Predictions about the greenhouse effect are creating a rising tide of concern.

ROBERT G. DEAN

THE ULTIMATE HIGH TIDE

Written into the geological record is evidence of substantial increases in the sea level since the last ice age ended some 20,000 years ago. Over the past 3,000 years, sea level has been more or less stable, fluctuating within 6 ft of the present level. On time scales more on the order of engineering projects, over the past century there has been a world-wide increase of several inches in the level of the sea. Now we may be on our way to a significant rise in the level of the oceans. If true, this rising tide may create a host of problems on the world's coasts.

Unprecedented consumption of fossil fuels and clearing of vegetation have spurred interest in the so-called "greenhouse effect." Under this scenario, a build-up of CO_2 and other gases in the atmosphere would trap heat next to the earth. This heat would increase the level of the sea by melting the polar ice caps and thermally expanding the upper layers of the ocean. Several studies have concluded that this is probable, however there are substantial differences in the predicted rates of increase in the sea level.

The rate at which the sea rises or falls is extremely important in planning appropriate engineering responses. Clearly the knowledge that sea level would rise substantially over the next 20 to 40 years would affect the planning and design of coastal projects.

Tide gage data measuring this rise are available for approximately the last century or so. However, these data provide the sea level relative to the base on which the gage is attached, and the land may either be sinking or rising. For example, long-term data from tide gages in Juneau, Alaska indicates that the relative sea level is actually lowering at a rate of 4.5 ft/century. The relative drop in the sea level in Juneau is due to the melting of glaciers, which reduced the weight on the land and allowed it to rise.

In addition to the complication of changing land elevations, the use of tide gage data is weakened due to the sparcity of tide gages in the southern hemisphere. Regardless of these limitations, careful and sophisticated analyses of tide gage studies have concluded that the sea has risen approximately 4.5 inches in the past century.

Another indicator of the severity of the greenhouse effect is carbon dioxide levels in the atmosphere. Recent examinations of these levels have demonstrated the probability of substantial increases in future rates of sea level rise.

Records from the top of Mauna Loa, Hawaii indicate that, in addition to substantial seasonal variations, there is an upward trend in mean CO_2 concentration, with an increase from 315 ppm to 340 ppm occurring from 1958 to 1981. A similar increase was noted from an Antarctic observation station. In addition to these documented increases, a rise of 17 ppm is estimated to have occurred from the 1870s to 1958.

A WARMER FUTURE?

Attempts to determine whether world-wide temperatures are increasing have not been entirely

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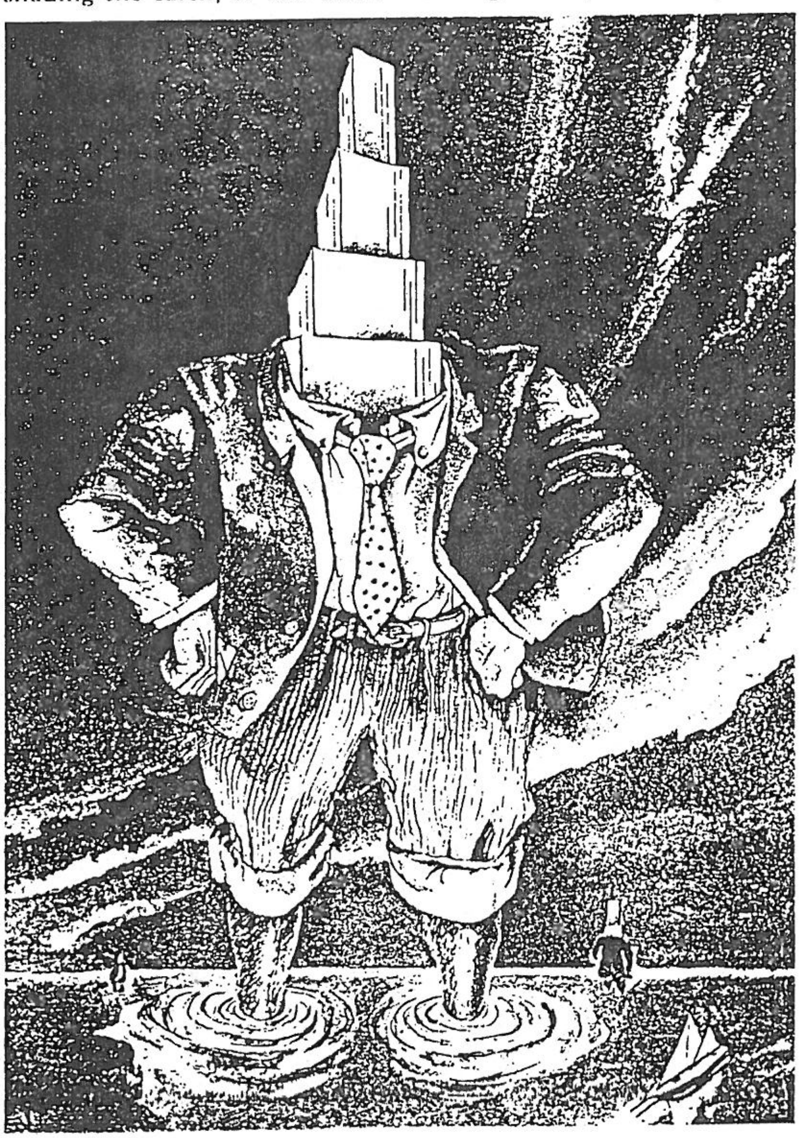
conclusive. Many of the land temperature monitoring stations are located near cities where anomalies exist. Moreover, although sea surface temperatures have been' monitored for the past 50 years or so, the procedures and standards for these measurements have evolved making past results questionable. Nevertheless, the weight of this evidence supports an increase in world-wide temperature over the last century.

Confronted with the difficulty of predicting future changes in temperature and sea level based only on the historical record, substantial efforts have been directed toward the development of models to make future estimates. The EPA's model uses various scenarios of consumption of fossil fuel, clearing of vegetation and the effects of volcanoes, which can either cool the earth if the material is ejected to very high elevations, thereby shading the earth, or can warm the earth if the material ejected is at a sufficiently low elevation to absorb solar radiation within the earth's atmosphere. Using the model and conservative assumptions, sea level increases of about 1.5 ft can be expected by the year 2100. Using extreme estimates, the EPA model predicts sea level rises as great as 11.5 ft.

The Polar Research Board of the National Research Council recently completed its projection of sea level rise by the year 2100. Its estimates range widely from approximately 2 ft to 5 ft, including an estimated value for the thermal expansion of the seawater.

Roger Revelle, as part of a study for the National Research Council, considered the effects of a mean world-wide temperature increase of 5.5F. He predicted it would yield a rise in the sea level in excess of 2 ft by 2085, with approximately 1 ft resulting from the melting of the polar ice caps. The remainder will be due to thermal expansion of the ocean. The potential error on these estimates is given as "at least 25%." There is also the possibility that the western Antarctic ice sheet is unstable and may disintegrate, raising water levels up to 20 ft over a period of about two centuries, causing substantial flooding in many coastal states.



Clearly more research is warranted to improve our predictions of future sea level rise and the associated effects on natural processes and engineered works. Analogs which may be studied are the abnormally high water levels currently plaguing the Great Lakes and the Great Salt Lake. Much more needs to be known about the natural responses to sea level rise, including beach erosion, salt water encroachment, marsh survival, etc.

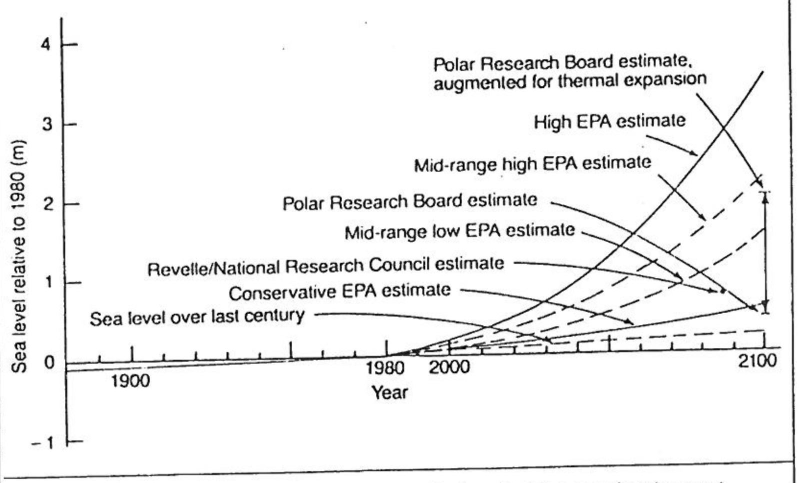
PUTTING THE BRAKES ON

We *do* know that the causes of the sea level rise are so pervasive and affect so many people and nations, that eliminating or significantly reducing man-related components are probably impractical. Nuclear energy, once considered as a relatively safe, inexpensive and inexhaustible source of energy, could reduce the emissions of CO_2 into the atmosphere. At present, approximately 20% of the United States' electrical energy generated is by nuclear power plants. However, due to the delays and increased costs of construction, it is highly doubtful that, within the next few decades, nuclear energy will command an increased share of world-wide energy production.

The banning of the use of chlorofluorocarbons (CFOs), which, like carbon dioxide, trap heat in the atmosphere, would be met by considerable resistance. At present only two countries do not allow the use of CFOs in spray cans.

Coastal communities can take a hand in their destinies, by evaluating the degree to which their removal of groundwater or hydrocarbons is contributing to the subsidence of their land. If significant, long-range plans should be explored to alter these patterns. In the case of Terminal Island, Calif., where the production of hydrocarbons had caused an alarming subsidence exceeding 20 ft, one barrel

FIGURE 1.
GETTING IN DEEPER?



Using 1980 as a baseline, the chart shows the level of the sea for the past century, and projects it into the future using a number of different models.

of seawater is pumped into the ground to replace each barrel of petroleum removed. This practice even caused some "rebound" of the land elevation.

HIGH AND DRY

If the rise of sea level is not preventable, at least for the next century or so, it will be necessary to alter engineering practices along the coastal zone. A wide range of alternatives exist, including retreating as the sea encroaches and holding the line by either soft approaches, like the addition of sand, or by hardening the shoreline.

Consider the case of a sandy shoreline which has value for recreation and/or storm protection of the upland structures. As sea level rises, the beach will tend to erode to maintain a so-called "equilibrium profile" relative to the elevated water level. Thus sand is transported offshore to increase the bottom elevation by an amount equal to the sea level rise.

The sand can be replenished, but communities will face the question, "Should it?" Whether or not beach nourishment is a feasible response to the rise in the level of the sea depends on the recreational value of the beaches and the value of the upland investment. Typically, for each unit the sea level rises, the shoreline recedes by a factor of 50 to 100. The cost of replacing this sand is approximately $10.00/cu yd. If a community dependent on beach-related tourism can direct, say 20% of its disposable income to stabilize a beach, it would probably be warranted. However, if this goal would require 100% or 150% of the disposable income, then clearly other strategies would be more appropriate. Communities with less disposable income, or those less dependent on the shoreline, may retreat as the shoreline advances.

In the State of Florida the cost of undeveloped beach property ranges from approximately $2,000/ft to $20,000/ft. The cost of maintaining the beach may be only .02% to 3.5% of the value of the land. This estimate does not consider that the sea level may rise enough to cause frequent flooding. This would necessitate the construction of dikes and clearly would require a higher estimate. Within the next 50 years, dikes will be required in very few locations along the United States coastline.

Increased flooding potential, however, will occur in low lying areas. Some United States cities, for example, Charleston, S.C. and several communities along the Texas coast, currently experience some inconvenience during spring tides. These difficulties would be exacerbated substantially by relatively small increases in sea level. The engineering options available for reducing the flood potential include dikes to protect the threatened areas and, in some cases, increased elevations, for example, on key roadways.

In addition, water supplies for some cities on or near the coast often are obtained from rivers sufficiently upland of substantial salt water penetration. The level of salt water penetration is obviously related to sea level. As an example, a sea level rise of 3 ft may result in an additional salt water encroachment of about 6 miles. In cases where stratification exists, it may be possible to limit the contamination by salt water in the lower layers through the construction of underwater sills. Where no stratification exists, relocation of the intake for potable water supplies could be required.

The responsible approach for civil engineering design incorporating the effects of sea level rise appears to be awareness of the near-certainty of continued sea level rise and the uncertainty and range of estimates of future rates. Sensitivity calculations of the consequences and probabilities of various scenarios will aid in the creation of optimal designs. Constructed projects should be reviewed periodically to determine whether updated measurements and projections of sea level rise rates warrant retro-fitting.

It appears clear that there will be an increased rate of sea level rise, but the quantification of that rate is far from definite. To adopt a position that sea level will rise as rapidly as some of the higher estimates would be as irresponsible as that there will be no sea level rise. Designing in the face of uncertainty is not new to the civil engineering profession. To quote Dr. William A. Nieremberg, Chairman of the National Academy of Sciences Committee on Carbon Dioxide Assessment, "We believe there is reason for caution, not panic."

Robert G. Dean, M. ASCE, is director of the Division of Beaches and Shores for the Florida Department of Natural Resources, Tallahassee, and is a graduate research professor in Coastal and Oceanographic Engineering at the University of Florida in Gainesville.

METRICS
1 ft=.3 m; 1 in.=2.5 cm.