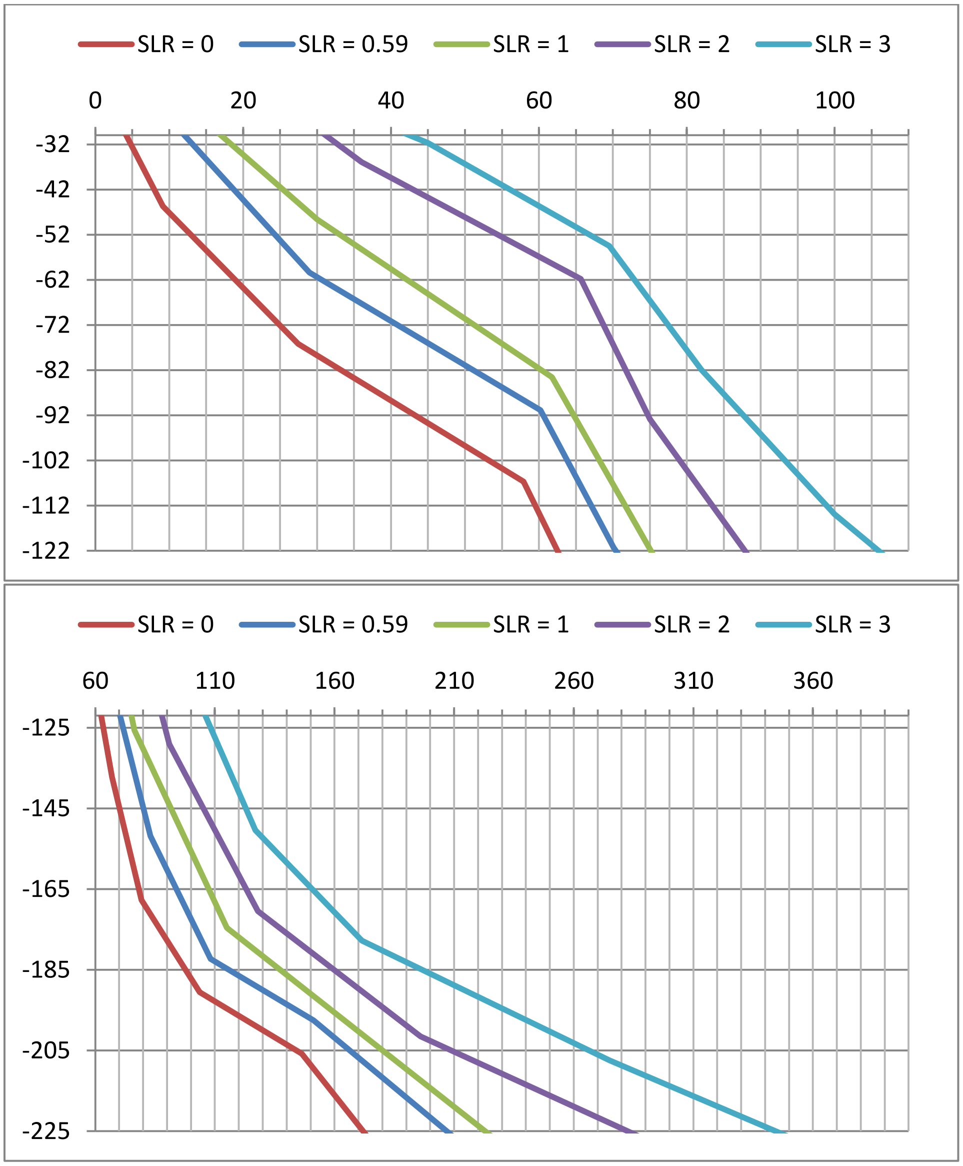

Figure 8 -- Saline/freshwater interface changes, post SLR, Ghyben-Herzberg, Aquifer depth versus distance inland in meters

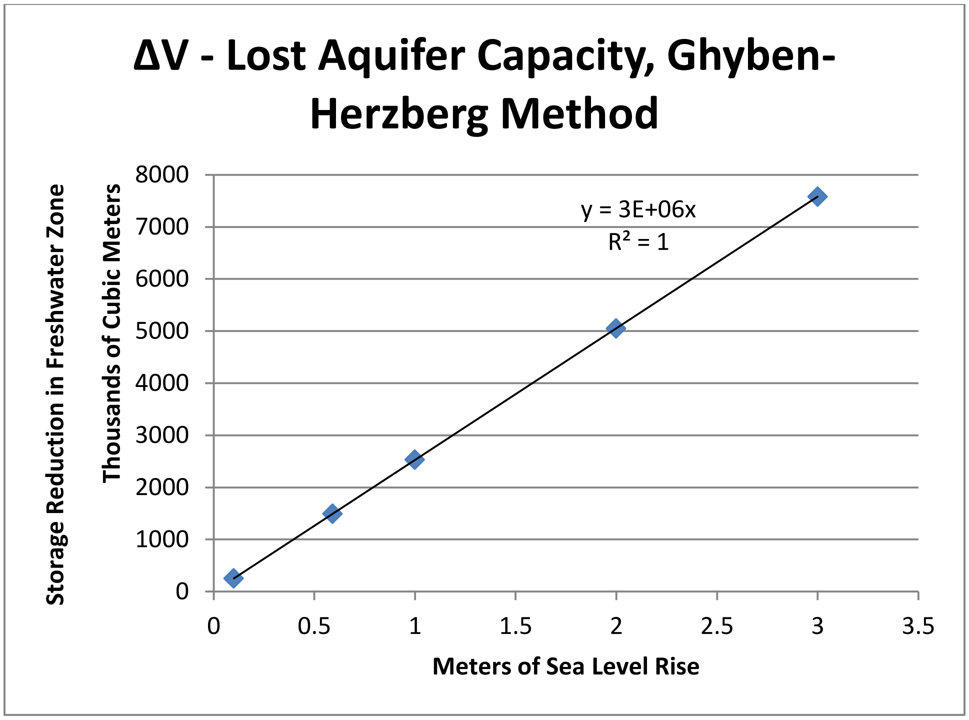

Figure 9 - ΔV - Lost Aquifer Capacity, Ghyben-Herzberg Method

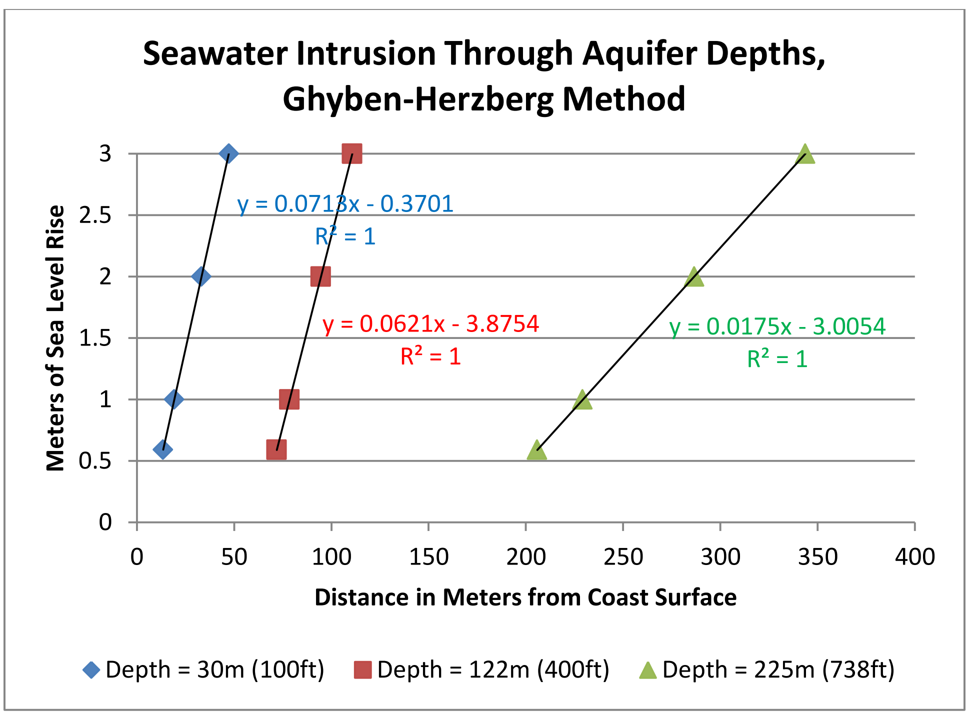

Figure 10 - Seawater Intrusion through Aquifer Depths, Ghyben-Herzberg Method

The Glover model is another approach designed to address the issue of irregular interface shapes within a coastal aquifer system. This is a conceptual model that relies on some basic simplifying assumptions about the aquifer involved, but still gives good approximations of saline and freshwater interface (Todd & Mays, 2004). The greatest difficulty in application of the model derives from inaccuracies created by complex, multi-layered aquifer systems.

With variable hydraulic conductivities, predicting the interface shape as it crosses boundary layers becomes an exercise in non-continuous functions. In many aquifers, the layers can be simplified into a composite layer, as this maintains an accurate prediction of both volumetric changes and changes in the water table surface, but can result in accumulating errors in the prediction of interface locations as the aquifer layers become more varied and insular.

EFFECTS ON GROUNDWATER

Scientists have suggested that climate change may alter the physical characteristics of aquifers. Higher CO_2 concentrations in the atmosphere are influencing carbonate dissolution and promote the formation of karstified soils which in turn may have a negative effect on the infiltration properties of top soils. This effect may derive from pH reduction in top soil exposed to post climate change precipitation (McCallum, 2010).

Others have argued the opposite; that increasing carbon dioxide levels will increase infiltration rates. From experimental data, some scientists have claimed that elevated atmospheric CO_2 levels may affect plants and the vadose zone in ways that may hasten infiltration from precipitation by up to 119% in a Mediterranean climate to up to 500% in a sub-tropical climate (Shah, 2009).

Diffusive groundwater recharge is the most important process in the restoration of groundwater resources. Changes to any of the variables that have an effect on diffuse recharge may have an impact on the amounts of water entering aquifers (Shah, 2009). Some efforts have been made to model changes predicted in diffuse aquifer recharge. To determine the impacts of climate change on the Edwards Aquifer in central Texas, USA a doubled atmospheric concentration of carbon dioxide was modeled for precipitation adjustments (McCallum, 2010). Changes to rainfall and streamflow were scaled based on this model, and by using a water-balance technique, the impact on recharge was determined. McCallum's review in "Impacts of Climate Change on Groundwater in Australia" observed that changes to rainfall and streamflow under such scenarios would yield reduced groundwater levels in the aquifer even if groundwater extraction was not increased. The reduction in groundwater levels might allow for additional seawater intrusion, impacting groundwater quality. This is inferred from the simple relationships between recharge and climate change.

Saltwater intrusion is not the only issue changing climates can create in groundwater systems. Certain hydrological conditions allow for spring flow in karst systems to be reversed. The resulting back flooding represents a significant threat to groundwater quality. The surface water could be contaminated and carry unsafe compounds back into the aquifer system (Joigneaux, 2011). Joigneaux and his team examined the possible impacts of future climate change on the frequency and occurrences of back flooding in a specific karst system in their article "Impact of Climate Change on Groundwater Point

Discharge." They first established the occurrence of such events in the study area over the past 40 years.

Preliminary investigations showed that back flooding in this Loiret, France karst has become more frequent since the 1980s. Adopting a downscaled algorithm relating large-scale atmospheric circulation to local precipitation special patterns, they viewed large-scale atmospheric circulation as a set of quasi-stationary and recurrent states, called weather types, and its variability as the transition between them (Joigneaux, 2011). Based on a set of climate model projections, simulated changes in weather type occurrence for the end of the century suggests that back flooding events can be expected to increase until 2075, at which point the event frequency will decrease.

As Joigneaux explains, alluvial systems and karst hydrogeological systems are very sensitive to small changes in hydrological components. Stream back flooding and the subsequent appearance of sink holes can occur because of relative changes between surface and underground drainage, which are controlled by both precipitation and discharge (Joigneaux, 2011). Consequently this type of system is sensitive to small climate variations, even at temperate mid-latitudes.

Dry weather streamflow is closely related to the rise and fall of groundwater tables. Since the 1980s, streamflow has deleted rapidly, owing to limited precipitation during the dry period and immoderate groundwater pumping for agricultural, domestic, and industrial uses. Ecologic and environmental disasters such as decreased number of species and population sizes, water quality deterioration, and interference with navigable waterways, have resulted from these changes. Kil Seong Lee and Eun-Sung Chung, in "Hydrological

Effects of Climate Change, Groundwater Withdrawal, and Land Use in a Small Korean Watershed," analyze the influences on total runoff during the dry periods and simulate its variability (2007).

Understanding these factors is very important for the watershed-level planning and management of water resources, especially in tropical climate areas. Chung particularly investigated how changing dry-weather climate would affect the use and withdrawal of water from stream and groundwater systems. By using surface waters as a set of boundary conditions, models like Chung's help demonstrate the effects of climate change on groundwater resources.

LOSS OF FRESHWATER

The use of freshwater supplies will have a growing impact in a variety of issues. Desalination might be used to ensure supplies of drinkable water, but it's an energy-intensive process. "Our energy use now could reduce the availability of freshwater and groundwater through the climate change process," Ibaraki says in summation of research he is undertaking at Ohio State University. "These resources are decreasing due to human activities and population increase." Another approach to protecting water supplies is to transfer water from regions that have it in abundance to regions that face water shortage. Unfortunately, both approaches require much energy (Tucker, 2008).

In the U.S., much of the agricultural land depends on irrigating crops using water from aquifers. This is true around much of the world, more or less, as the following figure depicts. However, these aquifers are being "mined" for agriculture at rates that exceed the recharge rate, thus depleting them. The Ogallala Aquifer stretches across the U.S Great Plains region, running from South Dakota, down to New Mexico and Texas; it is being pumped faster than the natural replacement rate, leading to a significant drop in the water table, possibly by hundreds of feet. When fossil aquifers like the Ogallala and the North China Plain are depleted, pumping will become impossible (Meyland, 2008). This will make the existing agricultural system unfeasible.

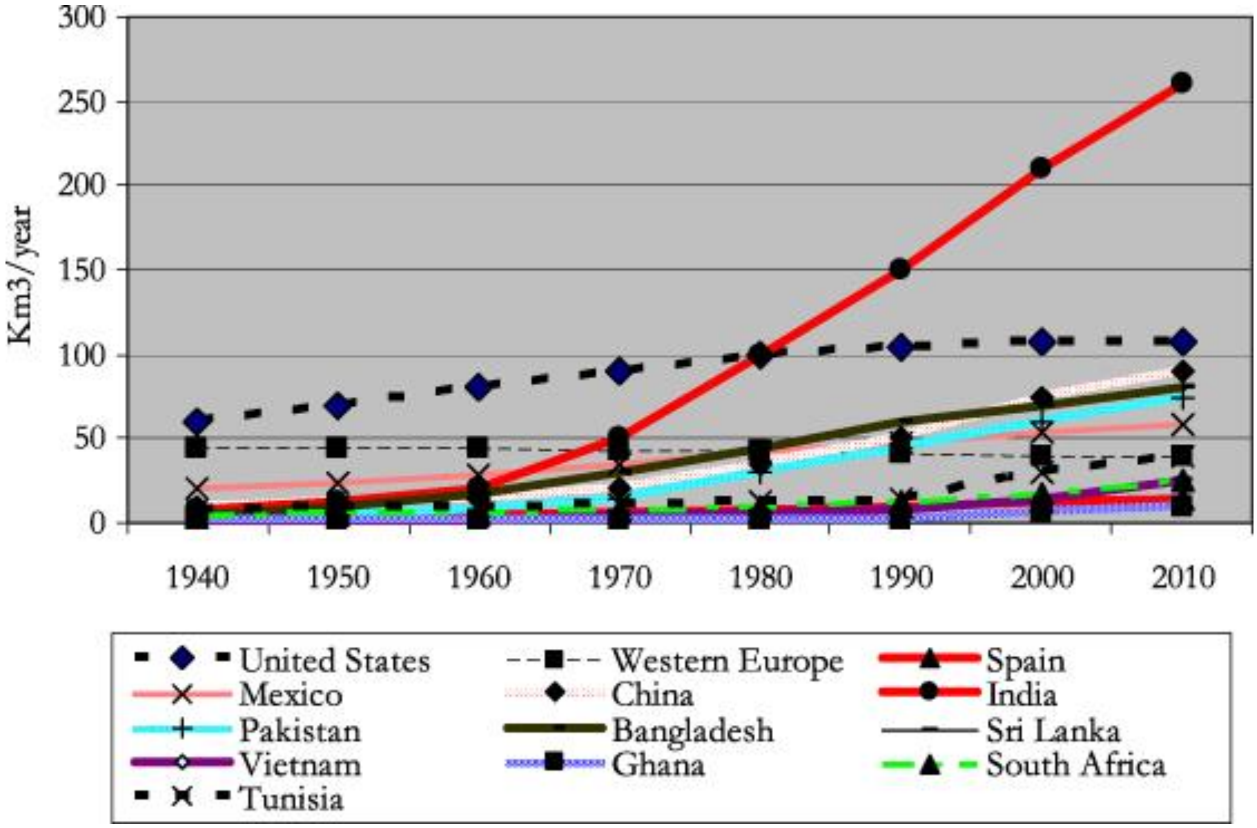

Figure 8 -- Increasing use of groundwater in agriculture (IPCC, 2007)

Groundwater is harder to manage and protect than surface water since it is difficult to monitor and model. Large efforts are needed to put groundwater systems under the management and protection of agencies dedicated to the job. Managing authorities could equitably administrate intrastate, interstate and international aquifer basins using scientific research and management plans, implemented by educated professionals. The management agencies can conduct studies, prepare management strategies, quantify the resources, determine equitable distributions of the water, and establish safety margins for allocations, anticipating climate swings such as severe drought. Groundwater will only become more important as a resource in the future. Effective management and protection of groundwater sources will become critical as the U.S. and the rest of the world work toward sustainable use of the Earth's water resources.

SUMMARY

A scientific consensus has been reached which states climate change is taking place around the globe. The expected temperature rise may range between 1° C to 4° C (IPCC, 2007). This is going to result in melting of icebergs, no matter how slow or fast. Such an action will raise the seawater level as much as 1 meter (or 3 feet). This rise will drive seawater interfaces globally inland, leading to loss of freshwater in coastal areas. In terms of the Ghyben-Herzberg approach, this can be examined as a shift upward in both the top of the water table and the saline-freshwater interface zone. This shift also reduces the total depth of freshwater in the aquifer in achieving a new equilibrium state.

CONCLUSIONS

In brief, climate change presents a complex group of factors which affect ground water. In relation to human usage, this can be reduced for easy presentation to a few salient topics and avenues of investigation.

1. Climate change will negatively impact recharge rates of freshwater aquifers in all climactic regions.
2. Sea level rise will drive the salt water interface of coastal aquifers inland, reducing their ability to store freshwater.
3. Monitoring and modeling difficulties will negatively impact authorities capabilities in regulating and managing groundwater resources.
4. As an intermediate measure, simple model approximations such as the Ghyben-Herzberg and Glover models can provide easy to understand numerical data for the direction of such policies.

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APPENDIX E

Paper 2

SALINE INTRUSION ANALYSIS IN THE OXNARD-MUGU AQUIFER

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ABSTRACT

In this work the Glover and Ghyben-Herzberg methods are used to predict the most likely loss of freshwater resources in the Oxnard-Mugu Aquifer in California, U.S. The comparative benefits and drawbacks of the methods are observed. Based on the determinations of the International Panel on Climate Change, the likely impact on the communities served by the aquifer are also noted.

Keywords: Aquifer, Climate Change, Glover, Ghyben-Herzberg, Groundwater, Modeling, Oxnard, California, Mugu, Saltwater Intrusion, Sea level Rise, SLR, U-Tube

INTRODUCTION

At the turn of the last century two investigators, working independently along the European coast, found that saltwater occurred underground, not at sea level but at a depth below sea level of about 40 times the height of the freshwater above sea level. This distribution was attributed to a hydrostatic equilibrium existing between the two fluids of different densities. The equation derived to explain the phenomenon is generally referred to as the Ghyben-Herzberg relation after its originators.

GENERAL FORM OF THE U-TUBE MODEL

The hydrostatic balance between fresh and saline water can be illustrated by the "U-Tube" manometer as shown in the figure on the following page. Pressures on each side of the tube must be equal; therefore an equation hydrostatic balance is established. For typical seawater conditions, that equation may be simplified such that:

$$z = 40\ h_f$$

By translating the U-tube to a coastal situation, h_f becomes the elevation of the water table above sea level and *z* is the depth to the fresh-saline interface below sea level. This is a hydrodynamic rather hydrostatic balance because fresh waters flowing toward the sea. From density considerations alone, without flow, a horizontal interface would develop with fresh water everywhere floating above saline water. It can be shown that when the flow is nearly horizontal the relation gifts satisfactory results. Only near the shoreline where vertical flow components become pronounced due significant errors in the position of the interface occur.

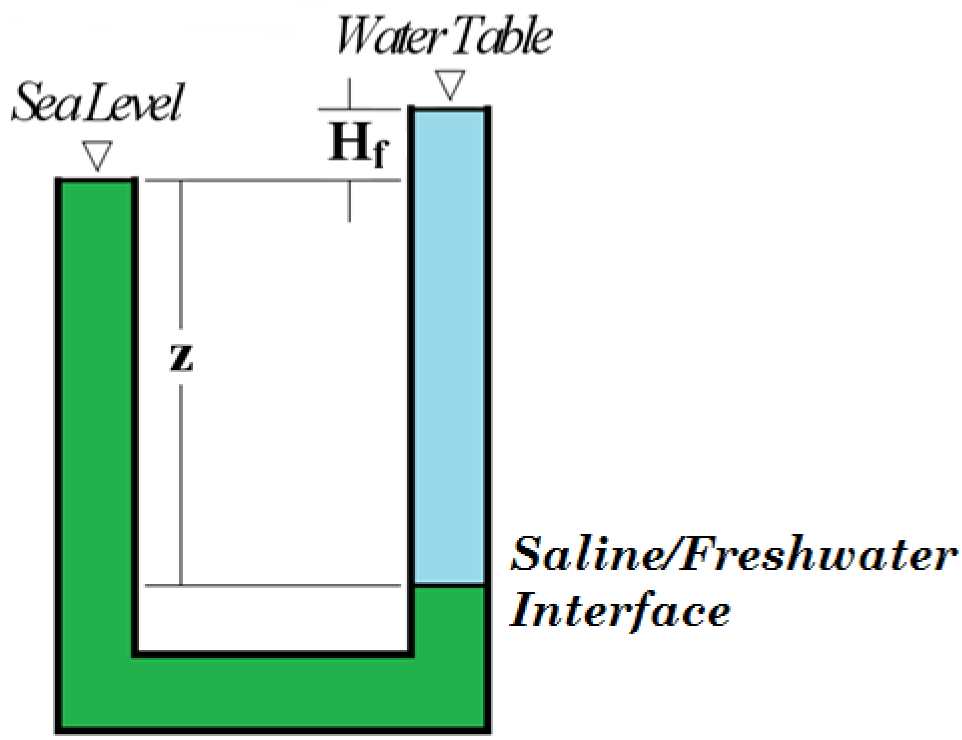

Figure 1 -- Manomenter approximation of the saline/freshwater interface

BENEFITS OF THE APPROACH

The Ghyben-Herzberg relation simplifies the balance in freshwater-seawater equilibrium down to only its most direct components. The effects of relative density are critical to this calculation, and the value presented here is unlikely to be notably affected even by significant sea level rise, due to the nature of the volumetric contribution. The greatest advantage of this method is of course its simplicity and ease of use. It can provide a reasonably confident rough estimate of the effects of changing mean sea level. The equation is conservative and provides cautionary results, as it does not account for some factors of hydrogeology which may mitigate sea level rise.

DRAWBACKS OF THE APPROACH

Although the results provided by this method are not extreme, they are transparently imprecise. The known factor of this conservative result can also be detrimental in policy modification. It discourages consideration of upper boundaries or excess change, beyond the most confident predictions.

What is perhaps the most obvious drawback of the method is its inability to account for the hydrodynamic properties of the geostructure in a groundwater basin of interest. The model considers a situation under which equilibrium between the fresh and saltwater reservoirs has been reached. This can be considered a minimal issue, since the sea level rise will occur over a long period, and allow adequate transmission through the interface. Further, the shape of the transition zone in the aquifer is not taken into account. The conservative nature of the estimates derives primarily from this fact. As the transition zone occupies a greater fraction of the aquifer depth when nearing the ocean boundary, the changing sea level reduces in impact.

FORM OF THE GLOVER MODEL

By recognizing the approximations inherent in the previous relationship, more exact solutions for the shape of the interface have been developed from potential flow theory. The results from the commonly used Glover equation have the form:

$$z^2 = \frac{2\rho q x}{\Delta\rho K} + \left(\frac{\rho q}{\Delta\rho K}\right)^2$$

In this equation, z represents the depth from the sea level at the coast to the saline interface in the aquifer. The components ρ and K are the water density of the saline region and transmissivity of the geostructure, respectively. The variable q is a calculated composite representing the rate of freshwater flow from the top of the aquifer toward the sea.

The sharp interface boundary described by the above equation between fresh and saline water does not normally occur under field conditions. Instead, the brackish transition zone of finite thickness separates the two fluids. This zone develops from dispersion by flow of the freshwater plus unsteady displacements of the interface by external influences such as tides, recharge, and pumping wells. In general, the greatest thickness of transition zones are found in highly permeable coastal aquifers subject to heavy pumping. Observed thicknesses vary from less than 1 m to more than 100 m.Additional parameters in this model are taken from the equations:

$$h_f = \left(\frac{2\Delta\rho q x}{(\rho + \Delta\rho)K}\right)^2$$

And:

$$x_0 = -\frac{\rho q}{2\Delta\rho K}$$

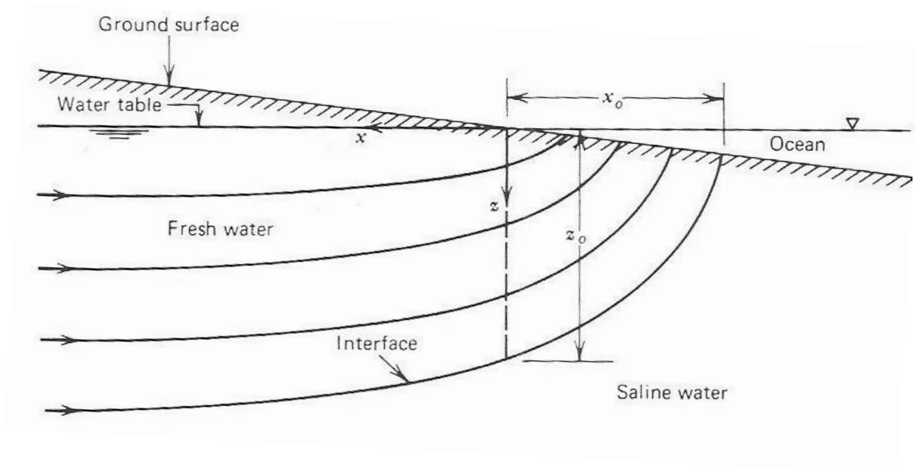

Figure 2 -- Abstract Glover interface (Todd & Mays, 2004)

While the figure 2 above demonstrates the abstracted relationship of these dimensions, it should be noted that real world aquifers will rarely demonstrate such a smooth thransition zone, and often have properties which restrict dispersion in either the vertical or horizontal direction.

An important consequence of the transition zone ended seaward flow is the transport of saline water to the pumping locations. This water originates from underlying saline water; hence, some continuity considerations, there must exist a small landward flow in the saline water region. Field measurements and experimental studies have confirmed the landward movement of the saline water bath. Where tidal action is the predominant mixing mechanism, fluctuations of groundwater, and hence the thickness of the transition zone, become greatest near the shoreline.

BENEFITS OF THE APPROACH

The Glover method for analysis is based on discovery of the freshwater-saltwater interface shape. Therefore, the method can be used to find the depth between the water table and the saline interface, and the changes in this depth in relation to sea level rise.

This value is also more accurate than the same value found through the Ghyben-Herzberg relationship. This method can also approximate the location at which the transition zone becomes of minimal impact on the total available depth of water.

DRAWBACKS OF THE APPROACH

There are not any significant drawbacks to this approach. It is less accurate than numerical modeling, though more accurate than the U-tube method. It requires more investigation of local conditions than the U-tube method, but significantly less than any numerical approach. Essentially, the greatest drawback is that this method is only slightly more effective than the U-tube method.

REQUIRED DATA

Like the U-tube analysis method, the Glover approach requires a known value for the densities of the waters in the problem situation. Similarly, it also requires a known value for the depth of fresh water in the aquifer. The table below includes both the idealized average depth of 1400 feet, and the approximate area of the aquifer, 120 square miles. Additionally, the method requires the Hydraulic conductivity, K, of the aquifer geostructure. The method also requires the unit flow of the aquifer interface. Most generally this is stated in terms of volumetric exchange per unit length of the shoreline. For the most accurate interface description, K and q must be adjusted for different layers of the aquifer. Table 1 below summarizes the data collected for this analysis, below.

Table 1 -- Physical parameters for the Oxnard-Mugu aquifer

K =	190	ft/d
A_{aqu} =	120	mi^2
ρ_f =	1.000	g/cm^3
ρ_s =	1.025	g/cm^3
D_{aqu} =	1400	ft
$\Delta\rho$ =	0.025	g/cm^3

As mentioned previously, the U-Tube model does not account for many physical properties of the aquifer being assessed. The only required information is the depth of the aquifer over which transmission occurs, the change in depth of either the saline or fresh water regions, and the known densities of the waters involved. The result can be expanded into something more useful by including the area of the aquifer, in order to obtain a resulting change in volume.

As seen in the table, the average depth of the aquifer has been previously established as approximately 1400 feet, below which the geostructure is consolidated and impermeable (U.S. Geological Survey, 1996). Simple surveying methods have established the boundaries and total area of the aquifer. The densities used in these calculations are based on standard values for fresh and saline waters, as there are no exceptional particulates in the constraints of the Oxnard-Mugu aquifer (Muir, 1982). Additional confirmation of this data has been obtained by non-governmental private interest groups, such as the California Groundwater Resource Management Association (Bachman, et al., 2005).

MEAN SEA LEVEL RISE

Based on proxy data, the magnitude of centennial-scale global mean sea level variations did not exceed 0.25 m over the past few millennia. This prediction can be made with medium confidence (Donnelly, 2006). The current rate of global mean sea level change, starting in the late 19th-early 20th century, is, with medium confidence, unusually high in the context of centennial-scale variations of the last two millennia. Tide gauge data also indicate a likely acceleration during the last two centuries (Douglas, 1997). Based on proxy and instrumental data, it is virtually certain that the rate of global mean sea level rise has accelerated during the last two centuries, marking the transition from relatively low rates of change during the late Holocene, order tenths of mm $yr_{–1,}$ to modern rates, of the order mm $yr_{–1}$ (Holgate & Woodworth, 2004).

Global mean sea level has risen by 0.19 [0.17 to 0.21] m, estimated from a linear trend over the period 1901– 2010, based on tide gauge records and additionally on satellite data since 1993. It is very likely that the mean rate of sea level rise was 1.7 [1.5 to 1.9] mm $yr_{–1}$ between 1901 and 2010. Between 1993 and 2010, the rate was very likely higher at 3.2 [2.8 to 3.6] mm $yr_{–1}$; similarly high rates likely occurred between 1930 and 1950.The rate of global mean sea level rise has likely increased since the early 1900 with estimates ranging from 0.000 to 0.013 [–0.002 to 0.019] mm $yr_{–2}$ (Intergovernmental Panel on Climate Change (IPCC), 2007). The figures on the following pages condense this information and demonstrated the scenarios most likely to occur in sea level rise. By most likely, it is meant that the scenario is within two standard deviations of current predictive information.

These figures, 3, 4, and 5, are built upon data collected via traditional methods and modern methods. The most recent predictors for sea level rise are established through satellite altimetry and the components of this data have significantly greater granularity than previous estimates (Nerem & Mitchum, 2001). The figures present a range scenarios within these bounds, and with 95% confidence it can be assumed sea level rise will be between 0.20 meters and 0.95 meters by 2100 (Bates, Kundzewics, Wu, & Palutikof, 2008).

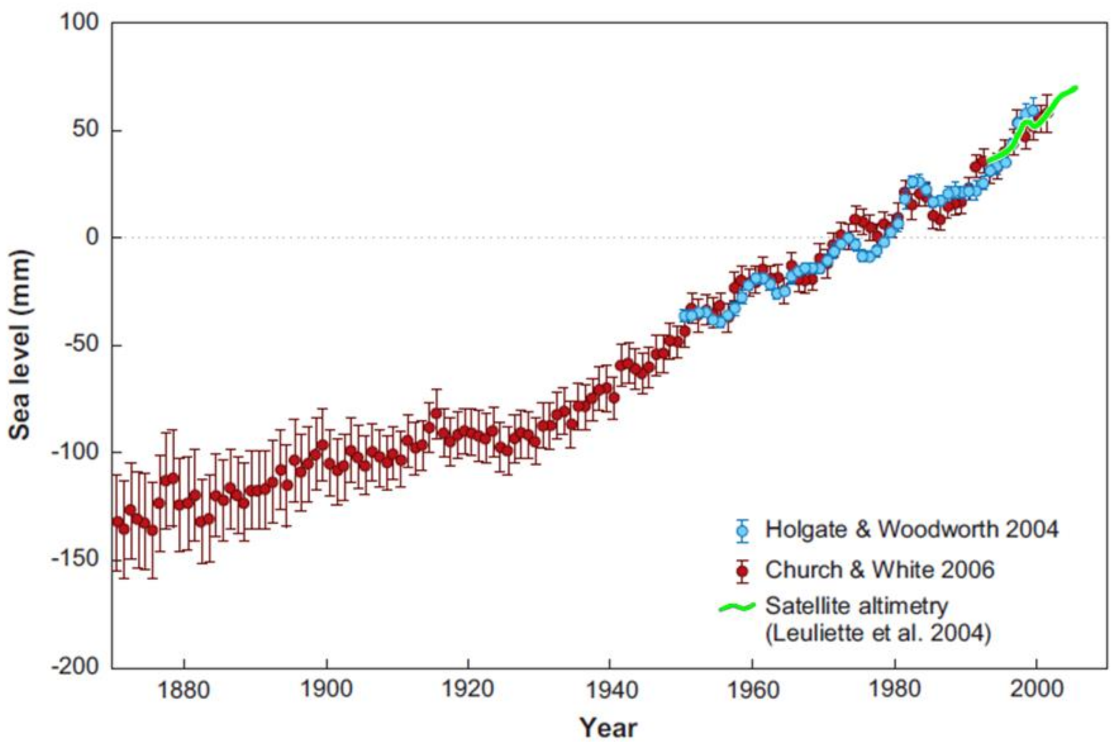

Figure 3 -- Global sea levels by tide gauges, altimetry, and satellite reading (IPCC 2008)

Please note that Figure 3 is reproduced as originally presented in the IPCC Fourth Assessment Report by the International Panel on Climate Change, per that organization's reference and publication requirements, and as such, requires some additional explanation. The predicted seal level rise shows a range both of scenarios and SLR changes within those cases, in order to produce a prediction with a much higher confidence interval. The 4 cases demonstrated in this figure are based on human emission patterns. RCP2.6 represents a significant reduction in human emissions and resulting global mean temperature increase of approximately 1 degree Celsius by 2100; RCP 2.6 represents a continuance of current emission growth and yields a likely global mean temperature increase of 3.7 degrees Celsius. RCP 4.5 and RCP 6.0 are intermediate scenarios for those two extremes. Figure 4 then demonstrates the combined observed data and predicted trend, in order to graphically demonstrate the confidence of the curve fit.

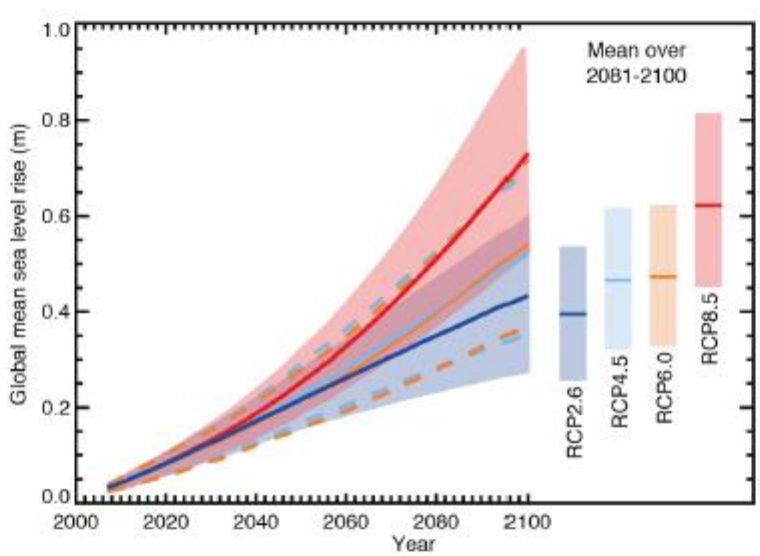

Figure 4 -- Predicted sea level rise per the IPCC fourth assessment report (IPCC 2008)

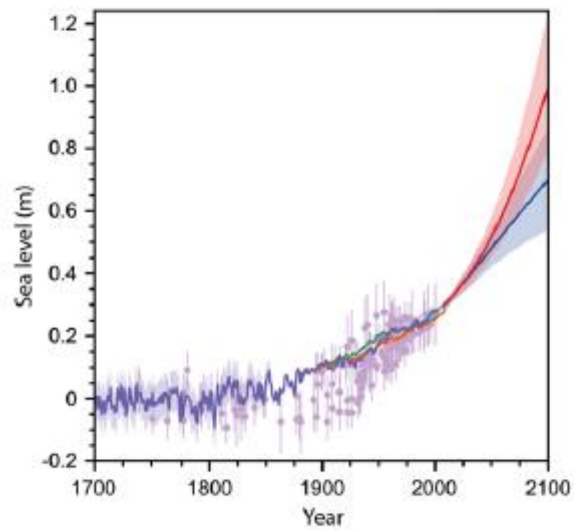

Figure 5 -- Past and future global sea level estimates

RESULTING DATA

By inserting a range of values for sea level rise, a spectrum of changes can be anticipated. The results illustrated in Table 2 following this estimate a volumetric change based on the changes in elevation for the top and bottom of the freshwater zone, ΔV. Of course, this model represents a linear progression of losses. Therefore, a total loss of potable groundwater per centimeter of sea level rise can also be established. This value of 20.5 acre-feet may be more valuable than any other result, as a method of simplifying and condensing the results of the analysis. This consistent with values typically generated by the model in established past studies (Bear, et. al, 2008).

Table 2 -- U-Tube estimates of water table changes in the Oxnard-Mugu aquifer

ΔD_{sea} Meters of sea level rise	ΔD_{aqu} Meters of lost aquifer depth	ΔV Thousands of cubic meters lost	ΔV Acre-feet lost
0.1	0.10	253	205
0.2	0.19	505	409
0.3	0.29	758	614
0.59	0.58	1490	1208
1	0.98	2530	2047
2	1.95	5050	4095
3	2.93	7580	6142

To further illustrate the effects of sea level rise on the water table, figure 4 on the following page demonstrates the visible difference in the interface boundary after the most likely change of 0.59 meters increase in global mean sea level. This value was read from the IPCC predicted data, for the 95% confidence interval case. For context, the figure also includes a base line average of the current depth of the interface across the aquifer, at 426 meters (1400 feet). Note, the dimensions of the figure have been shrunk, so as not to include the entire aquifer, in order to make the difference in interface profile more legible.

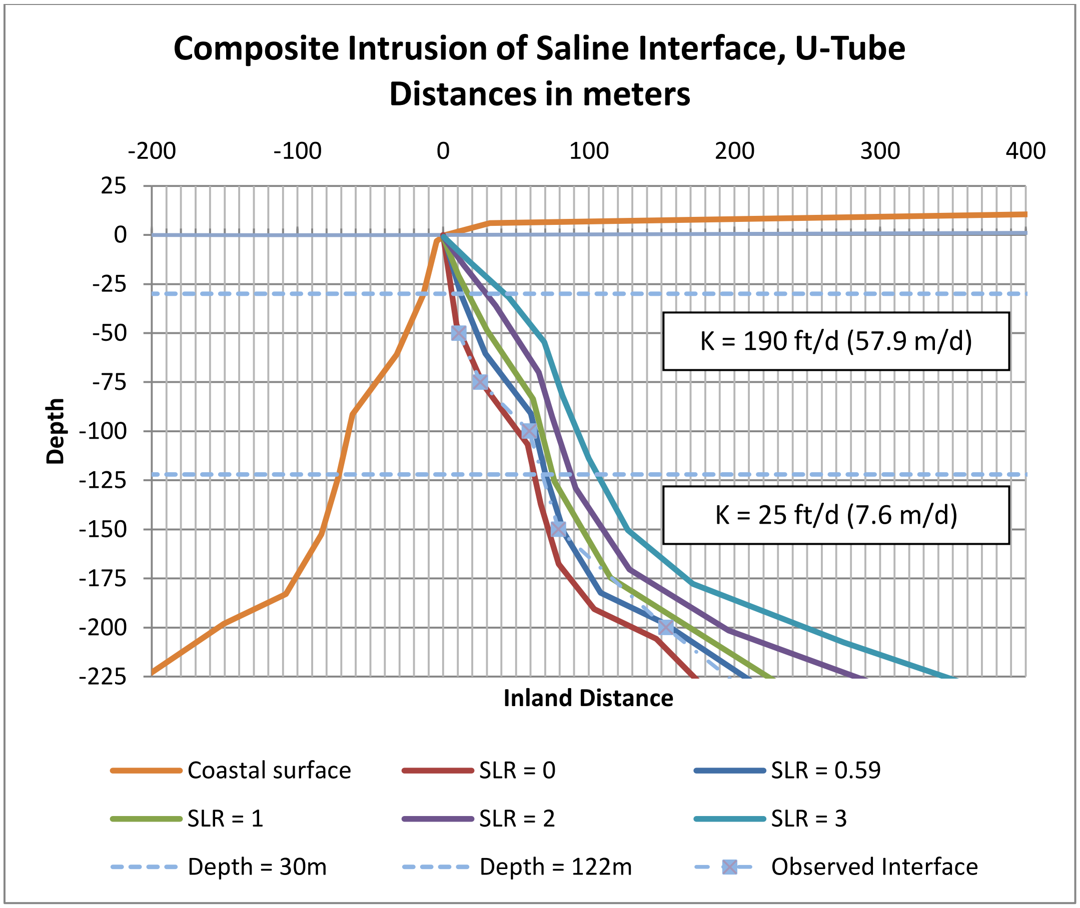

Figure 6 - Composite Intrusion of Saline Interface, U-Tube

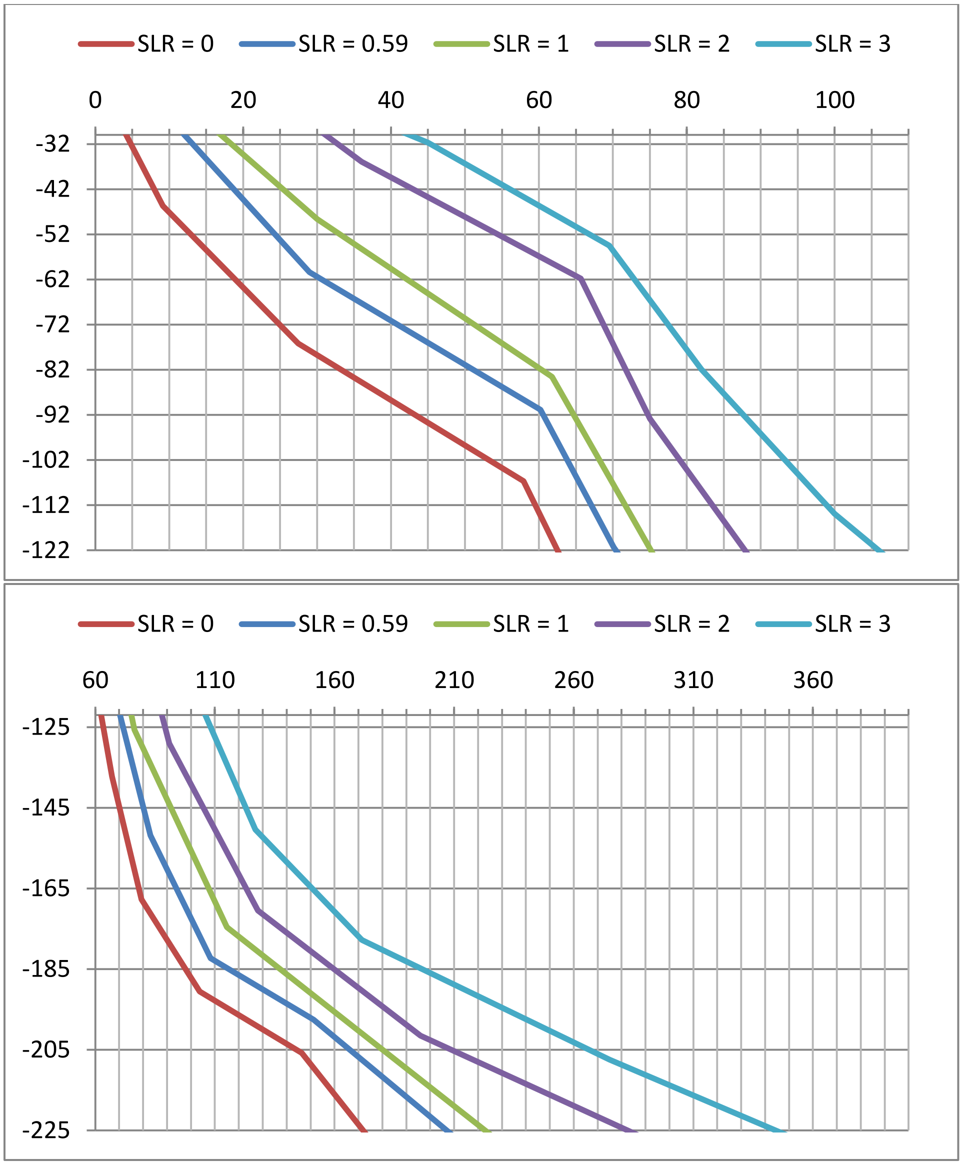

Figure 7 -- Saline/freshwater interface changes, post SLR, Ghyben-Herzberg, Aquifer depth versus distance inland in meters

Below is a summary in table 3 of results for the Glover analysis. The most important result is the loss of volume noted in the right columns, in metric and imperial units. In comparison to the results provided by the Ghyben-Herzberg method, it can be seen that the loss of volume is initially predicted to be smaller, but becomes greater as the rise in sea level increases. Since the method is nonlinear, this result makes qualitative since. As the method is known to be more accurate, this result provides a valuable caution to policy makers.

Table 3 - Glover estimates for changes in the Oxnard-Mugu aquifer

ΔD_{sea} Meters of sea level rise	ΔV Thousands of cubic meters lost	ΔV Acre-feet lost
0.1	291	24
0.59	1010	820
1	2910	2356
2	11508	9436
3	26200	21241

Further, these calculations can also produce a prediction for the landward advance of the saline-freshwater interface in the aquifer. Using a graphic area method with the equation:

$$\Delta\overline{L_i} = (A_{SLR} - A_0)/d_2 - d_1$$

A satisfactory estimate of the average intrusion of the interface inland can be found. In this calculation, $\Delta\overline{L_i}$ equals the average intrusion across a vertical region from a depth, d_2, up to a depth closer to ground surface, d_1. A_0 is the cross sectional area occupied by seawater in the aquifer, from the coastal structure to the interface, across the depth specified d_1 and d_2, under current environmental conditions; while A_{SLR} is the same region with the interface boundary position relocated after sea level rise. Considering the primary regions of water extraction to be the Oxnard-Mugu (30m to 122m) and the upper Hueneme (122m to 225m), Table 4, following this, has been prepared to show interface intrusion in the elected SLR cases. Also, observe that because the Glover method predicts, in each case, that the band of seaward flow is deeper than 30 meters, the intrusion at that depth is effectively still zero.

Table 4 - Saline-Freshwater Interface Landward Intrusion Due to SLR, methods compared

Method	Region of Concern	Oxnard-Mugu, Depth 30m to 122m (100 to 400 ft)				Upper Hueneme, Depth 122m to 225m (400 to 738 ft)			
	Sea Level Rise, SLR (m)	0.59	1.00	2.00	3.00	0.59	1.00	2.00	3.00
Ghyben-Herzberg	Interface Intrusion, $\Delta\overline{L_i}$ (m)	11.1	18.9	37.8	56.6	17.7	30.0	60.1	90.1
	Interface Intrusion, ΔL_{30} (m)	8.3	14.0	28.0	42.1	--	--	--	--
	Interface Intrusion, ΔL_{122} (m)	7.5	12.7	25.5	38.2	7.5	12.7	25.5	38.2
	Interface Intrusion, ΔL_{225} (m)	--	--	--	--	33.8	57.2	114.5	171.7
Glover	Interface Intrusion, $\Delta\overline{L_i}$ (m)	3.4	8.8	37.2	95.7	14.0	24.5	86.9	191.4
	Interface Intrusion, ΔL_{30} (m)	0	0	0	0	--	--	--	--
	Interface Intrusion, ΔL_{122} (m)	5.6	16.1	64.4	144.9	5.6	16.1	64.4	144.9
	Interface Intrusion, ΔL_{225} (m)	--	--	--	--	22.9	32.1	118.6	245.3

Following this table is figure 7 demonstrating these changes in the water table interface position. It is obvious while examining the figure that the location changes little, but represents significant volumetric losses in the cases exceeding more than 0.5 meters SLR. The interface contours has been drawn against a simplified cross section to help locate them.

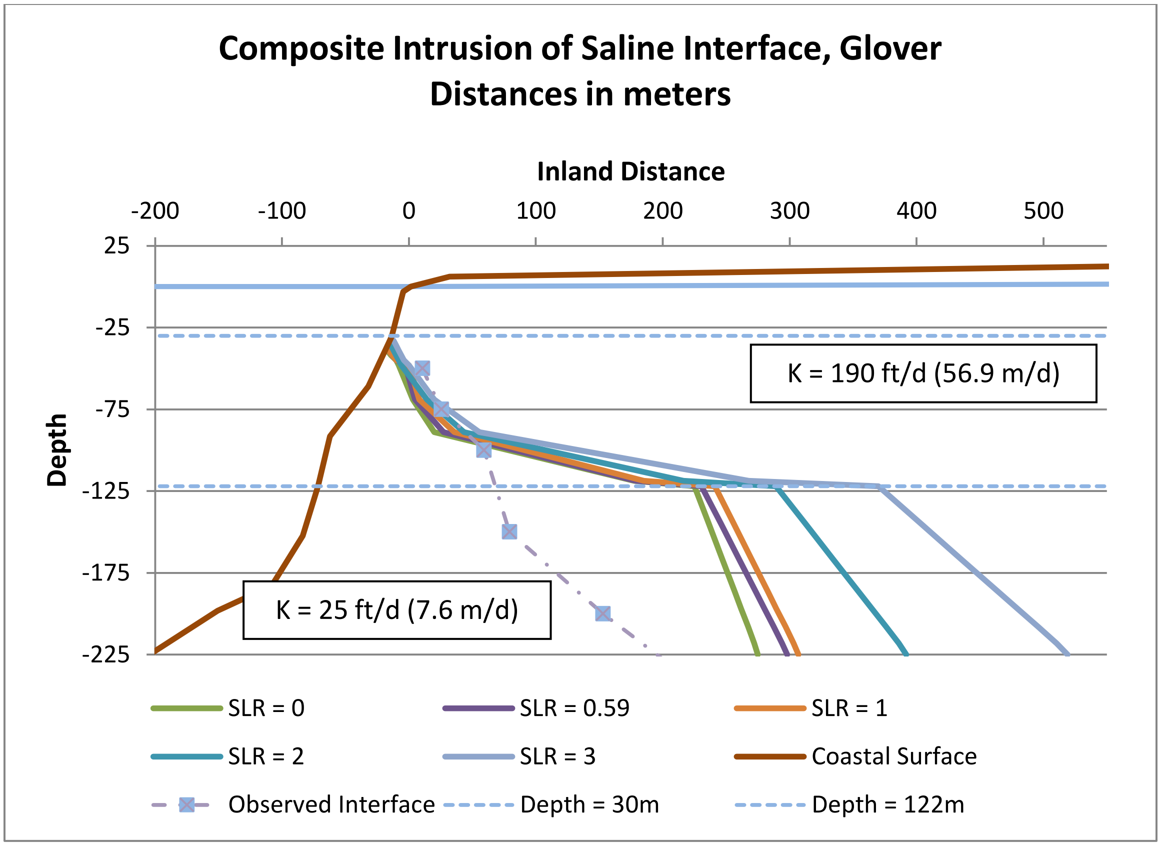

Figure 8 - Composite Intrusion of Saline Interface, Glover

By fitting the data from the calculation of storage capacity loss and intrusion distance to a trend line, a set of much simpler predictive equations can be established for the changes which will be predicted at different levels of sea level rise. Figures 10 and 11 show this for storage capacity losses, while figures 12 and 13 demonstrate it for intrusion distance. One should note that while a direct calculation for capacity loss is easily applied, at depths other than 30 meters (100ft), 122 meters (400ft), and 225 meters (738ft), interpolation between two other depths will be required for intrusion prediction.

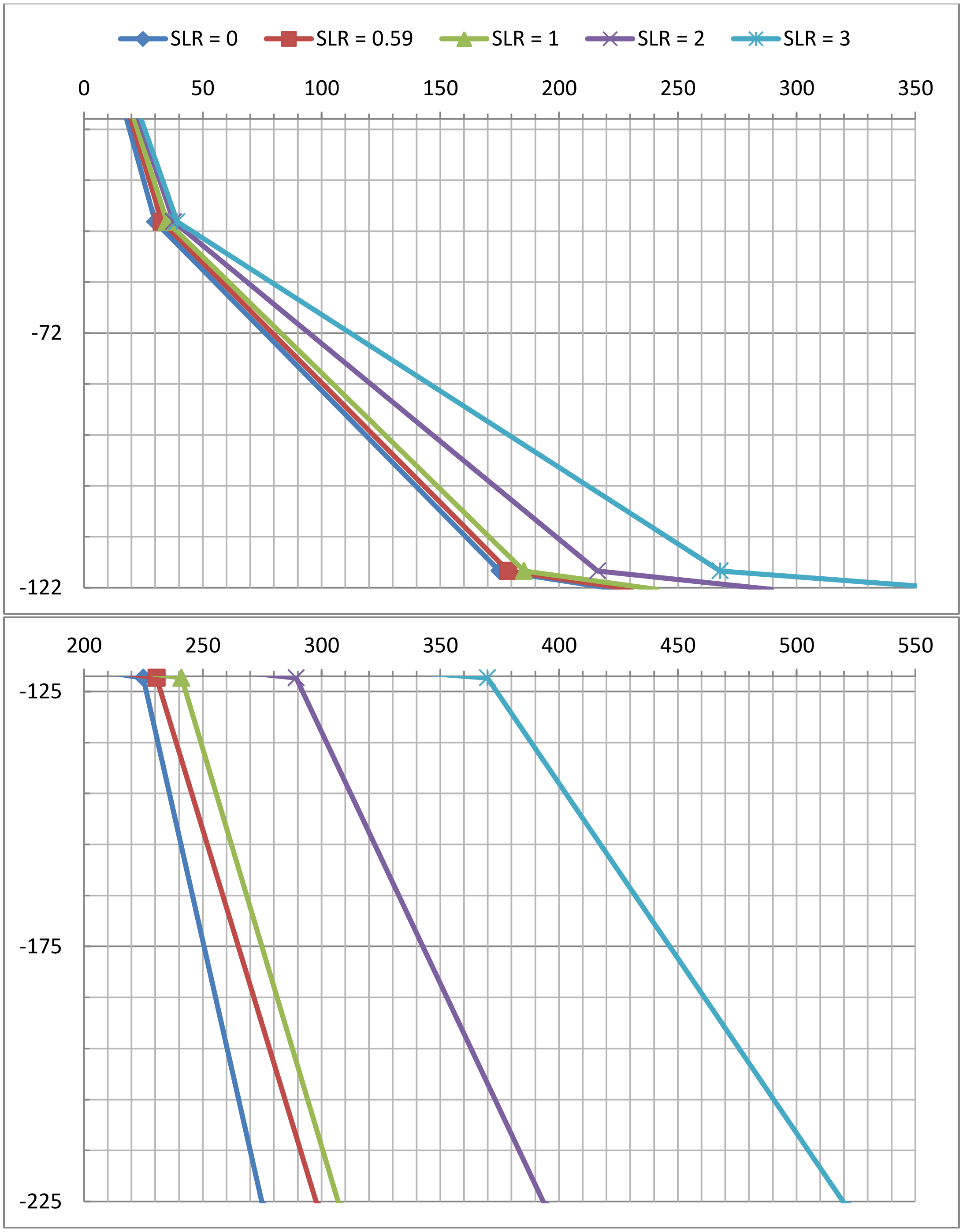

Figure 9 -- Interface changes post sea level rise, Aquifer depth versus distance inland in meters

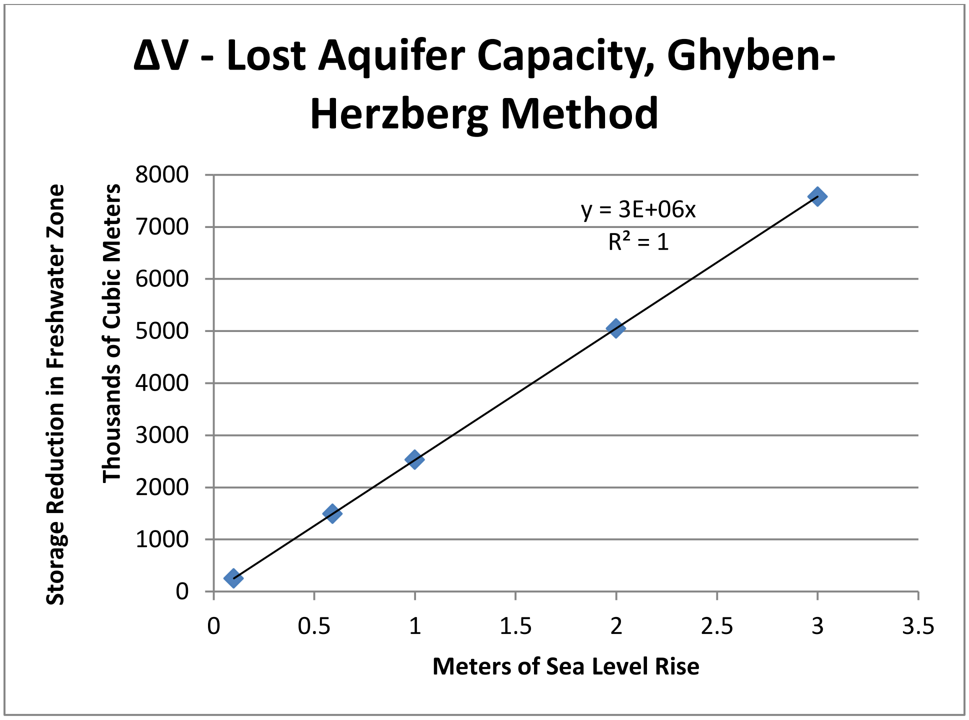

Figure 10 - ΔV - Lost Aquifer Capacity, Ghyben-Herzberg Method

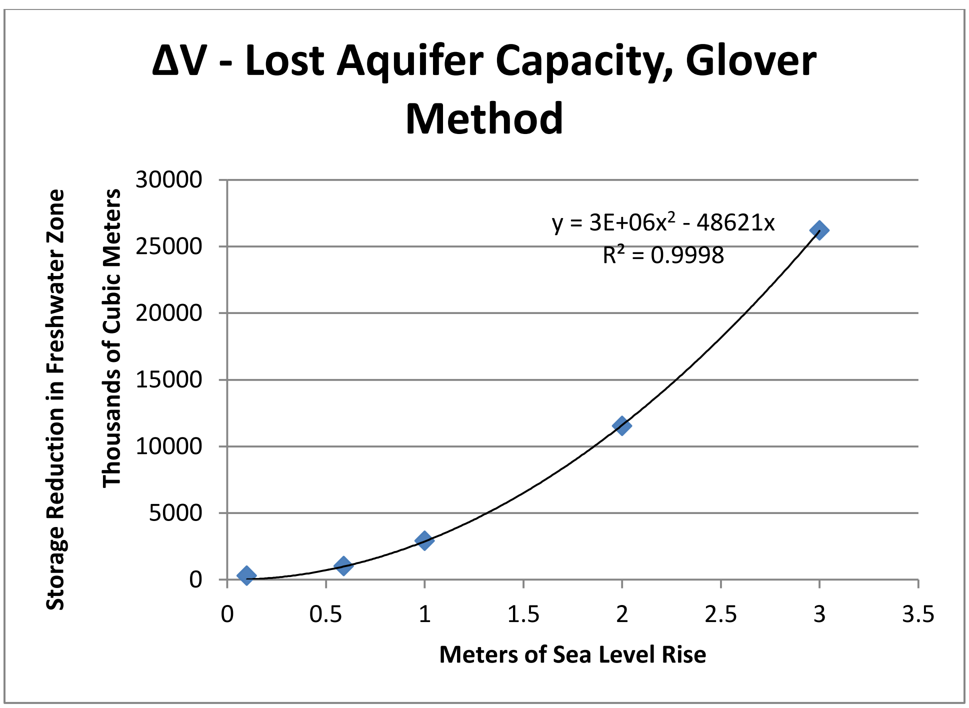

Figure 11 - ΔV - Lost Aquifer Capacity, Glover Method

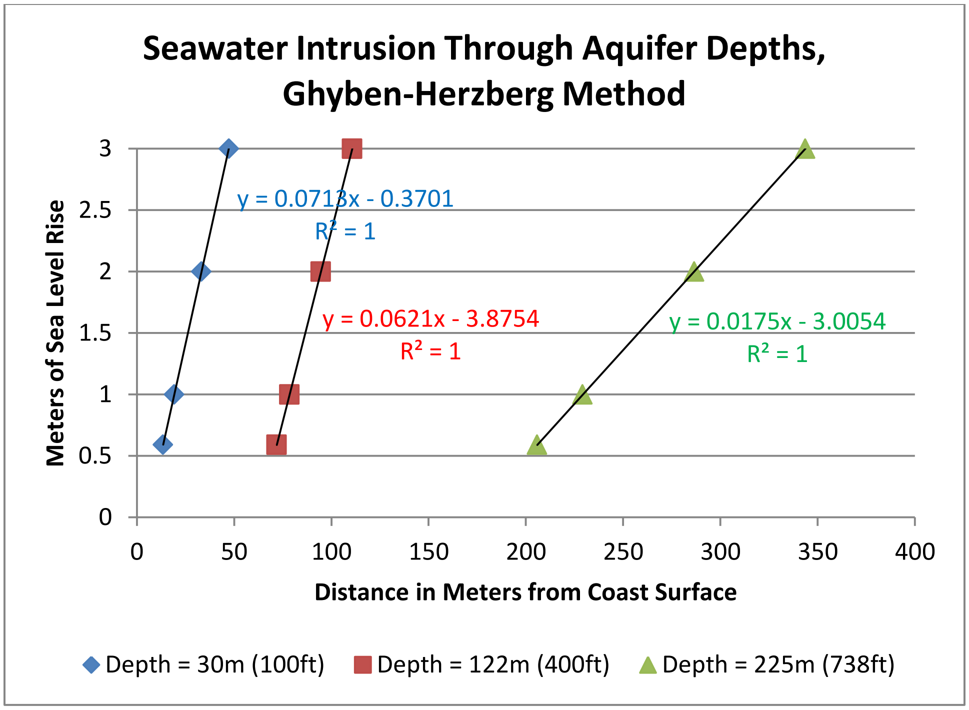

Figure 12 - Seawater Intrusion Through Aquifer Depths, Ghyben-Herzberg Method

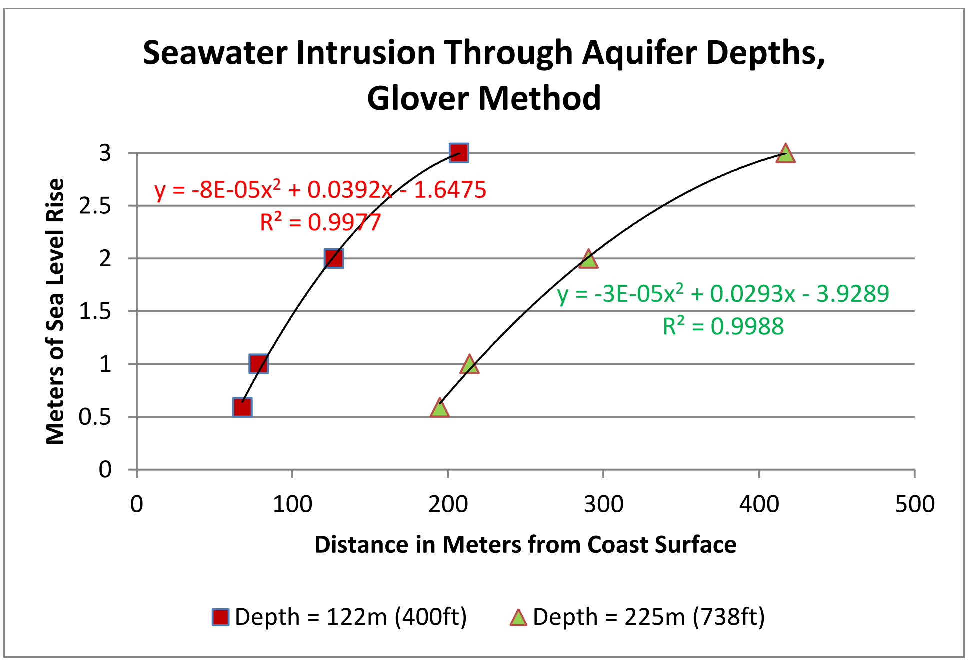

Figure 13 - Seawater Intrusion Through Aquifer Depths, Glover Method

CONCLUSIONS

In summarizing these results, we can observe the following.

1. The Ghyben-Herzberg method predicts a loss of potable water reserves for the Oxnard basin area of California by 20.5 acre-feet per centimeter of sea level rise.
2. By the Glover method, the losses could be considered marginal for any sea level rise of less than 0.5 meters.
3. The most likely scenario thus expects a loss of slightly more than 1200 acre-feet.
4. For the Oxnard basin, which is already pumped at just less than a maximum capacity rate of 246, 800 acre-ft/yr, this represents a 0.5% reduction in the serviceable population.
5. It should be noted however, that even for the likely 0.59 scenario, a loss of more than 800 acre-feet still requires a reduction of 0.3% of the serviced population.
6. Storage capacity losses can be predicted by the equation $\Delta V = 3E+06(SLR)$ under the u-tube approach and $\Delta V = 3E+06(SLR)^2 - 48621(SLR)$ for the Glover approach.
7. Intrusion distances can be estimated with the information in figures 12 and 13 via interpolation.

In scenarios of greater increase in sea level, it is more conservative and accurate to estimate losses via the Glover method, and in the most extreme scenarios (3.0 m SLR), it predicts losses an order of magnitude greater than the Ghyben-Herzberg method. The combined results in figure 8 following this demonstrate where discrepancies between methods occur and demonstrate the lower impact of coast geometry at greater depths for the Glover method.

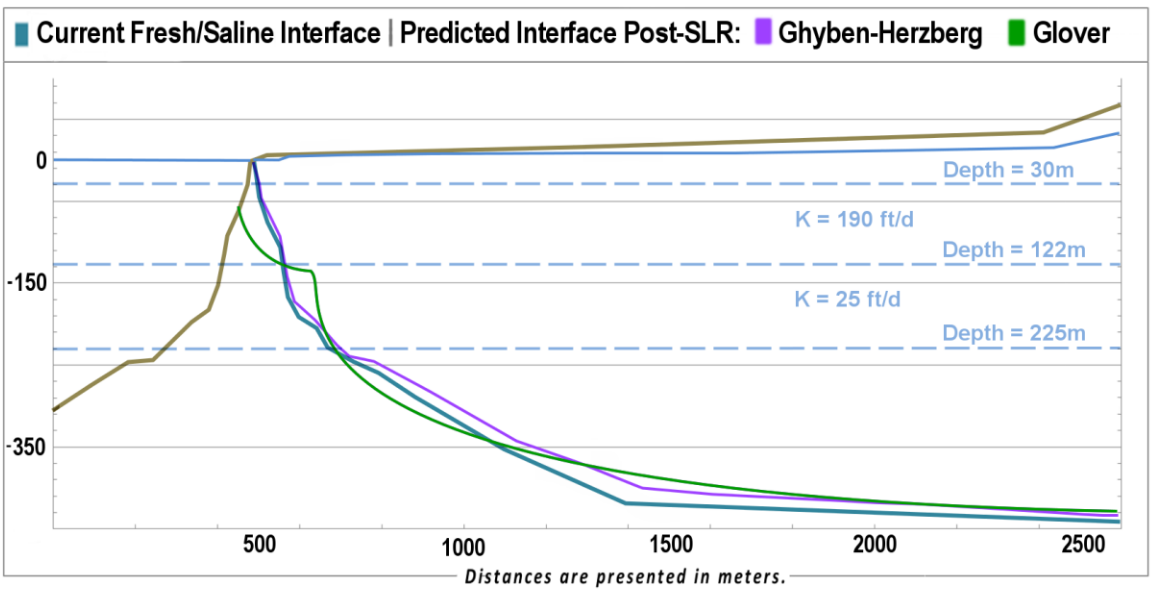

Figure 8 - Overlayed comparison of Ghyben-Herzberg and Glover methods

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