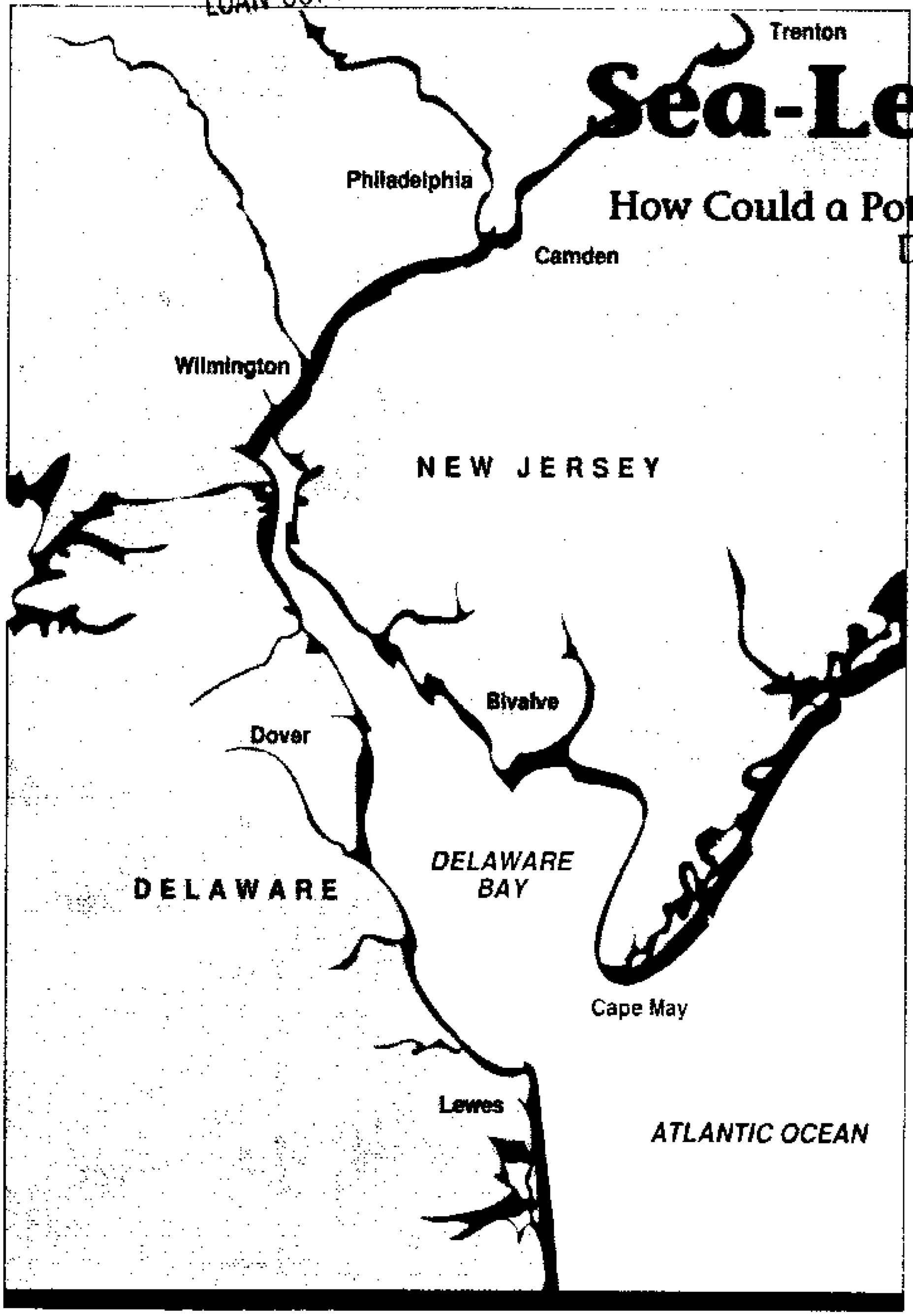
DELAWARE ESTUARY SITUATION REPORTS

This series of reports is devoted to discussion of current issues relevant to conservation, use, and development of Delaware Estuary resources, and of concern to managers, decision makers, and the general public.

Sea-Level Rise

How Could a Potential Rise in Sea Level Due to Global Warming Affect Delaware?

Pat Marx Washburn



The Delaware Estuary, a multi-purpose bistate resource.

Our atmosphere is largely transparent to the solar radiation that warms the Earth's surface. But rather than allowing all the warmth to be radiated back into space, clouds and certain gases naturally present in the atmosphere act remarkably like glass in a greenhouse, retaining part of the heat by absorption and reradiation (Figure 1). Without this natural phenomenon known as the greenhouse effect, the Earth's surface temperature would be 60°F colder than it is presently (Barth and Titus 1984).

Although human beings are not the primary cause of the greenhouse effect, many of our activities may enhance it, thereby altering global climate. Scientists who believe the climate balance will shift toward warmer temperatures see rising sea levels as a major consequence of such a change. The intent of this report is to inform the reader of how a rise in sea level may affect the state of Delaware, if indeed predictions of global warming prove correct. Those responsible for managing our natural resources and developed communities should neither ignore nor overreact to potential scenarios for climate warming or sea-level rise. Instead, they should be aware of the range of possibilities for the years ahead as a basis for precautionary action.

Ms. Washburn received her master's degree in geology from the University of Delaware in 1981. Her interests are in coastal geology and modern coastal processes. She has worked in the petroleum industry and is presently an independent consultant.

University of Delaware
Sea Grant College Program

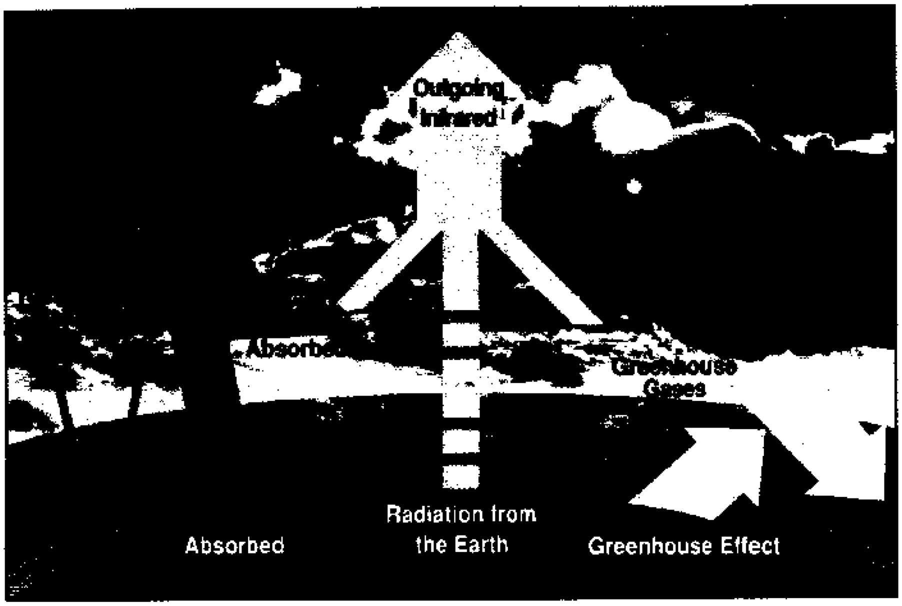


Figure 1. The Greenhouse Effect. *Clouds and particles in the atmosphere reflect about 30% of the incoming solar energy. The Earth's atmosphere and surface absorb and re-emit the remaining 70%. Clouds and greenhouse gases trap most of the Earth's surface radiation because it is a longer wavelength than radiation from the sun. (Adapted from Graedel and Crutzen 1989.)*

Greenhouse Gases

Carbon dioxide (CO_2) is the most prevalent gas contributing to the greenhouse effect. The average concentration of CO_2 in the atmosphere has increased from 290 to 350 parts per million over the last 100 years (Graedel and Crutzen 1989). Figure 2 shows the long-term increase in CO_2 concentration measured at Mauna Loa, Hawaii, over the past 30 years. Two major human sources of atmospheric CO_2 are fossil fuel combustion and deforestation. Deforestation not only adds CO_2 directly to the atmosphere through burning, but also removes the natural CO_2 absorption that plants supply.

Industry and agriculture produce additional greenhouse gases such as methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs). Although these gases constitute a relatively small proportion of the atmosphere, they are expected to have a major effect on climatic warming because they trap heat so efficiently. Sources of these gases include production and use of fossil fuels, fertilizers, aerosol sprays, refrigerants, and foams. Landfills, livestock, rice paddies, and deforestation by burning also contribute significant amounts of these trace greenhouse gases.

Global Warming

The general consensus among scientists is that an increase in the concentration of greenhouse gases will change the global climate, likely warming it. However, opinions on the rate and magnitude of the change are highly variable due to uncertainties about how various climatic feedback mechanisms may affect the ultimate outcome. These mechanisms are aspects of climate which would probably change as a result of an initial warming and therefore affect the final equilibrium temperature. For example, the amount of water vapor in the atmosphere could increase with initial warming, resulting in even greater heat retention. Also, the reduction of polar ice caps would decrease the amount of radiation reflected back to space, causing additional warming.

Two feedback mechanisms are not as well understood: clouds and oceans. The lack of information about how clouds will be affected by global warming and about the amount of heat the oceans can absorb and distribute lends a tremendous degree of uncertainty to models and predictions of future global climate. Some scientists have proposed, for example, that clouds may counteract the indicated global warming by reflecting incoming radiation from the sun, resulting in no change or even a cooling effect.

However, the majority of researchers agree that an increase in concentrations of greenhouse gases will cause warming of the Earth's atmosphere. Two National Research Council studies predict a doubling of CO_2 concentrations by the year 2100 (Climate Research Board 1979; 1982). These studies conclude that the equilibrium global surface warming from a doubling of CO_2 will be between 2.7°F and 8.1°F. An Environmental Protection Agency (EPA) study predicts a 3.6°F rise in temperature by the year 2040 (Seidel and Keyes 1983). The impact of trace gases could shorten the time frame even further. Other estimates tend to fall within the range of the studies cited.

According to another 1983 EPA report, the expected global warming will be rapid relative to historical rates of temperature change. In the last 2 million years, the Earth has never been more than 4°–5°F warmer than it is today. Since the Wisconsin glaciation peaked 18,000 years ago, the Earth has warmed about 7°F and, in the last century, about 0.7°F. Warming in the next century could be 10 times as rapid as the historical warming trend (Hoffman, Keyes, and Titus 1983).

Global Sea-Level Rise

If concentrations of atmospheric CO_2 and other greenhouse gases continue to increase and do create large-scale global warming, that warming is expected to cause a rise in global eustatic sea level. Eustatic sea level reflects a change in the volume of ocean water or the shape of the ocean floor, while relative sea level includes the effects of land movement and sediment compaction as well as eustatic change. Eustatic sea level is often difficult to measure apart from relative sea level.

Changes in global eustatic sea level due to global warming are dependent on two factors: (1) ocean temperature, which affects the density and volume of water, and (2) the amount of water in the ocean basins. In the first case, as surface temperatures rise, the volume of water in the oceans would increase by thermal expansion. In the second case, warming of the atmosphere would result in discharge of melted, land-based, glacial snow and ice

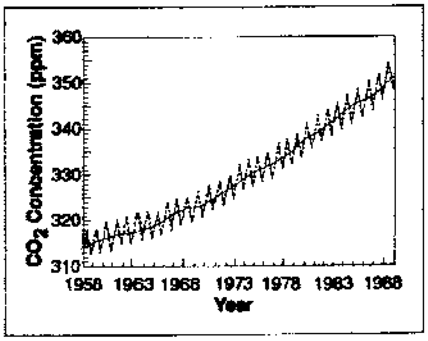


Figure 2. Monthly Average Carbon Dioxide Measurements at Mauna Loa, Hawaii. *The annual fluctuations reflect seasonal changes in CO_2 uptake by plants. (Adapted from Keeling et al. 1989.)*

into the sea. In addition, the amount of seawater could be affected by altered precipitation patterns resulting from climatic change. However, potential changes in the net amount and distribution of rain and snowfall are not yet predictable.

The basis for expecting a rise in sea level lies in understanding past changes in climate and sea level. Throughout geologic history, warmer climatic periods have indeed been accompanied by higher stands of sea level. When glaciers covered a large part of the northern hemisphere 18,000 years ago, sea level was about 300 feet below present (Hull and Titus 1986). A number of published sea-level curves confirm that since the end of the last ice age (10–15,000 years ago), worldwide sea level has been rising.

Research based on tide gauge data from around the world indicates that global sea level has risen 4–6 inches during the last century, coinciding with a temperature rise of 0.7°F (Hoffman, Keyes, and Titus 1983). The relationship between global temperature and sea-level rise during this period is illustrated in Figure 3. Much of this rise in sea level can be explained by climatic warming, but a number of local conditions such as relative subsidence of land masses, river flow, and weather could also have contributed to this effect.

Local Sea-Level Variations

Ever since the global climate began to warm at the end of the last glacial period about 15,000 years ago, sea level has been rising relative to the Delaware coast (Figure 4). From about 8,000–3,700 years before present, sea level rose approximately 1 foot/century. Since then, with the exception of the last 100 years, Delaware's relative sea level has risen less than 6 inches/century, generally close to the world average (Kraft 1971).

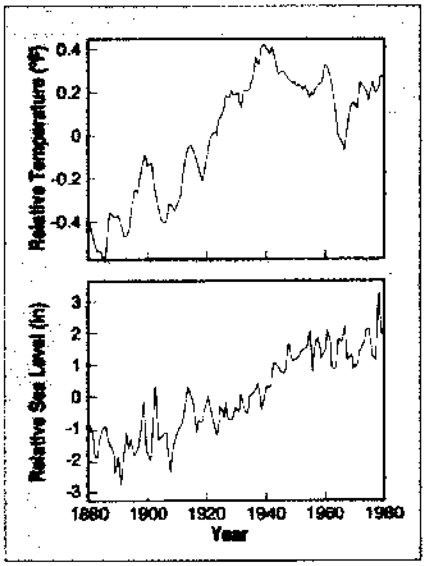


Figure 3. ***Relative Global Mean Temperature and Sea-Level Trends for the Last Century.*** *(Adapted from Hansen et al. 1981; Gornitz, Lebedeff, and Hansen 1982.)*

During the last century, however, mean sea level along the U.S. East Coast has risen faster than the world average. Relative sea level rose 0.1 inch/year in Philadelphia and 0.15 inch/year in Lewes, Delaware, between 1920 and 1980 (Hicks, Debaugh, and Hickman 1983). These measurements exceed the global trend of 0.06 inch/year primarily because of subsidence and sediment compaction within the Atlantic Coastal Plain.

Projections for Future Sea-Level Rise

Scenarios for future global and local sea-level rise have been developed by various research teams using different methodologies. Table 1 summarizes the results of some of these studies and provides a means of comparing predictions for global sea-level rise to those for local sea-level rise at Lewes, Delaware, and Ocean City, Maryland. All of these scenarios reflect the fact that relative sea level along the Atlantic coast is rising at a faster rate than worldwide.

The current-trend estimates in Table 1 depend on past rates of sea-level rise continuing into the future. Under such conditions, eustatic global sea level is predicted to rise 3–4 inches by the year 2050. In the same period, sea level may rise 12 inches at Lewes and 10 inches at Ocean City.

The low-to-high scenario studies incorporate a large number of variables that can influence sea level. These include trace gases, fossil fuel consumption, global warming of 2.7°–8.1°F, the diffusion of heat into the oceans, and the impact of snow and ice. A typical mid-range prediction is that global sea level will rise 21–31 inches by the year 2050 (Hoffman, Keyes, and Titus 1983). Consequently, sea levels at Lewes and Ocean City are expected to rise 30–40 inches and 26–36 inches, respectively (Hull and Titus 1986; Titus et al. 1985). Hoffman's 1986 revised estimates are less extreme for the first half of the 21st century. While these researchers conclude that sea-level rise will probably be somewhere in the middle range of estimates, they also concede the possibility that sea level at Lewes could rise by as much as 150 inches (12.5 feet) by the year 2100.

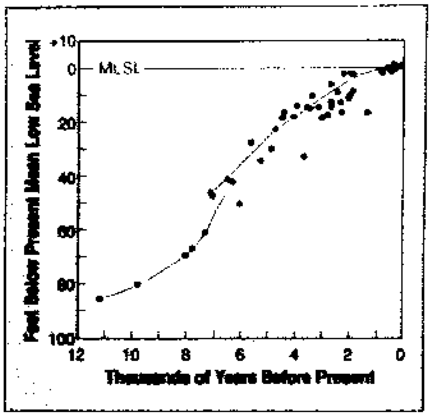


Figure 4. A Relative Sea-Level Curve for the Delaware Coastal Zone. *Dots represent discrete measurements of past sea level dated by marsh sediments. The steeper the line connecting the dots, the faster the rate of sea-level rise. (Adapted from Kraft, Belknap, and Demarest 1987.)*

Revelle's estimates for the National Academy of Sciences (1983) include the combined effects of thermal expansion and global meltwater, excluding Antarctica. According to his predictions, sea level will rise 28 inches globally and 40 inches at Lewes by the year 2080.

Impact of Sea-Level Rise

The Atlantic Coastal Plain, which includes most of Delaware, is characterized by a gently sloping surface with gradients of only several feet per mile near the shore (Committee on Engineering Implications of Changes in Relative Mean Sea Level 1987). A large percentage of land area in Delaware is less than 50 feet above sea level. The low elevation, the amount of land exposed to open water, and the sedimentary nature of the barrier islands, beaches, lagoons, and marshes along the coast make Delaware vulnerable to even a modest rise in sea level. Sea-level rise is expected to have the following direct physical effects on Delaware: (1) shoreline retreat, (2) coastal inundation, and (3) saltwater intrusion into aquifers and the Delaware Estuary.

Shoreline Retreat

Historically, sea-level rise and shoreline retreat have been occurring along the Delaware coast for the last 15,000 years. According to paleogeographic reconstructions, the maximum position of Delaware's Atlantic shoreline was approximately 46 miles seaward of its present position (Kraft, Belknap, and Demarest 1987). The various coastal environments (beach, marsh, and lagoon) have migrated landward and upward in elevation as a result of coastal erosion.

The nature of the coastal environment determines the manner in which erosion or landward migration of the shoreline occurs. In order for a barrier beach to maintain its size and elevation in the face of erosion on its seaward side, sediment must accumulate on its landward side. This is commonly accomplished along the Delaware coast by dune formation, overwash processes, and the build-up of flood tidal shoals in inlets. In all cases, sand from the ocean side of the barrier beach is transported to the landward side (Figure 5). During storms, when the most substantial erosion occurs, waves breach the dunes or back-barrier area and carry sand landward. This process is common along the Delaware Bay coast and low-lying, oceanfront beaches.

In the area south of Dewey Beach, the Rehoboth Marsh grows on tidal shoals formed by sand carried through a former, now closed, inlet (Maurmeyer and Carey 1985). Areas such as Rehoboth Beach and Bethany Beach are situated on headlands, not marshes or lagoons. Because of the hard, rocky nature of headlands, these locations are less prone to overwash and erode and, therefore, move landward more slowly.

Historic rates of change along the Delaware shoreline are illustrated in Figure 6. These data are based on analyses of historic maps, charts, aerial photos, and surveys from the mid-1800s to the mid-1900s. Various locations along the Delaware coast have been eroding at average rates of 1–15 feet/year during the last century. In general, the areas of greatest erosion have been along Delaware Bay where no wide beaches or barrier islands exist as a buffer zone to dissipate wave energy. Marsh surfaces are then in direct contact with wave action, and large sections of marsh muds can be undermined, broken off, and carried offshore by impinging waves and currents.

Table 1

Scenarios of Sea-Level Rise in Inches

YEAR	2000	2050	2080	2100
Global				
Current Trends	1	3–4	4–6	5–7
Hoffman et al. 1983				
Low	2	9	–	22
Mid-Low	3	21	–	57
Mid-High	5	31	–	85
High	7	46	–	136
Hoffman et al. 1986				
Low	1	8	–	22
High	2	22	–	145
NAS Estimate (Revelle 1983)	–	–	28	–
Lewes, Delaware				
Current Trends	5	12	17	19
Hull and Titus 1986				
Low	6	18	–	36
Mid-Low	8	30	–	71
Mid-High	9	40	–	99
High	11	55	–	150
NAS Estimate (Revelle 1983)	–	–	40	–
Ocean City, Maryland				
Current Trends	3	10	–	–
Titus et al. 1985				
Mid-Low	5	26	–	–
Mid-High	7	36	–	–

Predictions for future erosion along the Delaware shoreline have been made based on past rates of erosion, sediment transport and deposition processes, and various scenarios for sea-level rise. According to Hoffman, Keyes, and Titus (1983), even a 1-foot rise in sea level would erode most sandy shorelines along the Atlantic coast by at least 100 feet. If sea-level rise rates of the last century continue with no human intervention, changes such as this could occur within the next 100 years.

Kraft, Belknap, and Demarest (1987) have generated a map showing the projected Delaware coastal zone resulting from a 20-foot rise in sea level (Figure 7). They also predicted the length of time such a landward migration of the coastline would take given four different rates of sea-level rise and no further human intervention to halt erosion.

Three of the four scenarios are based on average rates of sea-level rise that have occurred during various periods of Delaware's past. The fourth and most sudden scenario, the CO_2-greenhouse scenario, is based on accelerating rates of sea-level rise rather than the continuation of current trends. Although the ultimate change in the shoreline is the same in all four scenarios, the period over which the change would occur varies from about 150 to 4,800 years.

According to Kraft and his colleagues, a 20-foot rise in sea level would enlarge the Delaware Bay via a shoreline retreat of approximately 6 miles. The Atlantic coast of Delaware would resemble the present barrier island/marsh/lagoon system but would migrate landward from 2–6 miles and be somewhat compressed due to the rising sea encountering higher land elevations more quickly.

Kraft's study presents a worst-case scenario for sea-level rise, but it makes an important point. If sea level along the Delaware coast continues to rise at present or accelerated rates, whether as a result of greenhouse warming or other factors, the impact could be great. The "worst case" is within the realm of possibility since sea level has met or exceeded the predicted level several times in the geological history of the region (Kraft, oral communication).

Coastal Inundation

The second direct physical impact of sea-level rise on Delaware's shores is coastal inundation. A large portion of the Delaware coast is fringed by low-lying wetlands. Coastal marshes comprise about 13% of the state's area. Tidal marshes are areas of vegetation that have adapted to repeated, periodic flooding. They play an important role not only in an ecological sense but also in storm protection, recreation, and pollution control. The marshes of Delaware provide a habitat and nursery area for a variety of animals vital to the food chain. They also act as a "sponge," protecting the coast from storm floods. Wetlands provide a setting for a number of recreational activities including fishing and bird watching. Finally, tidal marshes serve as a natural water filter, trapping pollutants during surface water runoff after heavy precipitation.

Because marshes are highly sensitive to local tidal elevations and durations and water-quality conditions, they will be one of the habitats most impacted by sea-level rise. Figure 8 illustrates the evolution of a Delaware Estuary-type marsh as sea level rises. At present rates of sea-level rise, sedimentation and vegetative growth can maintain the surface area of most wetlands through a natural process of landward and upward migration. If sea level rises more quickly than the marsh can grow, the marsh area will shrink, leaving only the most landward edge. Given enough time and space, new marsh could form landward. However, in areas where development and structural protection of human communities exist adjacent to wetlands, landward migration is not possible, and the marsh will be lost.

An EPA study predicts that Delaware Bay salt marshes may persist and even expand at the expense of undeveloped land or freshwater marshes throughout most of the 21st century (Titus 1988). However, this scenario is based on mid-range estimates of sea-level rise, assumes no development of the area behind present marshes, and varies with individual location. On the other hand, an escalating rate of sea-level rise and continuing erosion increase the likelihood of a loss of the major salt marshes in the long term. Even brackish coastal marshes may well be gone in 1,000–1,500 years (Kraft, oral communication). Coastal areas at slightly higher elevations not inundated by rising sea levels will be more susceptible to flooding from storm surges.

The impact of potential sea-level rise on coastal wetlands in Delaware will depend on the rate of sea-level rise and the manner in which the coastal zone is managed. Because of the time lags involved, decisions being made today will determine whether or not marsh ecosystems will be able to form inland in adaptation to future sea-level rise.

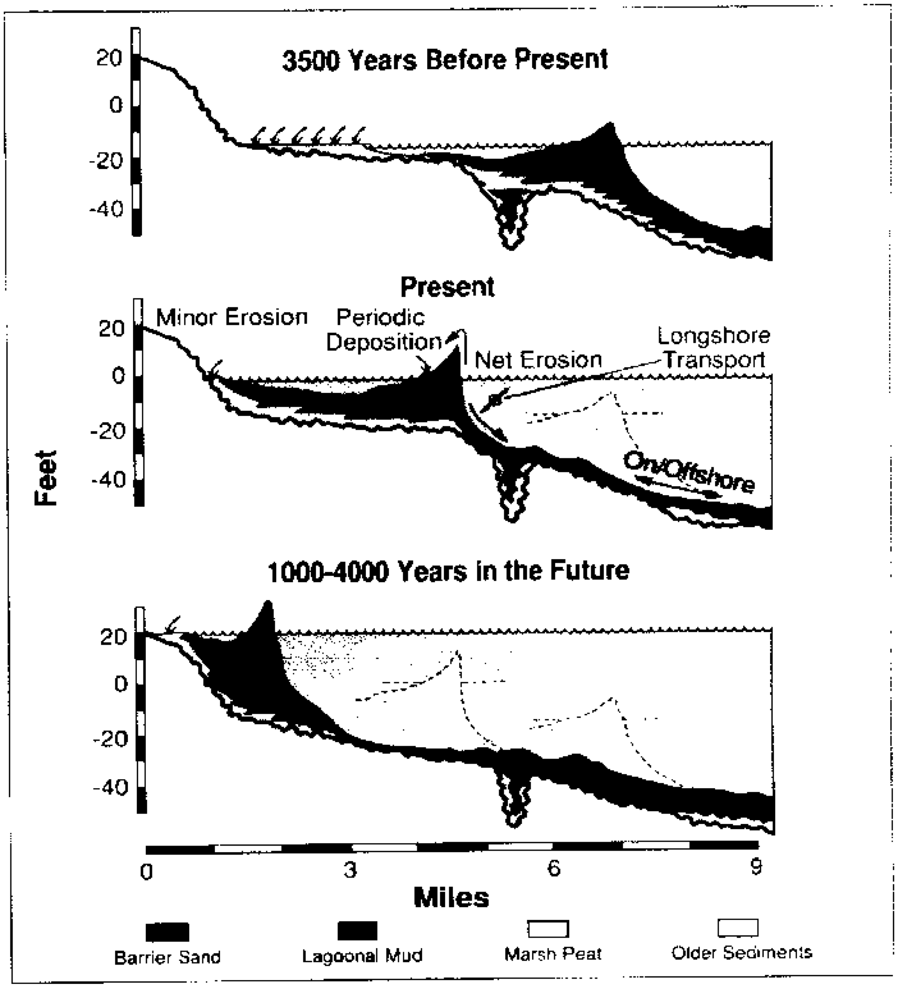


Figure 5. Profiles of the Changing Delaware Coast. *Sediment transport and deposition processes move barrier beaches landward as sea level rises. Dashed lines in the present and future profiles show the position of previous shorelines. The lower profile projects the change accompanying a 20-foot rise in sea level, the same level shown in an aerial view in Figure 7. (Adapted from Kraft, Belknap, and Demarest 1987.)*

Saltwater Intrusion

The third physical impact of sea-level rise would be saltwater intrusion. As sea level in Delaware has risen over the last 15,000 years, what was once a highly dissected freshwater river system has been invaded by the marine realm to form the Delaware Estuary. A continued rise in sea level will cause salt water to move even farther landward and intrude upon aquifers, tidal rivers, and estuary systems.

Salinity in an estuary ranges from seawater at the mouth to fresh water near the head of the tide. If all other factors are constant, a rise in sea level generally results in increased salt concentrations up the estuary. Decreased precipitation patterns, such as occurred in Delaware during the 1960s drought, can have a similar impact. The saltwater influx is increased in the first case, while the freshwater force is decreased in the second.

A 1979 study by Hull and Tortoriello determined the salinity increase induced in the Delaware Estuary by a 5-inch rise in sea level by the year 2000. They concluded that the increased salinity in the estuary over this short time period could be offset by freshwater augmentation from a medium-size reservoir. However, a 1986 study by Hull and Titus implied that accelerated rates of sea-level rise, even a moderate 24–36 inches by 2050 (equivalent to the mid-range, low estimate for Lewes, Delaware) would greatly increase salinity problems in the estuary.

The areas of Delaware most vulnerable to saltwater intrusion of surface and groundwaters are the lands adjacent to Delaware Bay and the bay's tidally influenced tributaries, the headlands abutting the Atlantic Ocean, and the cities of Rehoboth Beach, Bethany Beach, and Fenwick Island. The two greatest impacts of further salinity intrusion on Delaware

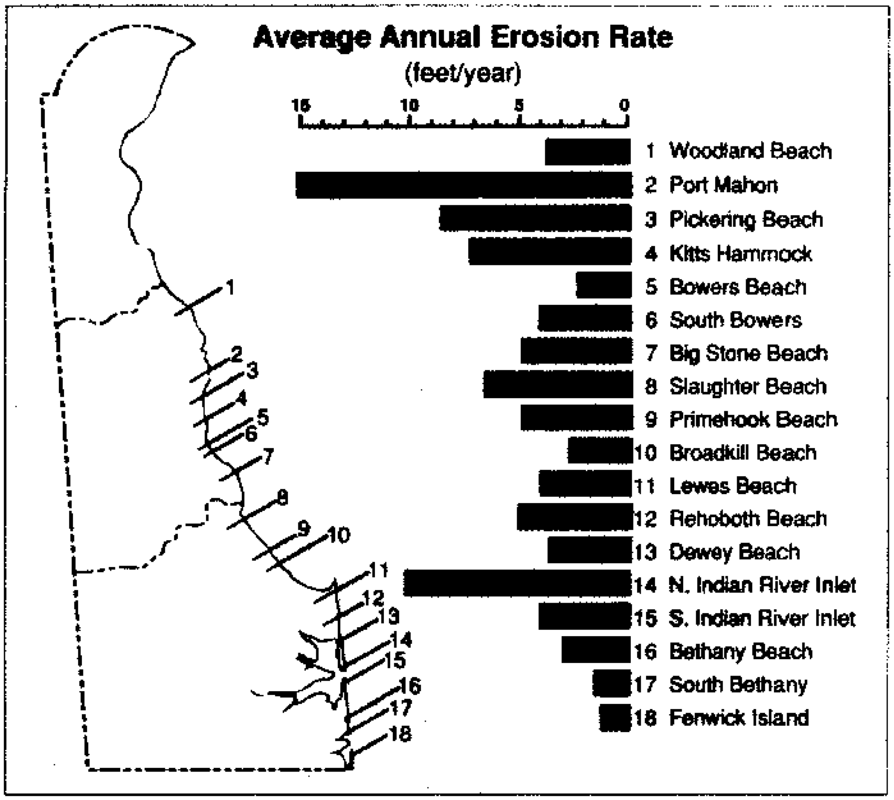


Figure 6. Historic Rates of Shoreline Change Along the Delaware Coast. *(Adapted from Maurmeyer 1978.)*

will be a reduction in the availability of fresh water and the contamination of ecosystems essential to sport and commercial fishing and shellfishing.

Most fresh water in Delaware is obtained from public groundwater supplies and private wells. The city of Wilmington receives most of its water from Brandywine Creek. If other variables remain constant, these sources are threatened by potential salinity increases.

In the northern section of the state, where the Delaware River flows adjacent to the outcropping Potomac Aquifer system, there is good hydraulic connection between the tidal river and the aquifer. This means that water flows freely between the river and the aquifer. Water-quality data from the U.S. Geological Survey reveals groundwater in the aquifer is being degraded by infiltration of river water and localized leaching of waste disposal sites (Phillips 1987). Rising sea level would aggravate this situation.

The Potomac Aquifer is both a coastal aquifer and one which is recharged by a river in certain areas. Figure 9 illustrates saltwater intrusion in a coastal aquifer whose water table slopes seaward. Due to density differences, a layer of fresh water floats on top of the denser salt water, which forms an intrusion wedge. When sea level rises, the wedge interface shifts landward and upward. If the aquifer is pumped so that groundwater levels fall below mean sea level, which can occur during drought conditions or overuse, the aquifer will be recharged by ocean or estuarine water.

Sea-level rise could affect the salinity of wells drilled in Delaware's coastal aquifers in two ways. First, as the freshwater/saltwater boundary moves landward and upward, wells drilled near the coast which are presently pumping fresh water may be contaminated by the intruding saltwater wedge. Second, the Potomac Aquifer, which has good hydraulic connection along the Delaware River Estuary, will be recharged by more saline water as the saltwater/freshwater interface moves farther up-estuary.

The second major impact of sea-level-induced salinity intrusion will be contamination of fragile ecosystems in the Delaware coastal zone. Plants and animals living in the relatively clean habitats of the lower estuary and sensitive to salinity variations will be forced up the estuary where pollution and other industrial hazards are greater. The up-estuary migration of brackish and saltwater species will be accompanied by the similar retreat of freshwater species.

Salinity changes accompanying a relatively slow rise in sea level have contributed to a decline in the Delaware Bay's oyster population (Hull and Tortoriello 1979). Oysters tolerate wide salinity variations, but as salinity increases they become more susceptible to infection by MSX, a devastating microparasite. Other species, especially less salt-tolerant species, may suffer severely from salinity changes in ways difficult to foresee.

Groundwater quality and estuary populations have already been affected by saltwater intrusion related to a gradual rise in sea level and drought. If sea-level rise continues at current rates or accelerates, Delaware's hydrologic system and the highly sensitive ecosystems of the Delaware Estuary will likely deteriorate further. Policy makers must decide whether to attempt to adapt to salinity changes or attempt to prevent them.

Summary and Conclusions

Scientists generally agree that higher concentrations of greenhouse gases in the atmosphere will change global climate. While it is not yet understood how climatic feedback from clouds and oceans will affect the equilibrium surface temperature, the majority of studies indicate that global warming will occur even after consideration of the numerous feedback mechanisms that might negate such an effect. The rate and magnitude of this change are still uncertain, but the ultimate impact of warmer atmospheric temperatures includes global sea-level rise resulting from thermal expansion of seawater and melting of land-based snow and ice.

During past geologic periods, cooler climates have coincided with a drop in sea level, and warmer trends have brought about rising seas. Part of this sea-level variation was due to climatic changes, but other factors like land movement and precipitation patterns could have contributed. Due to the uncertainty of future climate change, sea-level predictions are often made in low-to-high scenario formats. All of these predictions assume at least a continuation of current upward trends.

The major impacts of future sea-level rise on Delaware will be shoreline retreat, coastal inundation, and saltwater intrusion. The effects of existing rates of sea-level rise on erosion, wetland loss, and salinity increases have already become obvious in the state. The ability of natural and managed systems to adapt to change is dependent on rates of climate deviation and sea-level variation as well as human intervention. Ecosystems such as barrier islands and wetlands do have the natural ability to move in response to rising and falling seas unless the change is too rapid or development intrudes. Tidally influenced surface waters and freshwater aquifers are restricted in their ability to adapt to sea-level rise and increasing salinities. More human intervention and monitoring techniques may be needed to maintain their viability.

If sea level continues to rise at current rates or accelerates as a result of greenhouse warming, the fate of our coastal ecosystems and freshwater resources will depend on planning and management decisions. Researchers are continuing the quest for better computer models and sources of solid, long-term climate data to aid decision makers in this task. Relatively new technologies such as high-speed supercomputers and satellite imagery are being applied to the role played by clouds and oceans.

Dean (1991) suggests that scientists and engineers make the following responses to the problem of a probable but uncertain change in sea level:

(1) Strive to understand the natural system by authoritatively documenting the long-term erosion rates and other coastal responses characteristic to sea-level rise.

(2) Attempt to eliminate human-induced coastal erosion.

(3) Quantify the hazard level faced by U.S. shorelines in a manner that can serve as a basis for regulation and personal decision making.

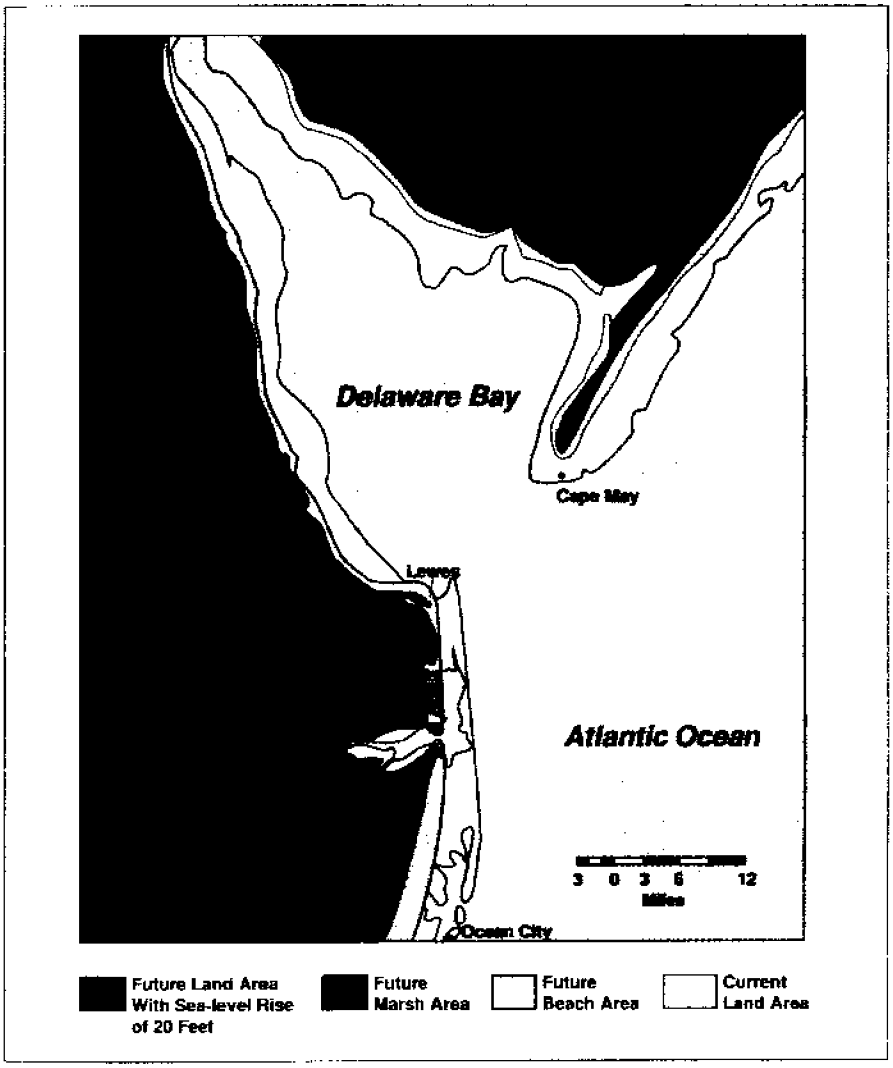


Figure 7. A Projection of Delaware's Coastal Zone Geography Accompanying a Rise of Sea Level to Approximately 20 Feet. *The projected coast (gray shaded areas) is based on sea levels equivalent to those in several interglacial periods over the past 2 million years. This projection could occur again under four different scenarios: in 100–200 years with extreme predictions of climate warming; in 1,500 years should sea level continue to rise at rates we have had over the past 50 years; in 2,900 years at rates similar to the past 900 years; and 4,800 years at the average rate of the past 2,000 years. (Adapted from Kraft, Belknap, and Demarest 1987.)*

(4) Continue research on early detection of sea-level trends and effects.

In the meantime, certain actions can be taken today that would protect coastal ecosystems if sea level rises and yet cost the public and individual property owners almost nothing if sea level does not reach scientists' expectations. We can allow property owners to use coastal lowlands as they choose now but set up a legal mechanism to ensure that the land is abandoned if and when sea level rises enough to inundate it. To implement this policy of "presumed mobility," governments could prohibit bulkheads, alter deeds on coastal property to require eventual abandonment as the sea rises, or convert land ownership into long-term leases (50–100 years) or conditional leases that expire when the sea rises enough to inundate the property. The latter approach has often been used by

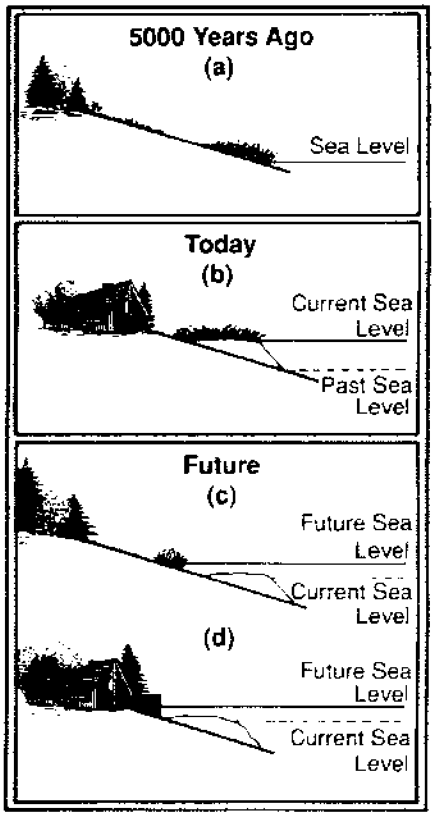


Figure 8. Evolution of a Coastal Marsh as Sea Level Rises: Two Future Scenarios.
(a) Coastal marshes have kept pace with the slow rate of sea level rise that has characterized the last several thousand years.
(b) Thus, the area of marsh has expanded over time as new lands have been inundated.
(c) If, in the future, sea level rises faster than the ability of the marsh to keep pace, the marsh will contract.
(d) Construction of bulkheads to protect economic development may prevent new marsh from forming and result in a total loss of marsh in some areas. (Adapted from Titus 1986.)

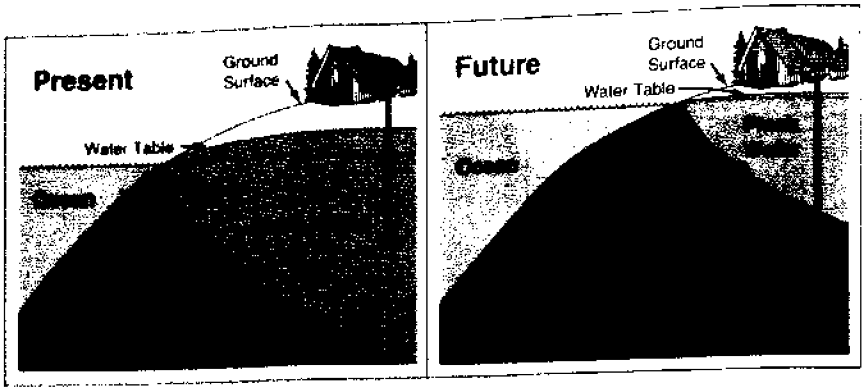


Figure 9. Saltwater Intrusion in a Coastal Aquifer. *As the saltwater intrusion wedge, which extends under the freshwater aquifer, advances landward and upward with rising sea level, coastal wells may begin pumping salt water. (Adapted from Barth and Titus 1984.)*

the National Park Service to take over private property when the current owner dies (Titus, 1991). Some details do remain to be worked out. However, implementation of a presumed mobility policy could help assure future environmental viability while eliminating the need for development restrictions and avoiding the high cost of sudden property abandonment. Today's decisions must make sense ecologically and economically for the present and the future.

References

Barth, M. C., and J. G. Titus, eds. 1984. *Greenhouse Effect and Sea Level Rise.* New York: Van Nostrand Reinhold.

Climate Research Board. 1979. *Carbon Dioxide and Climate. A Scientific Assessment.* National Research Council. Washington, DC: National Academy Press.

———. 1982. *Carbon Dioxide and Climate: A Second Assessment.* National Research Council. Washington, DC: National Academy Press.

Committee on Engineering Implications of Changes in Relative Mean Sea Level. 1987. *Responding to Changes in Sea Level: Engineering Implications.* National Research Council. Washington, DC: National Academy Press.

Dean, R. 1991. Impacts of global change: Engineering solutions. In *Our Changing Planet: Joining Forces for a Better Environment.* Proceedings of a symposium honoring the 20th anniversary of the Graduate College of Marine Studies. Newark, DE: University of Delaware.

Gornitz, V., S. Lebedeff, and J. Hansen. 1982. Global sea level trend in the past century. *Science* 215:1611–14.

Graedel, T. E., and P. J. Crutzen. 1989. The changing atmosphere. *Scientific American* 261(3): 70–79.

Hansen, J., D. Johnson, A. Lacis, S. Lebedeff, P. Lee, D. Rind, G. Russell. 1981. Climate impact of increasing atmospheric carbon dioxide. *Science* 213:957–66.

Hicks, S. D., H. A. Debaugh, Jr., and L. E. Hickman, Jr. 1983. *Sea Level Variations for the United States, 1855–1980.* Rockville, MD: National Oceanic and Atmospheric Administration.

Hoffman, J. S., D. Keyes, and J. G. Titus. 1983. *Projecting Future Sea Level Rise: Methodology, Estimates to the Year 2100, and Research Needs.* Washington, DC: U.S. Environmental Protection Agency.

Hoffman, J. S., J. B. Wells, and J. G. Titus. 1986. Future global warming and sea level rise. In *Iceland Coastal and River Symposium '85.* Reykjavik: National Energy Authority.

Hull, C. H. J., and J. G. Titus, eds. 1986. *Greenhouse Effect, Sea Level Rise, and Salinity in the Delaware Estuary.* Trenton, NJ: Delaware River Basin Commission and U.S. Environmental Protection Agency.

Hull, C. H. J., and R. C. Tortoriello. 1979. *Sea Level Trend and Salinity in the Delaware Estuary.* West Trenton, NJ: Delaware River Basin Commission.

Keeling, C. D., R. B. Bacastow, A. F. Carter, S. C. Piper, T. P. Whorf, M. Heimann, W. G. Mook, and H. Roeloffzen. 1989. A three-dimensional model of atmospheric CO_2 transport based on observed winds: 1. Analysis of observational data. In *Aspects of Climate Variability in the Pacific and the Western Americas,* D. H. Peterson, ed. Geophysical Monograph 55. Washington, DC: American Geophysical Union.

Kraft, J. C. 1971. Sedimentary facies patterns and geologic history of a Holocene marine transgression. *Geological Society of America Bulletin* 82:2131–58.

Kraft, J. C., D. F. Belknap, and J. M. Demarest. 1987. Prediction of effects of sea-level change from paralic and inner shelf stratigraphic sequences. In *Climate, History, Periodicity and Predictability,* M. R. Rampino, ed. New York: Van Nostrand Reinhold.

Maurmeyer, E. M. 1978. Geomorphology and evolution of transgressive estuarine washover barriers along the western shore of Delaware Bay. Ph.D. dissertation. Department of Geology, University of Delaware, Newark.

Maurmeyer, E. M., and W. L. Carey. 1985. *Striking a Balance: A Guide to Coastal Process and Beach Management in Delaware.* Dover, DE: Department of Natural Resources and Environmental Control.

Phillips, S. W. 1987. *Hydrogeology, Degradation of Ground Water Quality, and Simulation of Infiltration from the Delaware River into the Potomac Aquifers, Northern Delaware.* Towson, MD: U.S. Geological Survey.

Revelle, R. 1983. Probable future change in sea level resulting from increasing atmospheric carbon dioxide. In *Changing Climate: Report of the Carbon Dioxide Assessment Committee.* National Research Council. Washington, DC: National Academy Press.

Seidel, S., and D. Keyes. 1983. *Can We Delay a Greenhouse Warming?* Washington, DC: U.S. Environmental Protection Agency.

Titus, J. G. 1986. Greenhouse effect, sea level rise, and coastal zone management. *Coastal Zone Management Journal* 14(3): 147–71.

———, ed. 1988. *Greenhouse Effect, Sea Level Rise, and Coastal Wetlands.* Washington, DC: U.S. Environmental Protection Agency.

———. 1991. Greenhouse effect and coastal wetland policy: How Americans could abandon an area the size of Massachusetts at minimum cost. *Environmental Management* 15(1): 39–58.

Titus, J. G., S. P. Leatherman, C. H. Everts, D. L. Kriebel, and R. G. Dean. 1985. *Potential Impacts of Sea Level Rise on the Beach at Ocean City, Maryland.* Washington, DC: U.S. Environmental Protection Agency.

Acknowledgments

The author wishes to thank Beth Chajes, editor; David Barczak, graphic designer; and Pamela Donnelly, production supervisor, University of Delaware Marine Communications Office, for production assistance; and the University of Delaware Sea Grant College Program for financially supporting this report.

Published by the University of Delaware Sea Grant College Program.
DEL-SG-21-91. (11/91.1K)

Printed on recycled paper. ♻