City of San José

San José/Santa Clara Water Pollution
Control Plant Master Plan

TASK NO. 5
PROJECT MEMORANDUM NO. 4
ASSESSMENT OF IMPACTS AND IMPROVEMENTS TO ADDRESS SEA LEVEL RISE

FINAL DRAFT
February 2010

in association with

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CITY OF SAN JOSÉ

SAN JOSÉ/SANTA CLARA WATER POLLUTION CONTROL PLANT MASTER PLAN

TASK NO. 5
PROJECT MEMORANDUM NO. 4
ASSESSMENT OF IMPACTS AND IMPROVEMENTS TO ADDRESS SEA LEVEL RISE

TABLE OF CONTENTS

Page No.

LIST OF APPENDICES

LIST OF TABLES

LIST OF FIGURES

ASSESSMENT OF IMPACTS AND IMPROVEMENTS TO ADDRESS SEA LEVEL RISE

1.0 INTRODUCTION

The purpose of this project memorandum (PM) is to summarize the potential effects of future climate changes, specifically sea level rise, relevant to the San José/Santa Clara Water Pollution Control Plant (WPCP) for the San José/Santa Clara WPCP Master Plan (Master Plan). This information will be used in the consideration of sea level rise adaptation strategies as part of the land use alternatives being developed for the WPCP site.

2.0 BACKGROUND

The earth's climate is expected to change due to anthropogenic emissions altering the chemical composition of the atmosphere. Atmospheric greenhouse gases (GHGs) (water vapor, carbon dioxide, and other gases) trap heat in the atmosphere and create a natural greenhouse effect. Since the onset of the industrial revolution, however, human-generated emissions (e.g., carbon dioxide, methane, nitrous oxide, chlorofluorocarbons, and other gases) have been accumulating in the atmosphere at a much faster rate and are intensifying the earth's natural greenhouse effect.

Carbon dioxide (CO_2) levels today (~385 parts per million [ppm]) are higher than they have been over the past 800,000 years (Siegenthaler et al, 2005; Luthi et al, 2008). The Intergovernmental Panel on Climate Change (IPCC) projects that a doubling in CO_2 levels (from the pre-industrial level of 280 ppm) could increase global mean surface temperatures by an average of 3 degrees Celsius (5.4 degrees Fahrenheit). Consequences of such a temperature increase include dramatic changes to mountainous snowfall and snowmelt dynamics, increased intensity, duration, and frequency of storm events, increased melting of land ice (specifically in Greenland and Antarctica), and thermal expansion of the marine mixed layer of the ocean. Both melting land ice and thermal expansion of the marine mixed layer of the ocean contribute to sea level rise. Scientists agree the impacts are likely to accelerate over the next couple of decades. Therefore, water and wastewater agencies need to adopt more integrated, adaptive management strategies.

Although there is uncertainty about future emissions of GHGs and how and when the earth's climate will respond to the enhanced concentrations of GHGs, studies report that detectable changes are already under way. The most likely consequences are increases in temperature and changes in precipitation, soil moisture, and sea level, which could have adverse effects on many ecological systems, as well as on human health, infrastructure, and the economy. This PM summarizes the findings specific to historical and projected sea levels relevant to the WPCP's long-term land use planning.

3.0 SEA LEVEL RISE

There are multiple reasons why sea levels vary over daily or longer time horizons.

- Melting land ice.
- Thermal expansion of the ocean's marine mixed layer.
- Vertical land movement.
- Meteorological forcings.
- Lunar cycle.

Global climate change has increased the rate of melting land ice (specifically in Greenland and Antarctica) adding to the total mass of the oceans and also causes thermal expansion of the marine mixed layer of the ocean adding to the total volume. Independent of global climate change, vertical land movements[1] and meteorological forcings also contribute to relative sea level change and astronomical tides can cause changes in water level along the California coast of about 3 meters (10 feet) (Cayan et al, 2006). Since the processes contributing to changes in sea level all have significant spatial variability, it has been suggested that there will be considerable geographic variability in changes in the rate of relative sea level rise (Walsh et al, 2005).

4.0 SEA LEVEL RISE AND SAN JOSE/SANTA CLARA WATER POLLUTION CONTROL PLANT IMPACTS

Historical sea level data for the San Francisco Bay presented in this analysis were obtained from the National Oceanic and Atmospheric Administration's (NOAA) National Ocean Service Center for Operational Oceanographic Products and Services (NOS CO-OPS) website. Data were collected relative to the North American Vertical Datum established in 1988 (NAVD 88) from the Redwood City, Alameda, and San Francisco tide gages within the San Francisco Bay.

While the Redwood City tide gage is closest to the WPCP site, it has the least data on record - beginning in 1983 and recording through 1984, then began recording data again in 1997 to present. The Alameda tide gage has the second longest record from 1940 to present. San Francisco's tide gage has the longest record of all tide gages in the U.S., from approximately 1850 to present. Data from all three tide gages were used in the historical sea level rise analysis presented in this PM.

[1] Vertical land movement due to land subsidence/uplift has been monitored over time and is taken into account in the tide gage records. Since the 1970s, vertical land movement in the Santa Clara Valley (specifically spanning the WPCP site) has been managed via importation of surface water and aquifer management (Poland and Ireland, 1982; U.S.G.S., 2000).

To complete the analysis, the latest ranges of projections of sea level rise due to global climate change were researched and the most widely accepted (peer-reviewed) ranges were selected and included in this analysis, in addition to the National Research Council's (NRC) projections developed in 1987. These selected ranges of projections of sea level rise due to global climate change are shown in Table 1 and come from three sources:

1. Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report of 2007 (IPCC, 2007).

2. Rahmstorf paper (Rahmstorf, 2007) and the CALFED Independent Science Board (ISB) of 2007 (Mount, 2007). See Appendices A and B, respectively, for the original documents presenting the projected ranges of sea level rise.

3. U.S. Marine Board Commission on Engineering and Technical Systems National Research Council (NRC) of 1987 (U.S. NRC, 1987).

Table 1 Sources and Ranges of Projections for Sea Level Rise due to Global Climate Change
San José/Santa Clara Water Pollution Control Plant Master Plan
City of San José

Sources	2050		2100	
	Low(1)	High(1)	Low(1)	High(1)
IPCC 2007	3.8	12.5	7	23
Rahmstorf/CALFED ISB 2007	10.9	30.0	20	55
NRC(2) 1987	6.0	24.0	20	59

Note:
(1) Units are in inches.
(2) NRC curve I represents the low end of the range and curve III represents the high end.

The Rahmstorf/CALFED ISB projections shown in Table 1 take into account the latest observations and science of sea level rise (specifically, the latest understanding of ice sheet dynamics and the increasing rate of land ice melt observed at the polar ice caps). It is also important to note that seasonal land subsidence and uplift effects were also considered in this analysis. Since the 1970s, seasonal vertical land movement (i.e., subsidence and uplift) throughout the Santa Clara Valley has been prevented by importation of surface water and careful management of aquifer systems (Poland and Ireland, 1982; U.S.G.S., 2000).

The Army Corps of Engineers and others are currently using the NRC projections as part of the ongoing South San Francisco Bay Shoreline Study (Study) to identify and recommend federal funding for one or more projects to address a variety of land issues, one of which is sea level rise. This Study is in the process of developing floodplain maps that include the area of the WPCP based solely on the NRC projections (specifically, curves I and III). The results of the Study and the floodplain maps are scheduled for release in spring of 2010.

Figures 1 through 7 have been developed using data from the three tide gages as well as the three ranges of sea level rise projections provided in Table 1. All elevation data shown is adjusted to be with respect to NAVD 88[2].

Figure 1 shows both the historical monthly mean higher high water (MHHW) levels[3] based on the data collected from NOAA (shown for Redwood City, Alameda, and San Francisco) as well as the projected ranges of sea levels (from the three sources listed in Table 1) extending from the 1990 MHHW levels. Projected ranges of sea levels are shown with respect to 1990 MHHW levels, since this is the year from which climate models start to estimate the projected changes in sea level due to climate change.

Figure 1 also shows elevations of various locations across the WPCP site as points of reference, including the outfall weir. The outfall weir is of special concern, since an increase in the head above the outfall weir can result in a decrease of the capacity of the outfall pipes, as this capacity is a function of the driving head in the pipes.

Figures 2 through 7 were developed based on the three sources of projections listed in Table 1 and show the resulting projected impact of sea level rise in 2050 and 2100 assuming there are no levees in place. It is important to note that the existing levees were not designed with the intent to withstand future sea level rise, nor have there been regular risk assessments performed to document their condition.

Figures 2 and 3 show the inundation of the WPCP site based on the IPCC 2007 estimated low and high (light and dark blue, respectively) projections for 2050 and 2100, respectively. Figures 4 and 5 show the inundation of the WPCP site based on the Rahmstorf/CALFED ISB 2007 estimated low and high (light and dark blue, respectively) projections for 2050 and 2100, respectively. Figures 6 and 7 show the inundation of the WPCP site based on the NRC 1987 estimated low and high (light and dark blue, respectively) projections for 2050 and 2100, respectively.

In addition to the analysis presented in this PM, there are ongoing efforts to inform the public of the potential impact of sea level rise due to global climate change. Some of those efforts relevant to Santa Clara Valley and San Francisco Bay include:

- Santa Clara Valley Water District has a map-based tool link on their website developed by U.S. Geological Survey showing inundated areas of the South Bay under 3 scenarios (18 inches, 39 inches, and 55 inches of sea level rise): http://arcview.valleywater.org/Development/SLR/SLR_Map.html

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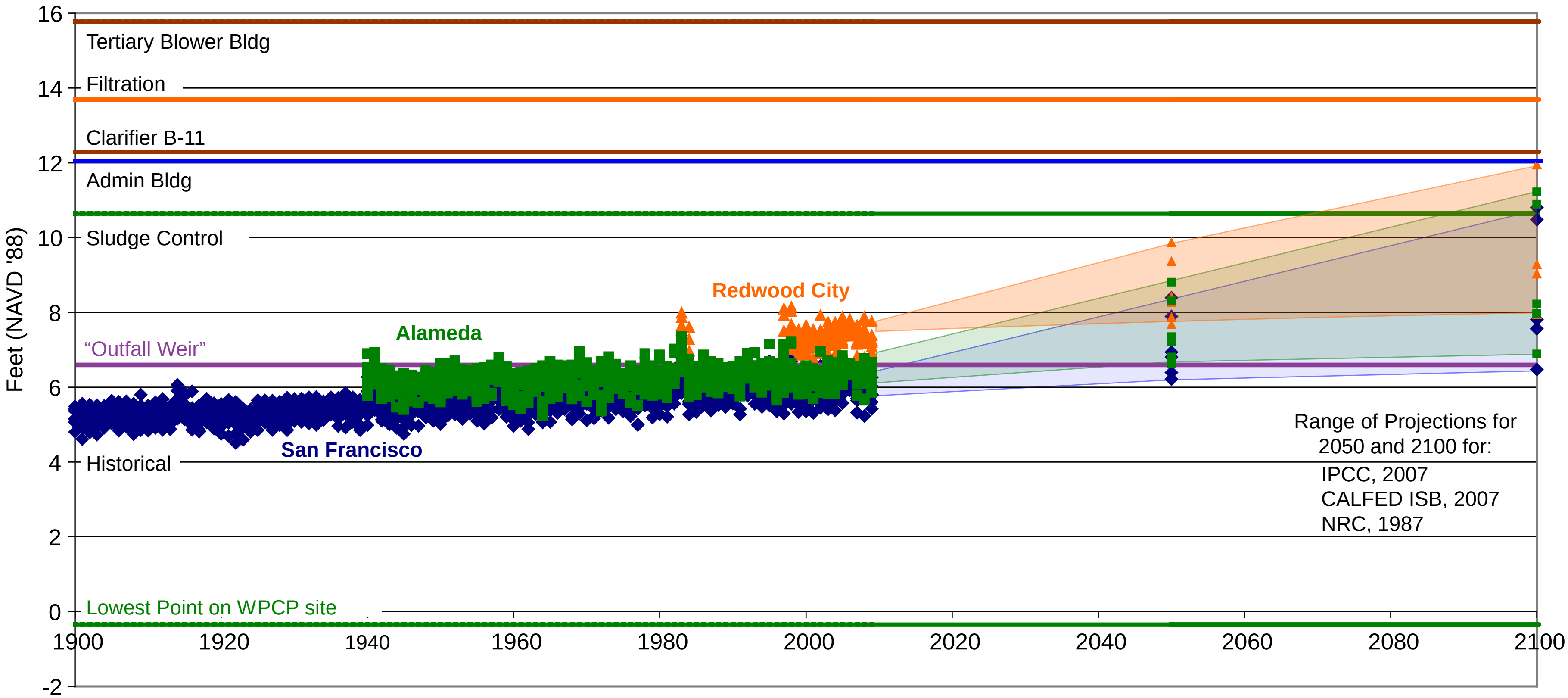
[2]According to verified tide gage data provided by the NOAA (http://tidesandcurrents.noaa.gov/) for South San Francisco Bay as well as surveying results generated for the WPCP Reliability Improvements Project of 2005, the "plant datum" is 2.4 feet above the National Geodetic Vertical Datum of 1929 (NGVD 29), and the NGVD 29 is 2.69 feet above the North American Vertical Datum of 1988 (NAVD 88). All values are accurate to within ± 0.2 feet.

[3] Mean Higher-High Water (MHHW) is a tidal datum that is defined as the average of the higher of two daily high water levels over a long period of time.



*Accuracy is to ±0.2 feet.

Figure 1

MONTHLY MEAN HIGHER HIGH WATER (MHHW) LEVEL AT SAN FRANCISCO, ALAMEDA, AND REDWOOD CITY TIDE GAGES AND RANGE OF WPCP ELEVATIONS RELATIVE TO NORTH AMERICAN VERTICAL DATUM (NAVD) '88

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CITY OF SAN JOSÉ

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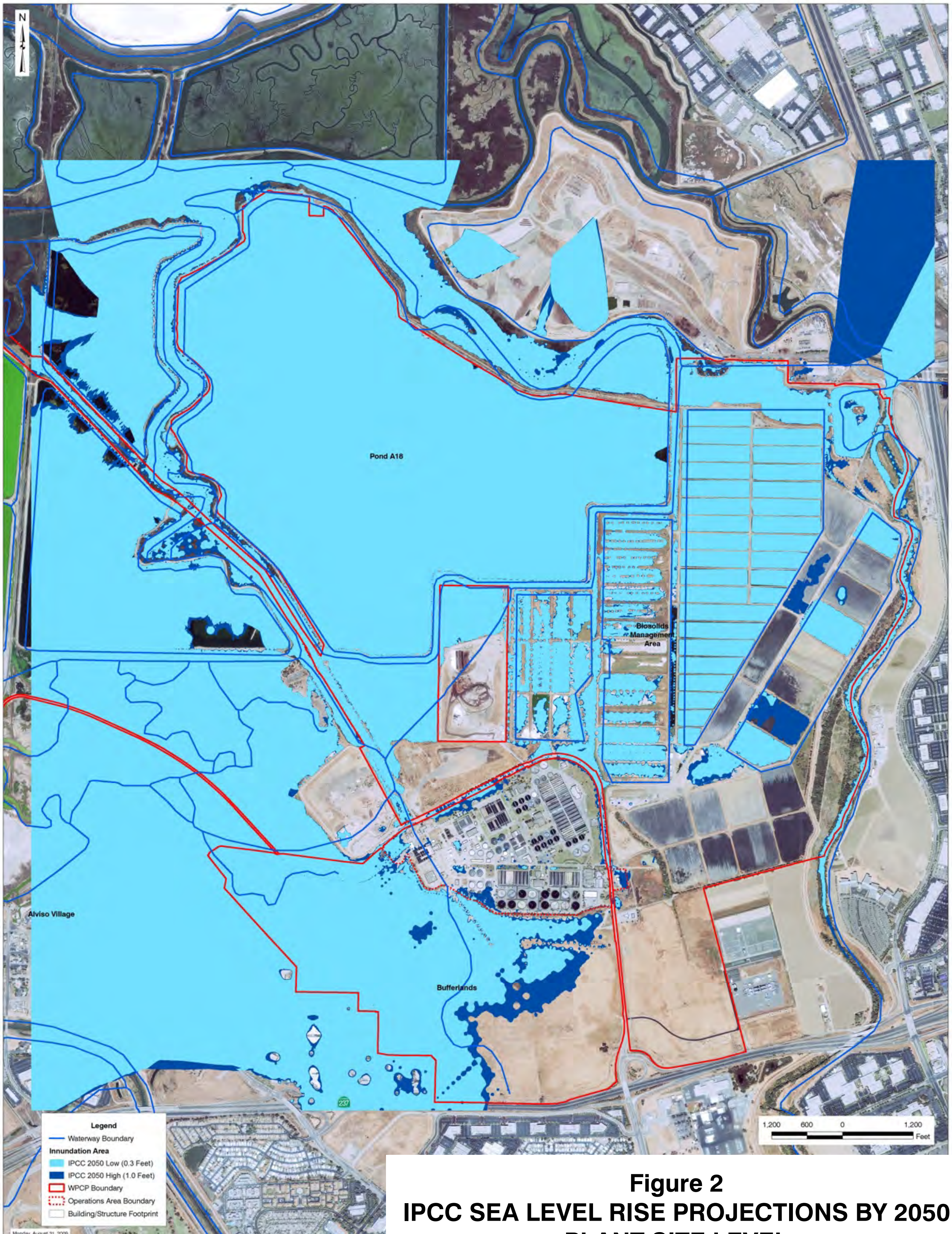

Figure 2
IPCC SEA LEVEL RISE PROJECTIONS BY 2050
PLANT SITE LEVEL
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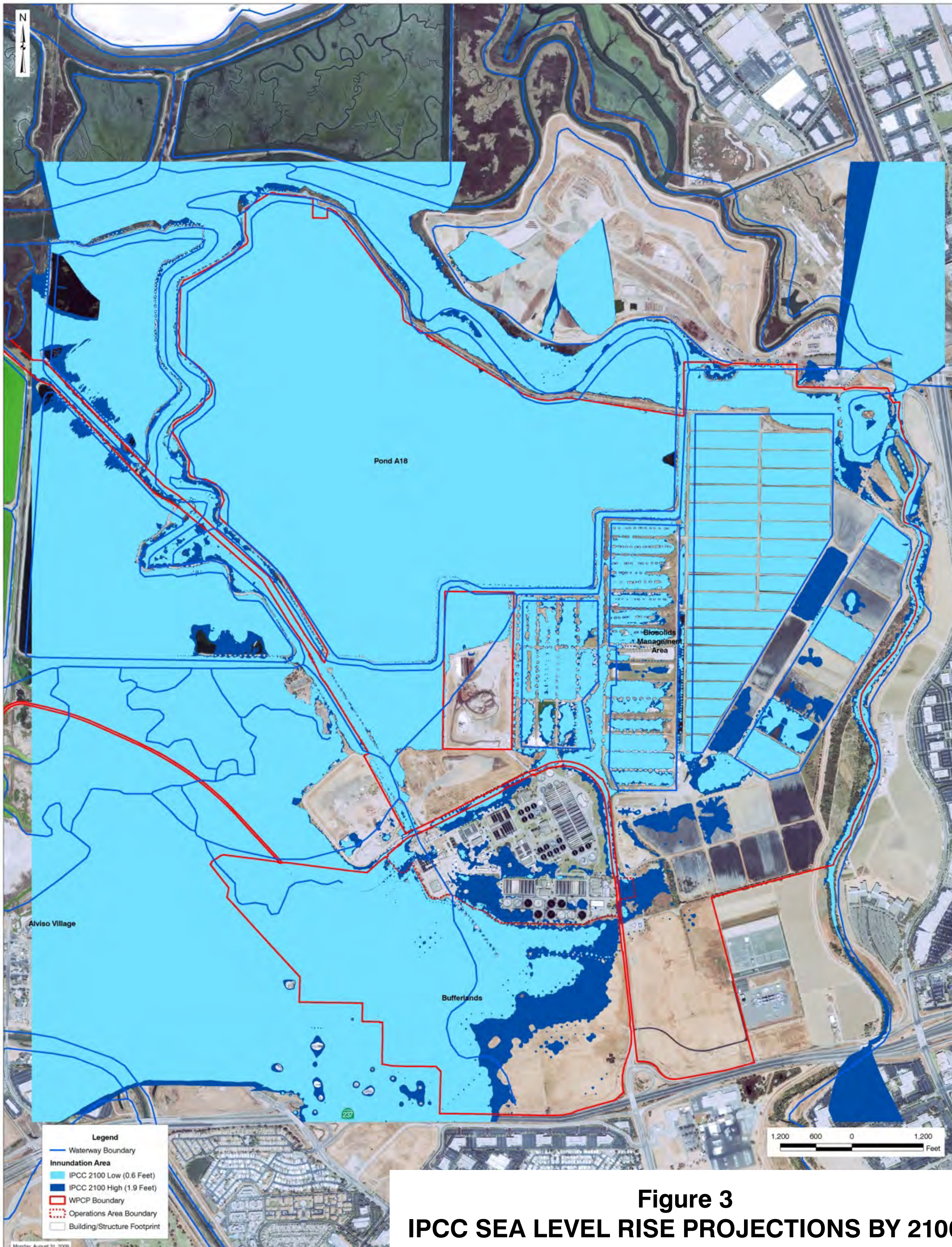

Figure 3
IPCC SEA LEVEL RISE PROJECTIONS BY 2100
PLANT SITE LEVEL
SAN JOSÉ/SANTA CLARA WPCP MASTER PLAN
CITY OF SAN JOSÉ

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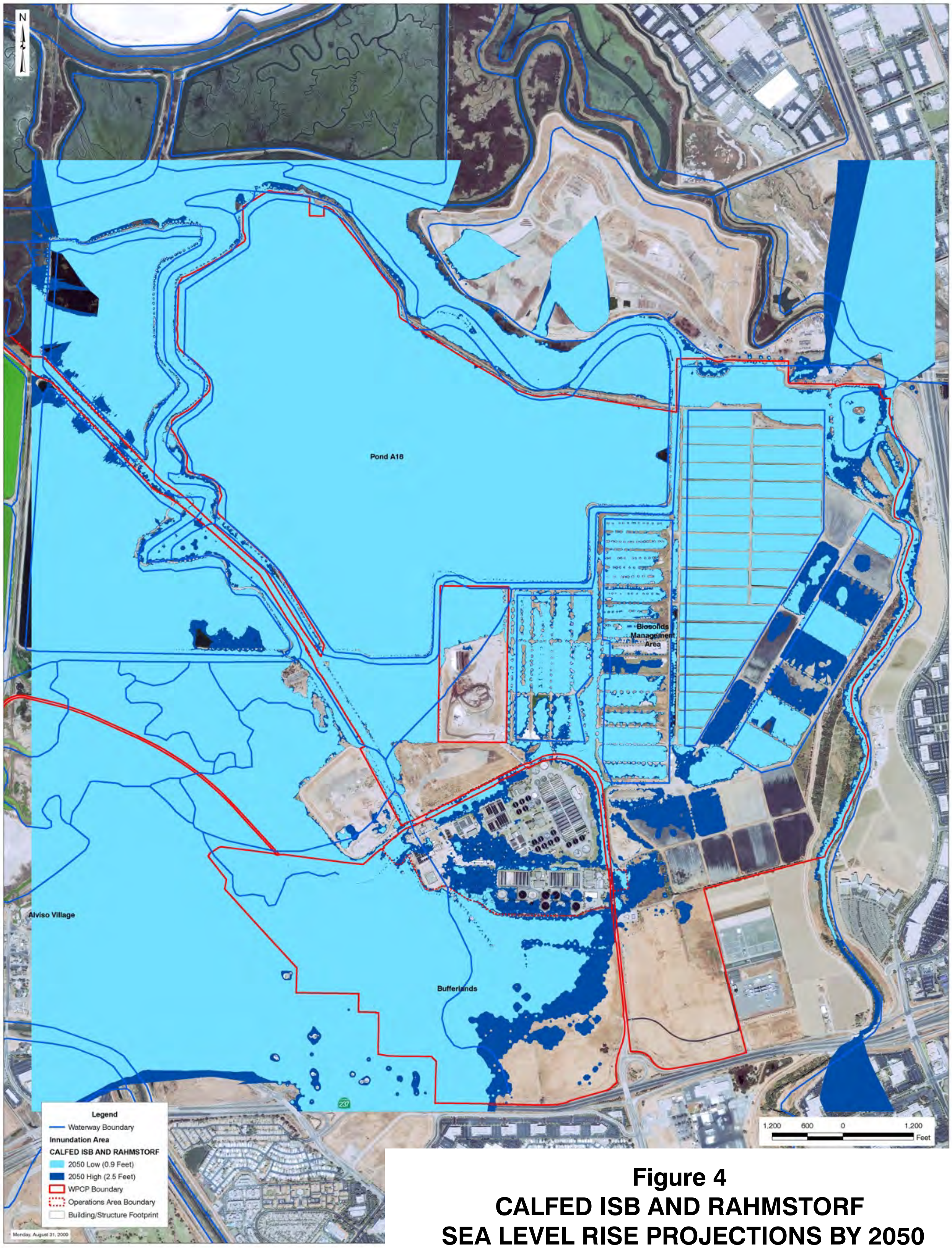

Figure 4
CALFED ISB AND RAHMSTORF
SEA LEVEL RISE PROJECTIONS BY 2050
PLANT SITE LEVEL
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CITY OF SAN JOSÉ

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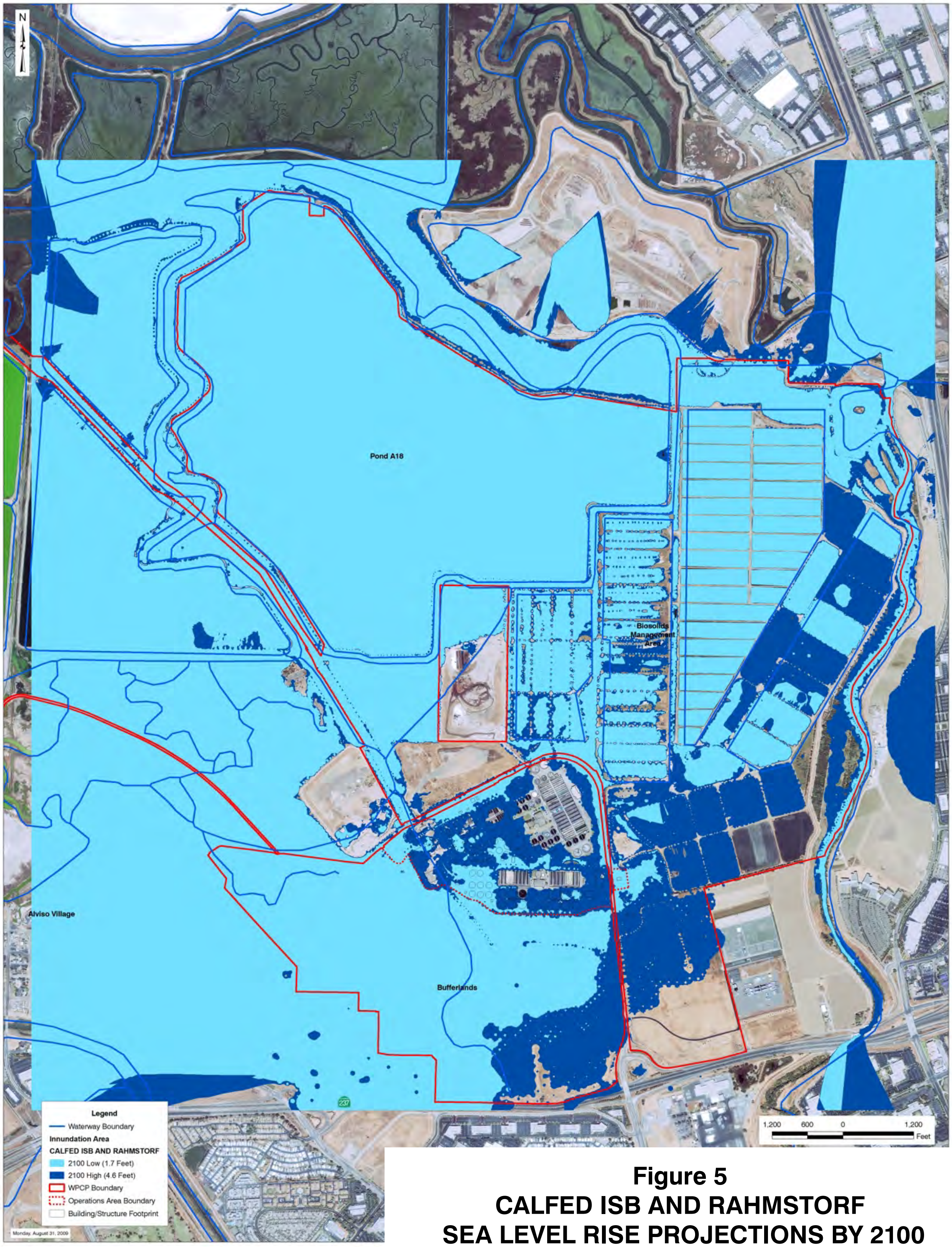

Figure 5
CALFED ISB AND RAHMSTORF
SEA LEVEL RISE PROJECTIONS BY 2100
PLANT SITE LEVEL
SAN JOSÉ/SANTA CLARA WPCP MASTER PLAN
CITY OF SAN JOSÉ

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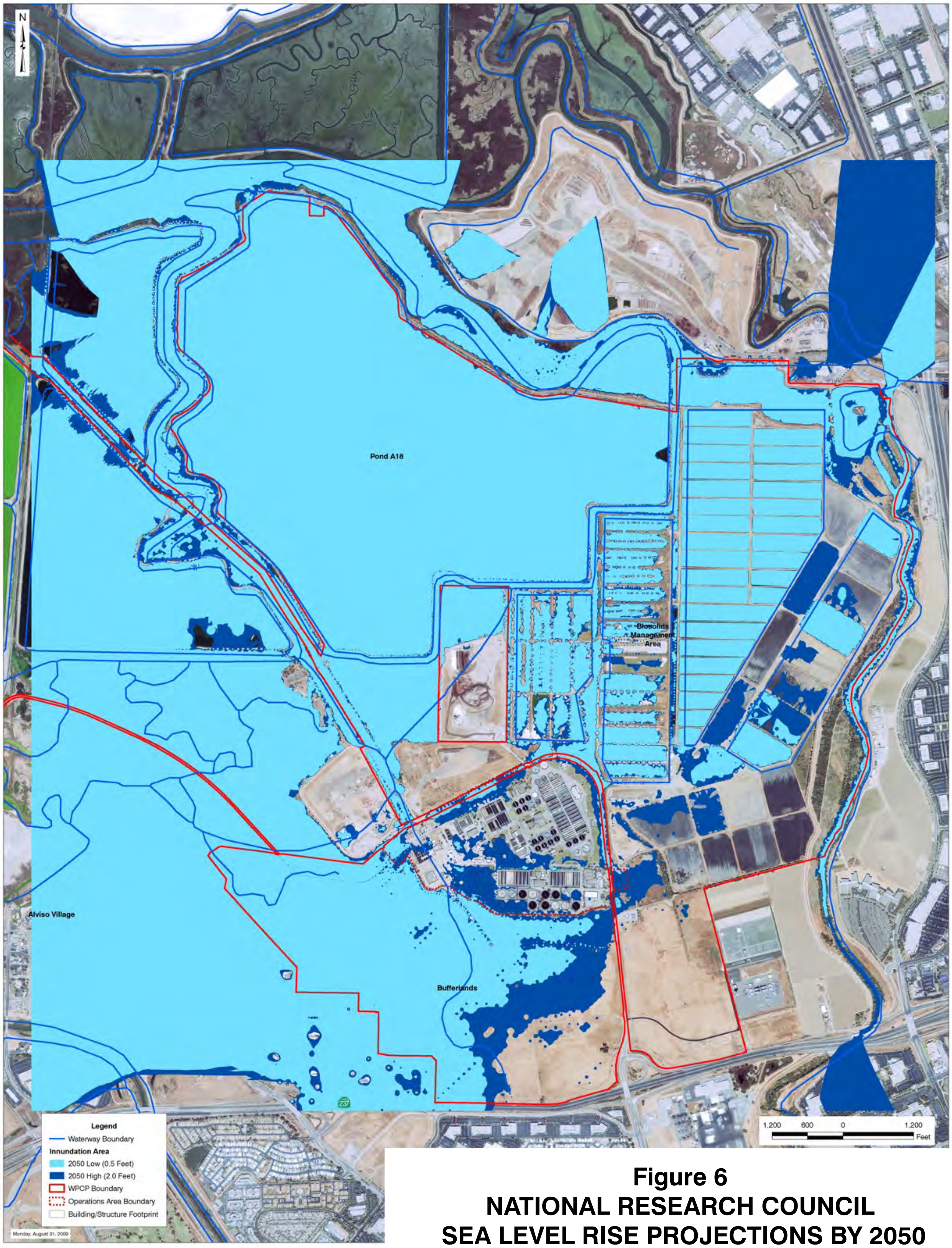

Figure 6
NATIONAL RESEARCH COUNCIL
SEA LEVEL RISE PROJECTIONS BY 2050
PLANT SITE LEVEL
SAN JOSÉ/SANTA CLARA WPCP MASTER PLAN
CITY OF SAN JOSÉ

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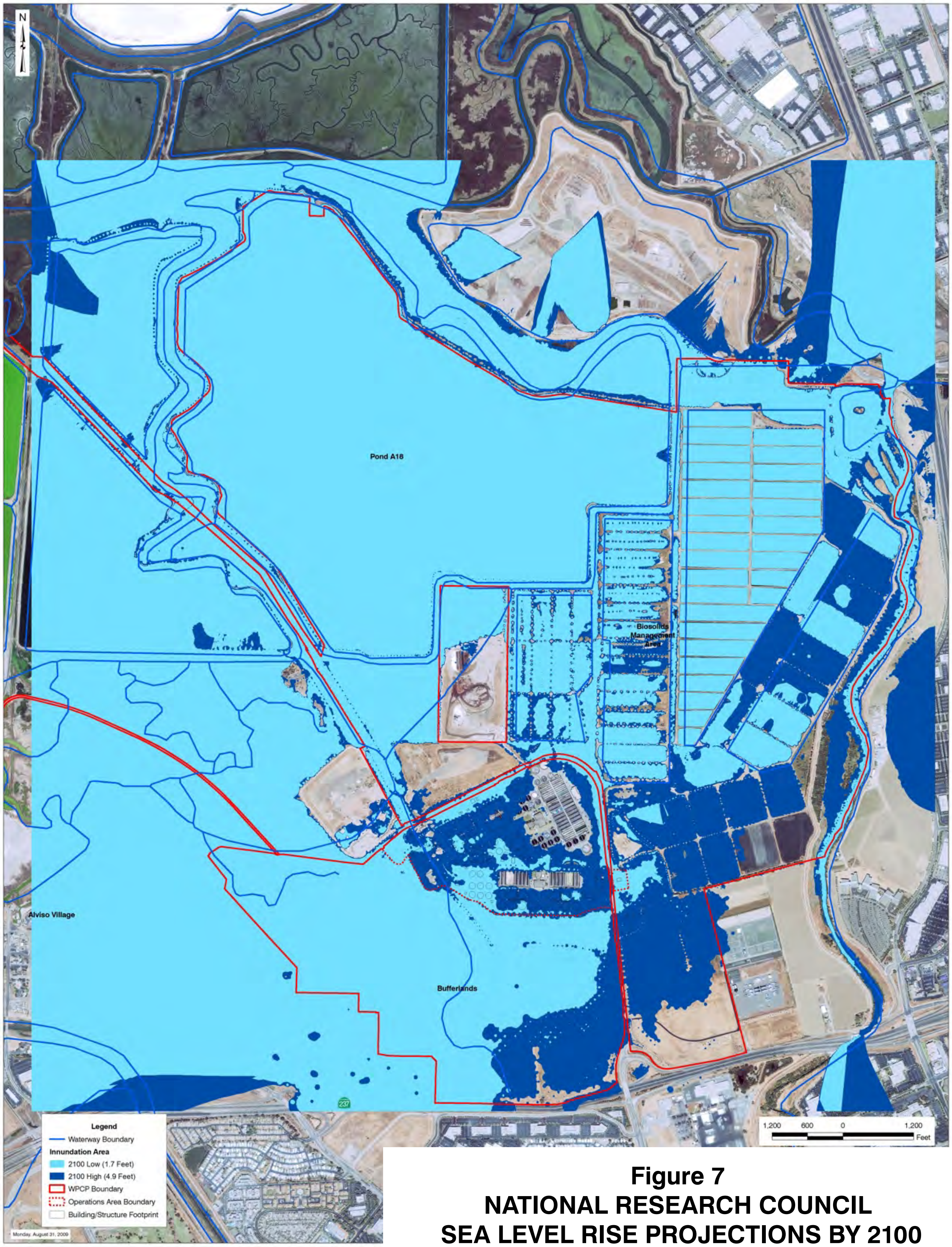

Figure 7
NATIONAL RESEARCH COUNCIL
SEA LEVEL RISE PROJECTIONS BY 2100
PLANT SITE LEVEL
SAN JOSÉ/SANTA CLARA WPCP MASTER PLAN
CITY OF SAN JOSÉ

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- The Nature Conservancy's Climate Wizard: http://www.climatewizard.org/
- San Francisco Bay Hydrodynamics Modeling Project by Stanford University and University of California - Berkeley: http://suntans.stanford.edu/projects/sfbay.php OR http://www.cal-span.org/calspan-media/metadata/COPC/COPC_07-06-14/0607COPC14_SF%20Bay%20Model.pdf
- San Francisco Bay Conservation and Development Commission's (BCDC) international design competition for ideas responding to sea level rise in San Francisco Bay and beyond. http://www.risingtidescompetition.com/risingtides/Home.html
- San Francisco BCDC report, *Living with a Rising Bay: Vulnerability and Adaptation in San Francisco Bay and on the Shoreline*. http://www.bcdc.ca.gov/planning/climate_change/climate_change.shtml
- U.S. Geological Survey's CASCaDE (Computational Assessments of Scenarios of Change for the Delta Ecosystem) Project. http://cascade.wr.usgs.gov/data/Task2b-SFBay/
- The Pacific Institute report, *The Impacts of Sea-Level Rise on the California Coast*, and maps. http://www.pacinst.org/reports/sea_level_rise/#
- Public Policy Institute of California. http://www.ppic.org/main/publication.asp?i=755
- California Natural Resources Agency's report, *2009 California Climate Adaptation Strategy*. http://www.energy.ca.gov/2009publications/CNRA-1000-2009-027/CNRA-1000-2009-027-F.PDF

5.0 SUMMARY & CONCLUSIONS

Figure 1 shows that without the existing levees, portions of the WPCP site are already inundated. The outfall weir is of special concern, since an increase in the head above the outfall weir can result in a decrease of the capacity of the outfall discharge system. In turn, this impacts the capacity of the existing bypass flow capability. In Figures 2 through 7, all three ranges of sea level rise projections (shown in Table 1) result in inundation of the majority of the WPCP site. As a consequence, steps are required to adapt to these impacts.

6.0 RECOMMENDATIONS

Portions of the WPCP site are already below sea level and will be significantly impacted if the existing levees fail. In addition, the projected ranges of sea level rise as presented in Table 1 of this PM (considered a minimum for planning purposes) will only increase this concern.

It is recommended that the sea level rise impacts discussed in this PM be taken into account and potential solutions be addressed as part of the land uses that are developed and proposed for the Land Use Plan. It is also recommended that implementation and operations and maintenance costs be estimated as well.

Figure 8 shows some potential solutions for adapting to sea level rise including levees, berms, sea walls, and graduated beaches with mud flats and upland riparian habitat.

As the South San Francisco Bay Shoreline Study progresses, it is recommended that efforts be taken to coordinate results, specifically with respect to any proposed projects and funding mechanisms. It is also recommended that the projected range of sea level rise be evaluated regularly (at least every five years), as models are improving and producing more accurate results.

Lastly, other countries have already implemented measures for adapting to rising sea levels, including Italy, England, Germany, the Netherlands, and Japan. It is recommended to review the performance of technologies already implemented.

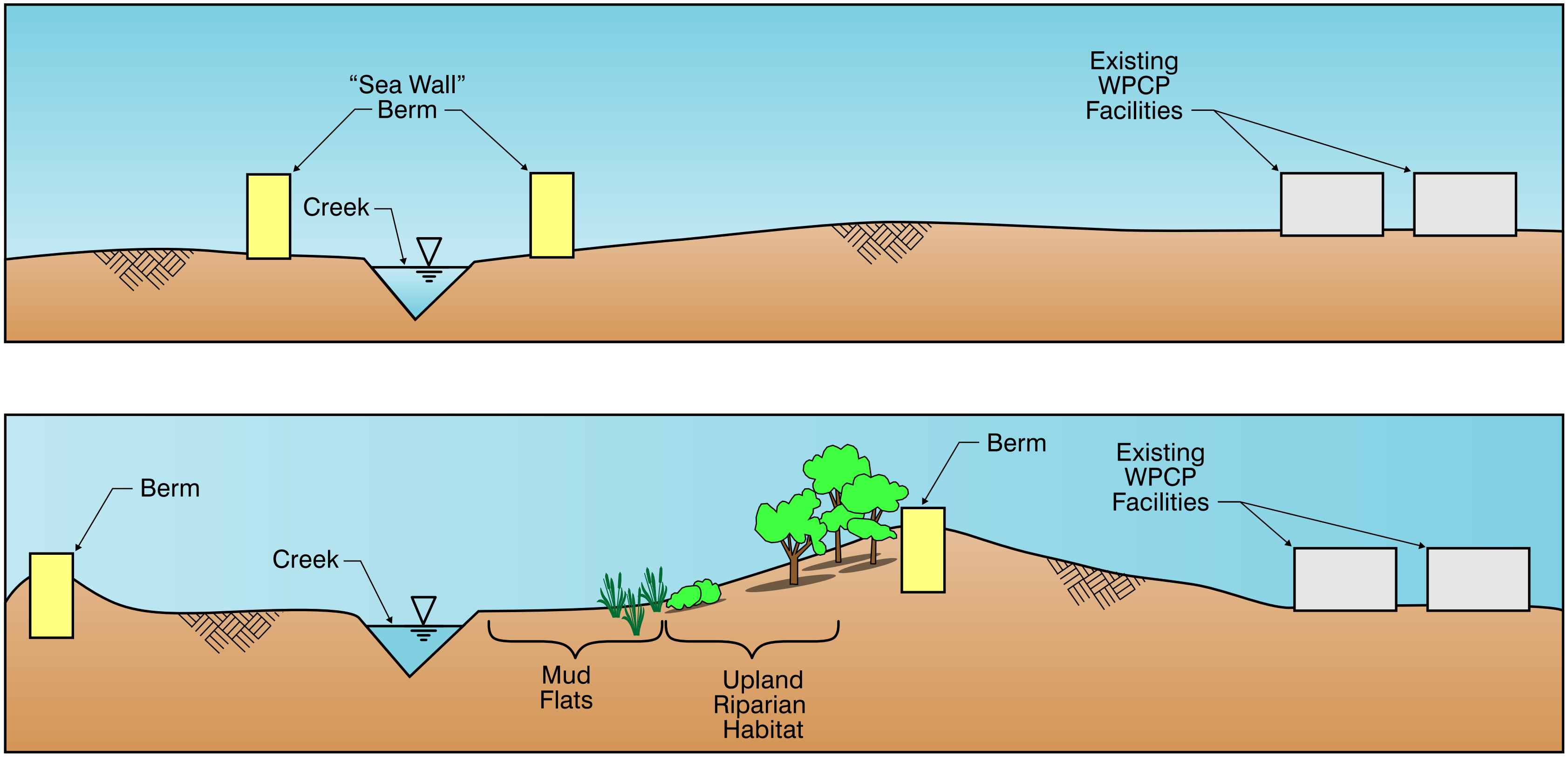

Figure 8
POTENTIAL ADAPTATION OPTIONS AT WPCP FOR FUTURE SEA LEVEL RISE DUE TO GLOBAL CLIMATE CHANGE
SAN JOSÉ/SANTA CLARA WPCP MASTER PLAN
CITY OF SAN JOSÉ

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APPENDIX A - A SEMI-EMPIRICAL APPROACH TO PROJECTING FUTURE SEA-LEVEL RISE

A Semi-Empirical Approach to Projecting Future Sea-Level Rise

Stefan Rahmstorf, *et al.*

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melt fraction will be more gradual, reflecting the gradual increase of water solubility in olivine and orthopyroxene.

Our results therefore support the concept that the low-velocity zone may be related to partial melting (*1*, *2*, *6*). However, even in the absence of melting, the partitioning of water between olivine and orthopyroxene would strongly depend on depth. The high water solubilities in aluminous orthopyroxene at low pressure and temperature will effectively "dry out" olivine, and this may also contribute to a stiffening of the lithosphere. In any case, however, our results imply that the existence of an asthenosphere—and therefore of plate tectonics as we know it—is possible only in a planet with a water-bearing mantle.

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SOM Text
Figs. S1 and S2
References

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A Semi-Empirical Approach to Projecting Future Sea-Level Rise

Stefan Rahmstorf

A semi-empirical relation is presented that connects global sea-level rise to global mean surface temperature. It is proposed that, for time scales relevant to anthropogenic warming, the rate of sea-level rise is roughly proportional to the magnitude of warming above the temperatures of the pre–Industrial Age. This holds to good approximation for temperature and sea-level changes during the 20th century, with a proportionality constant of 3.4 millimeters/year per °C. When applied to future warming scenarios of the Intergovernmental Panel on Climate Change, this relationship results in a projected sea-level rise in 2100 of 0.5 to 1.4 meters above the 1990 level.

Understanding global sea-level changes is a difficult physical problem, because complex mechanisms with different time scales play a role (*1*), including thermal expansion of water due to the uptake and penetration of heat into the oceans, input of water into the ocean from glaciers and ice sheets, and changed water storage on land. Ice sheets have the largest potential effect, because their complete melting would result in a global sea-level rise of about 70 m. Yet their dynamics are poorly understood, and the key processes that control the response of ice flow to a warming climate are not included in current ice sheet models [for example, meltwater lubrication of the ice sheet bed (*2*) or increased ice stream flow after the removal of buttressing ice shelves (*3*)]. Large uncertainties exist even in the projection of thermal expansion, and estimates of the total volume of ice in mountain glaciers and ice caps that are remote from the continental ice sheets are uncertain by a factor of two (*4*). Finally, there are as yet no published physically based projections of ice loss from glaciers and ice caps fringing Greenland and Antarctica.

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For this reason, our capability for calculating future sea-level changes in response to a given surface warming scenario with present physics-based models is very limited, and models are not able to fully reproduce the sea-level rise of recent decades. Rates of sea-level rise calculated with climate and ice sheet models are generally lower than observed rates. Since 1990, observed sea level has followed the uppermost uncertainty limit of the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (TAR), which was constructed by assuming the highest emission scenario combined with the highest climate sensitivity and adding an ad hoc amount of sea-level rise for "ice sheet uncertainty" (*1*).

While process-based physical models of sea-level rise are not yet mature, semi-empirical models can provide a pragmatic alternative to estimate the sea-level response. This is also the approach taken for predicting tides along coasts (for example, the well-known tide tables), where the driver (tidal forces) is known, but the calculation of the sea-level response from first principles is so complex that semi-empirical relationships perform better. Likewise, with current and future sea-level rise, the driver is known [global warming (*1*)], but the computation of the link between the driver and the response from first principles remains elusive. Here, we will explore a semi-empirical method for estimating sea-level rise.

As a driver, we will use the global average near-surface air temperature, which is the standard diagnostic used to describe global warming. Figure 1 shows a schematic response to a step-function increase in temperature, after climate and sea level parameters were at equilibrium. We expect sea level to rise as the ocean takes up heat and ice starts to melt, until (asymptotically) a new equilibrium sea level is reached. Paleoclimatic data suggest that changes in the final equilibrium level may be very large: Sea level at the Last Glacial Maximum, about 20,000 years ago, was 120 m lower than the current level, whereas global mean temperature was 4° to 7°C lower (*5*, *6*). Three million years ago, during the Pliocene, the average climate was about 2° to 3°C warmer and sea level was

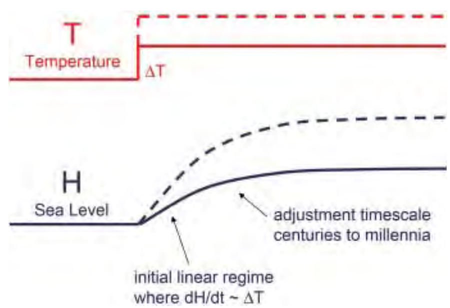

Fig. 1. Schematic of the response of sea level to a temperature change. The solid line and the dashed line indicate two examples with different amplitude of temperature change.

25 to 35 m higher (7) than today's values. These data suggest changes in sea level on the order of 10 to 30 m per °C.

The initial rate of rise is expected to be proportional to the temperature increase

$$dH/dt = a\,(T - T_0) \qquad (1)$$

where H is the global mean sea level, t is time, a is the proportionality constant, T is the global mean temperature, and T_0 is the previous equilibrium temperature value. The equilibration time scale is expected to be on the order of millennia. Even if the exact shape of the time evolution $H(t)$ is not known, we can approximate it by assuming a linear increase in the early phase; the long time scales of the relevant processes give us hope that this linear approximation may be valid for a few centuries. As long as this approximation holds, the sea-level rise above the previous equilibrium state can be computed as

$$H(t) = a\int_{t0}^{t}(T(t') - T_0)\,dt' \qquad (2)$$

where t' is the time variable.

We test this relationship with observed data sets of global sea level (8) and temperature [combined land and ocean temperatures obtained from NASA (9)] for the period 1880–2001, which is the time of overlap for both series. A highly significant correlation of global temperature and the rate of sea-level rise is found ($r = 0.88$, $P = 1.6 \times 10^{-8}$) (Fig. 2) with a slope of $a = 3.4$ mm/year per °C. If we divide the magnitude of equilibrium sea-level changes that are suggested by paleoclimatic data (5–7) by this rate of rise, we obtain a time scale of 3000 to 9000 years, which supports the long equilibration time scale of sea-level changes.

The baseline temperature T_0, at which sea-level rise is zero, is 0.5°C below the mean temperature of the period 1951–1980. This result is consistent with proxy estimates of temperatures in the centuries preceding the modern warming (10), confirming that temperature and sea level were not far from equilibrium before this modern warming began. This is consistent with the time scale estimated above and the relatively stable climate of the Holocene (the past 10,000 years).

In Fig. 3, we compare the time evolution of global mean temperature, converted to a "hindcast" rate of sea-level rise according to Eq. 1, with the observed rate of sea-level rise. This comparison shows a close correspondence of the two rates over the 20th century. Like global temperature evolution, the rate of sea-level rise increases in two major phases: before 1940 and again after about 1980. It is this figure that most clearly demonstrates the validity of Eq. 1. Accordingly, the sea level that was computed by integrating global temperature with the use of Eq. 2 is in excellent agreement with the observed sea level (Fig. 3), with differences always well below 1 cm.

We can explore the consequences of this semi-empirical relationship for future sea levels (Fig. 4), using the range of 21st century temperature scenarios of the IPCC (1) as input into Eq. 2. These scenarios, which span a range of temperature increase from 1.4° to 5.8°C between 1990 and 2100, lead to a best estimate of sea-level rise of 55 to 125 cm over this period. By including the statistical error of the fit shown in Fig. 2 (one SD), the range is extended from 50 to 140 cm. These numbers are significantly higher than the model-based estimates of the IPCC for the same set of temperature scenarios, which gave a range from 21 to 70 cm (or from 9 to 88 cm, if the ad hoc term for ice sheet uncertainty is included). These semi-empirical scenarios smoothly join with the observed trend in 1990 and are in good agreement with it during the period of overlap.

We checked that this analysis is robust within a wide range of embedding periods (i.e., smoothing) of the observational time series. The slope found in Fig. 2 varies between 3.2 and 3.5 mm/year per °C for any embedding period between 2 and 17 years, causing only minor variations in the projected sea level. For short embedding periods (around 5 years), the rate of sea-level rise (Fig. 3, top) closely resembles that shown in (8) with large short-term fluctuations. For embedding dimensions longer than 17 years, the slope starts to decline, because the acceleration of sea-level rise since 1980 (Fig. 3) is then progressively lost by excessive smoothing. For very long embedding periods (30 years), the rate of sea-level rise becomes rather flat such as that shown in (11).

The linear approximation (Eq. 1) is only a simplistic first-order approximation to a number of complex processes with different time scales. The statistical error included in Fig. 4 does not include any systematic error that arises if the linear relationship breaks down during the forecast period. We can test for this systematic error using climate models, if only for the thermal expansion component of sea-level rise that these models capture. For this test, we used the CLIMBER-3α climate model (12), which uses a simplified atmosphere model coupled to a three-dimensional general circulation ocean model with free surface (i.e., that vertically adjusts). We used a model experiment initialized from an equilibrium state of the coupled system in the year 1750 and, with historic radiative forcing, forced changes until the year 2000. After 2000, the model was forced with the IPCC A1FI scenario. The global mean temperature increases by 0.8°C in the 20th century and by 5.0°C from 1990 to 2100 in this experiment.

Temperature and sea-level rise data from this model for the time period 1880–2000 were treated like the observational data in the analysis presented above, and graphs corresponding to Figs. 2 and 3 look similar to those derived from the observational data (figs. S1 and S2). The slope found is only 1.6 mm/year per °C (i.e., half of the observed slope) because only the thermal expansion component is modeled. Using the semi-empirical relation as fitted to the period 1880–2000, we predicted the sea level for the 21st century (fig. S3). Up to the year 2075, this predicted sea level remains within 5 cm of the actual (modeled) sea level. By the year 2100, the predicted level is 51 cm whereas the actual (modeled) level is 39 cm above that of 1990 (i.e., the semi-empirical formula overpredicts sea level by 12 cm).

For the continental ice component of sea-level rise, we do not have good models to test how the

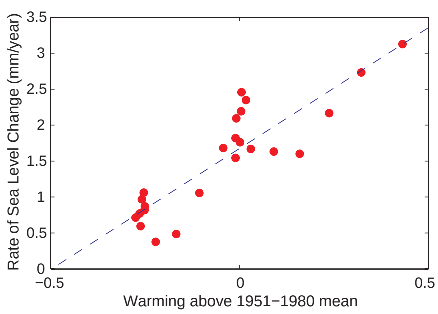

Fig. 2. Correlation of temperature and the rate of sea-level rise for the period 1881–2001. The dashed line indicates the linear fit. Both temperature and sea-level curves were smoothed by computing nonlinear trend lines, with an embedding period of 15 years (14). The rate of sea-level change is the time derivative of this smoothed sea-level curve, which is shown in Fig. 3. Data were binned in 5-year averages to illustrate this correlation.

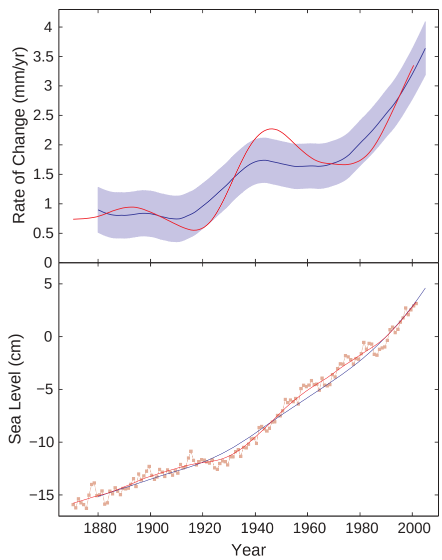

Fig. 3. (**Top**) Rate of sea-level rise obtained from tide gauge observations (red line, smoothed as described in the Fig. 2 legend) and computed from global mean temperature from Eq. 1 (dark blue line). The light blue band indicates the statistical error (one SD) of the simple linear prediction (15). (**Bottom**) Sea level relative to 1990 obtained from observations (red line, smoothed as described in the Fig. 2 legend) and computed from global mean temperature from Eq. 2 (blue line). The red squares mark the unsmoothed, annual sea-level data.

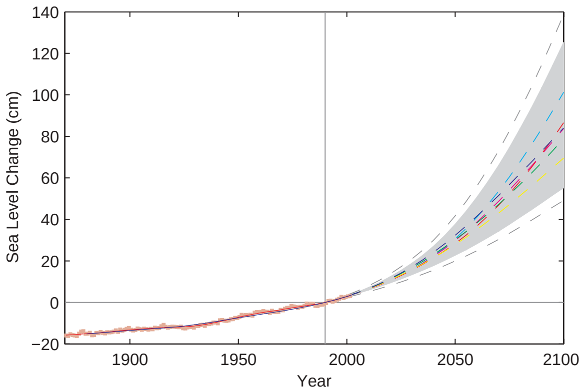

Fig. 4. Past sea level and sea-level projections from 1990 to 2100 based on global mean temperature projections of the IPCC TAR. The gray uncertainty range spans the range of temperature rise of 1.4° to 5.8° C, having been combined with the best statistical fit shown in Fig. 2. The dashed gray lines show the added uncertainty due to the statistical error of the fit of Fig. 2. Colored dashed lines are the individual scenarios as shown in (*1*); the light blue line is the A1FI scenario, and the yellow line is the B1 scenario.

linear approximation performs, although the approximation is frequently used by glaciologists ("degree-days scheme"). Given the dynamical response of ice sheets observed in recent decades and their growing contribution to overall sea-level rise, this approximation may not be robust. The ice sheets may respond more strongly to temperature in the 21st century than would be suggested by a linear fit to the 20th century data, if time-lagged positive feedbacks come into play (for example, bed lubrication, loss of buttressing ice shelves, and ocean warming at the grounding line of ice streams). On the other hand, many small mountain glaciers may disappear within this century and cease to contribute to sea-level rise. It is therefore difficult to say whether the linear assumption overall leads to an over- or underestimation of future sea level. Occam's razor suggests that it is prudent to accept the linear assumption as reasonable, although it should be kept in mind that a large uncertainty exists, which is not fully captured in the range shown in Fig. 4.

Regarding the lowest plausible limit to sea-level rise, a possible assumption may be that the rate shown in Fig. 3 stops increasing within a few years (although it is difficult to see a physical reason for this) and settles at a constant value of 3.5 mm/year. This implies a sea-level rise of 38 cm from 1990 to 2100. Any lower value would require that the rate of sea-level rise drops despite rising temperature, reversing the relationship found in Fig. 2.

Although a full physical understanding of sea-level rise is lacking, the uncertainty in future sea-level rise is probably larger than previously estimated. A rise of over 1 m by 2100 for strong warming scenarios cannot be ruled out, because all that such a rise would require is that the linear relation of the rate of sea-level rise and temperature, which was found to be valid in the 20th century, remains valid in the 21st century. On the other hand, very low sea-level rise values as reported in the IPCC TAR now appear rather implausible in the light of the observational data.

The possibility of a faster sea-level rise needs to be considered when planning adaptation measures, such as coastal defenses, or mitigation measures designed to keep future sea-level rise within certain limits [for example, the 1-m long-term limit proposed by the German Advisory Council on Global Change (*13*)].

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15. The statistical error was calculated by means of the Matlab function "polyval" for the linear fit shown in Fig. 2.
16. The author thanks J. Church for providing the observational data and M. Stöckmann for the model data. They as well as J. Gregory and B. Hare are thanked for valuable discussions.

Supporting Online Material
www.sciencemag.org/cgi/content/full/1135456/DC1
Figs. S1 to S3

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Nonequilibrium Mechanics of Active Cytoskeletal Networks

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Cells both actively generate and sensitively react to forces through their mechanical framework, the cytoskeleton, which is a nonequilibrium composite material including polymers and motor proteins. We measured the dynamics and mechanical properties of a simple three-component model system consisting of myosin II, actin filaments, and cross-linkers. In this system, stresses arising from motor activity controlled the cytoskeletal network mechanics, increasing stiffness by a factor of nearly 100 and qualitatively changing the viscoelastic response of the network in an adenosine triphosphate–dependent manner. We present a quantitative theoretical model connecting the large-scale properties of this active gel to molecular force generation.

Mechanics directly control many functions of cells, including the generation of forces, motion, and the sensing of external forces (*1*). The cytoskeleton is a network of semiflexible linear protein polymers (actin filaments, microtubules, and intermediate filaments) that is responsible for most of the mechanical functions of cells. It differs from common polymer materials in both the complexity of composition and the fact that the system is not at thermodynamic equilibrium. Chemical nonequilibrium drives mechanoenzymes (motor proteins) that are the force generators in cells. The cytoskeleton is thus an active material that can adapt its mechanics and perform mechanical tasks such as cell locomotion or cell division.

Here, we show how nonequilibrium motor activity controls the mechanical properties of a simple three-component in vitro model cytoskeletal network. The nonequilibrium origin of this active control mechanism can be seen directly in the violation of a fundamental theorem of statistical physics, the fluctuation-dissipation (FD) theorem, which links thermal fluctuations of systems to their response to external forces. The FD theorem is a generalization of Einstein's description of Brownian motion (*2*). Although it is valid only in equilibrium, its possible extension to out-of-equilibrium systems such as granular materials and living cells has been debated (*3*–*5*). Prior studies in cells have suggested violations of the FD theorem (*3*), but this has not been directly observed. We show that an in vitro model system consisting of a cross-linked

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APPENDIX B - DELTA VISION BLUE RIBBON TASK FORCE LETTER 2007

CALFED BAY-DELTA PROGRAM

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P. Joseph Grindstaff,
Director

September 6, 2007

To: John Kirlin, Executive Director
Delta Vision Blue Ribbon Task Force

From: Mike Healey
CALFED Lead Scientist

RE: PROJECTIONS OF SEA LEVEL RISE FOR THE DELTA

Recognizing that sea level rise would likely be an uncertain but contentious issue for the Delta Vision Blue Ribbon Task Force (Task Force) to address, the Science Program requested that the Independent Science Board (ISB), examine the current literature and offer comments, and if possible, recommendations on sea level rise to aid the Task Force. The response of the ISB is attached to this memo. In my opinion, the ISB has provided a very helpful summary of the extensive and confusing science around climate related sea level rise. They also make specific recommendations concerning which of the many projections of sea level rise should guide the Task Force in developing its vision.

Key points made in the ISB memo are first, that current projections of sea level rise by the Intergovernmental Panel on Climate Change (IPCC), are likely very conservative as the models used to develop these projections underestimate recent measured sea level rise. Second, extrapolation from empirical models of sea level rise yields significantly higher estimates of sea level over the next few decades than the IPCC projections. The ISB suggests that the empirical projections are probably a better basis for short to mid term planning. And third, that neither approach to estimating future sea levels takes account of melting of ice in Greenland and Antarctica, which recent studies suggest is accelerating.

Based on their analysis, the ISB suggests that a mid-range rise in sea level this century is likely to be at least 70-100 cm, significantly greater (~200 cm) if ice cap melting accelerates. While the absolute rise is alarming enough, even more alarming is the fact that only a few centimeters of sea level rise will greatly increase the frequency, intensity and duration of extreme water levels. It is these events that pose the greatest risk to Delta levees, infrastructure and private property.

The ISB assessment of rates and magnitude of sea level rise greatly increases one of the key risk factors in decisions about land use, levee integrity, water conveyance, public safety and other important considerations in the Delta Vision. In my view, it is essential that all the current planning processes take the likelihood of greater sea level rise into account. This is particularly true for the Delta Risk Management Strategy

(DRMS) study, which did not factor any sea level rise into its assessment of levee needs in its draft Phase 2 report.

I trust that you will convey the ISB memo to the Task Force. I will copy it to the DRMS Technical Advisory Committee, The Bay Delta Conservation Plan Steering Committee Members (BDCP), the Ecosystem Restoration Program (ERP) Implementing Agency Managers and other interested parties. Please let me know if you or the Task Force have any questions.

Sincerely,

Mike Healey
CALFED Lead Scientist

Attachment

cc: Joe Grindstaff, Director, CALFED
CALFED Deputy Directors
DRMS Technical Advisory Committee
BDCP Steering Committee Members
ERP Implementing Agency Managers

September 6, 2007

TO: Michael Healey, Lead Scientist
CALFED Bay-Delta Program

FROM: Jeffrey Mount, Chair
CALFED Independent Science Board

RE: Sea Level Rise and Delta Planning

In July of this year, you asked that the Independent Science Board (ISB) examine the array of sea level rise projections available in published reports and, based on current scientific understanding, advise the Science Program about which projections are most appropriate for incorporating into on-going planning for the Delta. The ISB discussed this issue at their August, 2007 meeting and have developed recommendations detailed in this memo. It is important to note that this is not an assessment of the state of sea level rise science, but is intended to highlight the large uncertainty in sea level rise projections and recommend ways to incorporate this uncertainty into planning.

Background

Sea level plays a dominant role in the San Francisco Bay-Delta. Water surface elevations and associated fluctuations due to tides, meteorological conditions and freshwater inflows drive Bay-Delta hydrodynamics. Hydrodynamics, in turn, dictate the location and nature of physical habitat, the quantity and quality of water available for export, and the design of the flood control/water supply infrastructure. Change in sea level has the potential to substantially alter Bay-Delta conditions and to constrain future management options.

Global sea level rise is a well-documented phenomenon, both in the paleoclimatic record as well as the historical record. Tidal gage records indicate that sea level during the 20th century has risen an average of 2mm/yr (.08 in) during a period of 0.7°C warming. Recent studies suggest that since 1990, global sea level has been rising at a rate of approximately 3.5 mm/yr (.14 in/yr)[1]. The cause of sea level rise stems from two processes: 1) thermal expansion of sea water as the surface layer warms, and 2) increase in mass of sea water associated with melting of land-based glaciers, snowfields and ice sheets.

Recent research supported by the California Energy Commission[2] (CEC) and continued under the CALFED-sponsored CaSCADE program, shows that sea level

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[1] Church, J.A and N.J. White 2006 *A 20th Century Acceleration in Global Sea-Level Rise* Geophysical Research Letters, v. 33, article no. L01602
[2] Cayan, D. *et al.* 2006 *Projecting Future Sea Level* California Climate change Center White Paper CEC-500-2005-202-SF Accessed at http://www.climatechange.ca.gov/research/climate/projecting.html

rise will impact the Delta principally by increasing the frequency, duration and magnitude of water level extremes. These extreme events occur at various periodicities and are associated with high astronomical tides and Pacific climate disturbances, such as El Niño. The CEC study showed that under moderate climate warming and a sea level rise of 3 mm/year (12 in./century), extreme high water events in the Delta--those that exceed 99.99% of historical high water levels and severely impact levees--increases from exceptionally rare today to an average of around 600 hours/year by 2100. This work also showed that roughly 100 of these hours would coincide with very high runoff conditions, further amplifying the impacts of sea level rise. In sum, even under modest sea level rise and climate warming projections, extreme high water levels that are considered rare today will likely be very common by the end of this century.

Sea Level Rise Projections

Early in 2007, the Intergovernmental Panel on Climate Change (IPCC) released its latest assessment of the scientific basis for projections of future climate conditions, including global average sea level rise[3]. As noted in the press, in comparison with the IPCC's 2001 assessment, the latest sea level rise projections appear to have narrowed the range of potential sea level rise and lowered the magnitude of projected sea level rise. This was viewed by some outside of the IPCC as indication that: 1) uncertainty regarding sea level rise had decreased and 2) the problem of sea level rise itself appeared to be less than originally stated. However, both the methods used to derive the IPCC 2007 sea level projections, along with extensive new published research in 2007 suggest that this more optimistic view of future sea level rise may be unwarranted.

The IPCC projections are based on physical models that attempt to account for thermal expansion of the oceans and storage changes in land-based glaciers and ice fields. These models, by necessity, simplify the complex processes of ocean circulation and ice melting. The IPCC midrange projection for sea level rise this century is 20-43 cm (8-17 inches), with a full range of variability of 18-59 cm (7-23 inches). The range of variability reflects model differences and uncertainties as well as differences in greenhouse gas emission scenarios. The IPCC model effort is consensus-based, reflecting the agreement of numerous international scientists.

During the past year, there have been major advances in the science of sea level rise. Paradoxically, these advances have increased the uncertainty of projections in sea level rise, at least temporarily. These advances have also led to strong criticism of the approach that the IPCC used in establishing its projections[4]. One criticism is that the models used to project sea level rise tend to under-predict historical sea level rises, most notably failing to capture recent increases. Indeed, models that use empirical historical relationships between global temperatures and sea level rise perform better

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[3] IPCC 2007 *Climate Change 2007: The Physical Basis—Summary for Policymakers* Accessed at http://www.ipcc.ch/SPM2feb07.pdf

[4] summary in Kerr 2007 *Science NOW* Accessed at http://Sciencenow.sciencemag.org/cgi/content/full/2007/215/2

than the IPCC 2007 models[5]. When applied to the range of emission scenarios used by IPCC 2007, empirical models project a mid-range rise this century of 70-100 cm (28-39 in.) with a full range of variability of 50-140 cm (20-55 in.), substantially higher than IPCC 2007 projections. However, foremost among the criticisms is the failure of the IPCC to include dynamical instability of ice sheets on Greenland and Antarctica in their projections for sea level rise.

Melting of the ice sheets of Greenland and Antarctica has the potential to raise sea level 70 m. For most of the 20th century, the ice sheets have remained relatively stable, with melting contributing a minor fraction to sea level rise. However, during the past year numerous studies have demonstrated that the mass balance (input from snowfall versus losses due to melting or detachment) of these ice sheets is shifting toward more rapid loss, most likely in response to warming of the atmosphere and oceans[6]. The recent rate of mass loss in these ice sheets exceeds current physical model predictions. As many authors have pointed out, increased rates of ice sheet flow involving meltwater lubrication of the ice sheet bed or the removal of buttressing ice shelves, may be accelerating the rate of ice loss on Antarctica and Greenland. The IPCC 2007 report explicitly chose not to incorporate the uncertainty associated with this process into their sea level projections. Recent publications that have examined this issue suggest that, under business as usual emissions scenarios, dynamical instability of ice sheets may add as much as 1 m (39.4 in) to sea level rise by 2100[7].

Recommendations

The ability of current physical models to project sea level rise are limited. This stems in part from our poor understanding of and current inability to model the response of Greenland and Antarctic ice sheets to atmospheric and oceanic warming. Given the costs associated with levee failure in the Delta, the ISB feels it would be a mistake for the various planning processes now underway (BDCP, Delta Vision, DRMS) to base their planning on the conservative 2007 IPCC estimates of sea level rise. Although there is some disagreement about mechanisms of ice sheet disintegration, current advances in understanding coupled with new physical measurements all point toward the same conclusion: dynamical instability of ice sheets will likely contribute significantly to future sea level rise, with the potential for very rapid increases of up to a meter (39.4 in.) by 2100 from ice sheets alone. For this reason, the range of sea level projections based on greenhouse gas emission scenarios contained in the IPCC 2007 report should be viewed, at best, as minima for planning purposes.

The board recommends that planning efforts use three approaches to incorporate sea level rise uncertainty. First, given the inability of current physical models to accurately simulate historic and future sea level rise, until future model refinements

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[5] Rahmstorf, S 2007 *A Semi-Empirical Approach to Projecting Sea-Level Rise* Science v. 315, pp. 368-370.

[6] Shepherd, A. and D. Wingham 2007 *Recent Sea-Level Contributions of the Antarctic and Greenland Ice Sheets* Science, v. 315, pp. 1529-1532.

[7] Hansen J *et al* 2007 *Dangerous human-made interference with climate: a GISS modelE study* Atmospheric Chemistry and Physics, v. 7, pp.2287-2312.

are available, it is prudent to use existing empirically-based models for short to medium term planning purposes. The most recent empirical models project a mid-range rise this century of 70-100 cm (28-39 in.) with a full range of variability of 50-140 cm (20-55 in.). It is important to acknowledge that these empirical models also do not include dynamical instability of ice sheets and likely underestimate long term sea level rise. Second, we recommend adopting a concept that the scientific and engineering community has been advocating for flood management for some time. This involves developing a system that can not only withstand a design sea level rise, but also minimizes damages and loss of life for low-probability events or unforeseen circumstances that exceed design standards. Finally, the board recommends the specific incorporation of the potential for higher-than-expected sea level rise rates into long term infrastructure planning and design. In this way, options that can be efficiently adapted to the potential for significantly higher sea level rise over the next century will be favored over those that use "fixed" targets for design. After all, the current debates over uncertainty in sea level rise are less about how much rise is going to occur and more about when it is going to occur.