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GREENHOUSE EFFECT, SEA LEVEL RISE, AND COASTAL DRAINAGE SYSTEMS

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ABSTRACT: Increasing concentrations of carbon dioxide and other gases are expected to warm the earth several degrees in the next century, which would raise sea level a few feet and alter precipitation patterns. Both of these changes would have major impacts on the operation of coastal drainage systems. However, because sea level rise and climate change resulting from the greenhouse effect are still uncertain, most planners and engineers are ignoring the potential implications. Case studies of the potential impact on watersheds in Charleston, South Carolina, and Fort Walton Beach, Florida, suggest that the cost of designing a new system to accommodate a rise in sea level will sometimes be small compared with the retrofit cost that may ultimately be necessary if new systems are not designed for a rise. Rather than ignore the greenhouse effect until its consequences are firmly established, engineers and planners should evaluate whether it would be worthwhile to insure that new systems are not vulnerable to the risks of climate change and sea level rise.

INTRODUCTION

In the last few decades, coastal drainage systems that prevent roads and residences from being flooded have improved to the point where, in most areas, flooding from rainfall rarely amounts to more than a minor inconvenience. These improvements have occurred in part because developers, highway engineers, and flood insurance officials have decided that the benefits from less flooding outweigh the costs, and in part because those who design drainage systems have become better able to determine the size necessary for the desired level of flood prevention.

The design of a coastal drainage system depends on the amount of runoff expected during a major storm and the elevation of the area being drained. Although the amount of rainfall and the severity of the worst storm vary from year to year, it has been reasonable to assume that historical weather records provide a reliable guide to future precipitation and runoff over the design life of the project. With few exceptions, one could assume that the elevation of an area will not change. Provided that the system has been maintained properly, it could be assumed to maintain its ability to remove water at the design flow rate.

Recent developments in climatology, however, suggest that design conditions that have been fixed in the past may change substantially in the future. The National Academy of Sciences (NAS) and atmospheric scientists from around the world have concluded that increasing concentrations of carbon dioxide, methane,

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and other gases will raise the earth's average temperature a few degrees (C) in the next century. Such a warming would alter precipitation patterns and raise sea level. The former impact would change the load on coastal drainage systems, while the latter would reduce their efficiency.

Assessments of these changes have generally focused more on sea level than precipitation. Existing climate models cannot yet forecast precipitation changes for specific regions. Because sea level depends primarily on global and latitudinal temperature increases, which the models can forecast, rough predictions of sea level rise have been possible. Available estimates generally imply a rise on the order of one meter in the next century.

Should the assumption of future sea level rise be incorporated into the designs of projects initiated today, and if so, how much of a rise? Although all major assessments of the greenhouse effect have concluded that sea level and precipitation will change significantly, most engineers and planners implicitly assume that these changes will not occur.

Engineers have ignored the consequences of the greenhouse effect for several reasons. Information transfer is slow, and projections of future seal level rise have only been available since 1983. Furthermore, there is considerable uncertainty regarding the magnitude of future sea level rise and future precipitation changes. Moreover, the consequences of the greenhouse effect are still in the future; and until now, no one has attempted to assess whether the benefits of preparing for that future would justify the costs. Nevertheless, there are many decisions being made today that are sensitive to even the possibility of a rise in sea level, but cannot wait until current uncertainties are resolved.

This paper summarizes previous studies estimating sea level rise and climate change resulting from the greenhouse effect; examines the impacts on coastal drainage systems and possible responses; summarizes the results of two case studies on watersheds in South Carolina and Florida; and discusses the implications of those case studies. In light of the current uncertainties about future sea level rise, the writers conclude that in the South Carolina watershed, it would be cost-effective to insure against the risk of a rise by installing larger pipes when the system is overhauled.

GREENHOUSE EFFECT AND SEA LEVEL RISE

For over a century scientists have known that the carbon dioxide and water vapor in the earth's atmosphere warm our planet by absorbing outgoing infrared radiation. This feature of the climate is commonly known as the "greenhouse effect"; gases that absorb infrared radiation are known as "greenhouse gases." Without the greenhouse effect the earth would be 33^o C (60^o F) colder than it is currently (Hansen, et al. 1984).

Human activities have released enough CO_2 into the atmosphere to raise the concentration 20% since the industrial revolution and 8% since 1958 (Keeling, et al. 1982). The concentration is generally expected to double its preindustrial level between 2050 and 2100 (Nordhaus and Yohe 1983). Although there are numerous uncertainties regarding the precise impact of such a doubling on world climate, two panels of leading climatologists convened by the National Academy of Sciences have concluded that the earth's average surface temperature would warm by 1.5-4.5^o C (3-8^o F) (Charney, et al. 1979; Smagorinski, et al. 1982). Moreover, if current trends continue, the combined impact of methane, chlorofluorocarbons, and several other greenhouse gases will be as great as that of CO_2 alone (Ramanathan, et al. 1985).

A global warming of a few degrees could be expected to raise sea level in the future, as it has in the past (Mercer 1970; Gornitz, et al. 1982). The best understood mechanism is the warming and resulting expansion of sea water, which could raise sea level 30-50 cm (12-20 in.) in the next century (Revelle 1983). Mountain glaciers could melt and release enough water to raise sea level 10-30 cm (5 in.) (Meier 1984). A melting of Greenland's glaciers could add another 10-30 cm in the next century (Revelle 1983; Bindschadler 1985). Although the impact of Antarctica is unknown, it is generally agreed that a complete deglaciation of the west antarctic ice sheet—which would raise seal level 5-7 m (about 20 ft)—would take three to five centuries (Bentley 1983; Hughes 1983).

Since 1983, three independent reports have estimated future sea level rise. In the NAS report *Changing Climate*, Revelle (1983) estimated that sea level will rise 70 cm (2-1/3 ft) by 2080, ignoring the impact of Antarctica. In a report by the Environmental Protection Agency (EPA) entitled *Projecting Future Sea Level Rise*, Hoffman, et al. (1983) estimated that future sea level rise is likely to be between two midrange scenarios of 26 to 39 cm (11 to 15 in.) by 2025 and 91 to 136 cm (3 to 41/2 ft) by 2075. However, they also concluded that a rise as great as 211 cm (7 ft) or as little as 38 cm (15 in.) by 2075 cannot be ruled out. In 1985, the NAS estimated that glaciers could contribute between 20 and 160 cm but did not revise Revelle's estimates of thermal expansion (Meier, et al. 1985). All of these estimates imply a substantial acceleration over the 10- to 15-cm (4- to 6-in.) worldwide rise in the last century (Gornitz, et al. 1982).

It is generally recognized that a global warming will result in a worldwide increase in precipitation (Rind and Lebedeff 1984). A warmer atmosphere can retain more water vapor; thus, a global warming would intensify the hydrologic cycle in coastal areas and over open ocean. However, climate is expected to be drier in interior areas (Manabe, et al. 1981). Because climate models use grid cells that are 1,000 km wide, it is not possible to accurately project precipitation changes for specific regions.

COASTAL FLOODING AND DRAINAGE SYSTEMS

Designers of coastal drainage systems recognize the unique characteristics of coastal flooding, particularly the impacts of tides, low elevations, and high groundwater tables (Kuo 1980). The rate at which gravity can drain an area depends in part on the difference in elevation between the area being drained and the place to which the water flows. The greater the difference in elevation, the greater the slope of the "hydraulic head" and the faster the water can drain.

Coastal areas generally are low-lying and thus vulnerable to flooding. High tides can decrease the elevational difference and further slow gravity drainage. Moreover, storm surges in coastal areas frequently occur during rainstorms, and can completely stop natural drainage.

High water tables in coastal areas also limit natural drainage. With water tables just below the land surface, a rainstorm can rapidly saturate the soil (raise the water table to the surface). The saturated soil increases runoff by decreasing the ability of water to percolate into the ground.

Coastal flooding can also be exacerbated by problems frequently not considered in designing the drainage system. Storm waves may overtop a seawall; and sediment and debris may block inlets, outlets, and storm sewer pipes and canals. During the worst storm surges, coastal areas may be completely inundated by the sea, leaving the drainage system ineffective until water levels have receded.

Areas that are currently below sea level require forced drainage. New Orleans, most of which is well below sea level, is completely encircled by levees. Drainage pipes under the street lead to an extensive network of drainage canals, from which water is pumped into the Mississippi River or Lake Pontchartraine. Almost every drop of rainfall, plus groundwater that seeps under the levees, must be pumped out of the city.

IMPACTS OF GREENHOUSE WARMING

Sea level rise would exacerbate coastal flooding in many ways. Decreased hydraulic head and higher water tables would reduce both natural and artificial drainage. More areas would be flooded by spring tides. Storm surges would be higher. Areas that were above sea level and relied on gravity drainage would now be below sea level and have to rely on pumping.

The impact of sea level rise on gravity drainage could substantially increase flooding. Natural drainage would be decreased both because (1) higher groundwater tables could decrease the ability of rainwater to percolate into the soil and (2) higher tailwater levels would slow the flow through streams. The reduced natural drainage would increase the requirements of the man-made system of ditches, pipes, and/pr canals. However, higher tailwaters would also reduce the capacity of these systems. Furthermore, the decreased flow rates would allow more siltation and deposition or debris, further reducing capacity or necessitating additional maintenance.

Areas that are just above sea level today would be below sea level. This inundation would render gravity drainage systems useless and require modifications to prevent seawater from backing up into the community. In areas that are already below sea level, pumping stations would have to pump water farther upward, which would reduce pumping capacity.

The loss of wetlands expected to result from sea level rise (Titus 1985) could increase flooding in some areas while decreasing it in others. By reducing hydraulic roughness, it would improve the natural drainage of rainwater. On the other hand, wetland loss would remove an important natural barrier to storm surges. Current sea level trends are largely responsible for the loss of over 100 km^2 (40 sq. miles) of wetlands per year in Louisiana, which is expected to increase the flood risks in metropolitan New Orleans (Gagliano, et al. 1981).

Increased precipitation may increase flood frequencies. Model results indicate that for some communities, the month with highest precipitation could have 50% more rainfall than today when CO^2 doubles (Rind and Lebedeff 1984). No one knows whether this implies more frequent storms or more rainfall during the same number of storms, but the latter possibility cannot be ruled out. In Norfolk, Virginia, e.g., the 5-yr storm produces 5 cm (2 in.) of rain in a single hour, whereas the 50-yr storm produces 8 cm (3 in.) in a single hour. If severe storms in Norfolk have 50% more rainfall in the future than in the past, today's 50-yr event will occur every five years. Although the impact of a global warming on the magnitude of storms cannot yet be determined, the possibility of increased rainfall may warrant measures to make areas less vulnerable.

POSSIBLE SOLUTIONS

The potential responses to drainage problems caused by sea level rise and increased precipitation fall broadly into three categories: enhanced gravity drainage, forced drainage, and adaptation to increased flooding. These measures vary in the extent to which implementation requires anticipation of future climate change rather than reacting as it happens.

Gravity drainage can be enhanced by using larger pipes or wider drainage channels. Communities with drainage systems in place can either install supplemental pipe systems or replace old pipes with larger ones. In many cities, new larger pipes will be preferable because the area underground may already be overcrowded. Furthermore, most older cities may have to replace old broken pipes anyway. Thus, incorporating greater capacity in anticipation of sea level rise as part of a necessary overhaul will tend to favor the use of larger pipes. Installation of a supplemental system, on the other hand, would generally occur as a reaction to sea level rise because little can be saved by implementing such a system before it is actually needed.

Communities that rely on drainage canals may have to widen them. Although, the widening itself need not take place until drainage problems occur, it may be prudent to ensure that buildings and roads are not put so close to the canal that future widening is impossible. The gravity drainage can also be improved by deepening a particular canal or by reducing its hydraulic roughness, e.g., by lining it with asphalt or concrete. These methods require less anticipation; but they are relatively expensive, and may pose safety, aesthetic, or environmental problems.

Because of the low elevations of coastal areas, gravity drainage is not always possible. To be drained by gravity, a road must not only be above sea level, but must have sufficient elevation for drainage pipes underneath to have adequate cover and be above sea level themselves. Thus, many areas have forced drainage (pumps). As sea level rises, some areas that currently have gravity drainage may have to shift to forced drainage. Locks and flap gates may provide a cost-effective interim solution for such areas. During low tide, the gates could be open to permit gravity drainage, while during high tides they could be closed.

Areas that currently use forced drainage will also require modifications. Larger pumps may be necessary to work against the higher tailwaters and to handle the larger capacity resulting from decreased natural drainage and percolation, and possibly increased runoff. While new systems may require larger pumps, existing systems are more likely to use additional pumps. In addition to increasing pump capacity, it will often be necessary to increase the capacity of the system that delivers the stormwater to the pumping station.

Detention basins are widely used to control surface runoff in urban and suburban areas. The concept of detention can be applied in ways other than detention basins, such as rooftop detention, infiltration trenches, porous pavement, storage in low playgrounds and parking lots, and in-line storage in the storm sewer pipes. As the drainage capacities of storm sewer pipe systems, drainage channels, and pumping facilities decrease with sea level rise, one alternative design would be to include more detention facilities in the drainage basin, preferably located near the headwaters of the basin. The detention scheme would be able to reduce the peak discharge, delay the peak time of a storm, and therefore reduce the flow loading onto the storm sewer pipes, drainage channels, and pump station. After the storm has ended, the runoff volume stored in the detention facilities could then be released gradually into the drainage systems without exceeding its capacity.

Besides improving their drainage systems to prevent flooding, communities might choose to implement a combination of planning and structural measures to adapt to increased flooding. Buildings in low areas can be made floodproof; construction of basements can be avoided; and new buildings and streets can be constructed at higher elevations. At some point it might be necessary to discourage building in the increasingly flood-prone areas. Existing coastal management programs that do so include reduced government subsidies, zoning measures, and higher flood insurance rates (Barth and Titus 1984).

In some instances the most appropriate response to sea level rise and climate change can be implemented if and when the consequences occur. In other instances—particularly urban systems being overhauled today—the most cost-effective approach would be to prepare for these consequences before they occur and possibly before people are certain that they will occur. Only if civil engineers soon begin to consider the implications of the greenhouse effect, will it be possible to take advantage of all the possible solutions.

CASE STUDIES

Qualitative descriptions of the problem and possible solutions are instructive, but they do not indicate whether or when planners and engineers should incorporate the impacts of the greenhouse effect into project designs. That decision depends upon costs and benefits of design improvements that vary from location to location.

To obtain realistic insights into this issue the writers conducted case studies of the impacts of sea level rise and precipitation changes on particular watersheds in Charleston, South Carolina, and Fort Walton Beach, Florida. Although the writers considered these areas to be typical coastal communities within these jurisdictions, they focused on watersheds that would be likely to require design changes before other watersheds.

The goal of the case studies was to identify cost-effective options for accommodating the consequences of the greenhouse effect in some watersheds. Because the answer depends on how much the sea level will rise and precipitation will change— both of which are uncertain— the writers examined the impacts of the two EPA midrange scenarios and a possible 10% increase in precipitation during a design rainstorm. This paper focuses primarily on the implications of the EPA midrange low scenario, which is consistent with the NAS projection and will be called “projected sea level rise.” When adjusted for local subsidence trends along the Atlantic and Gulf coasts (Hicks, et al. 1983), this scenario implies a 30-cm (1-ft) rise by 2025 and a 1-cm (3.4-ft) rise by 2075. (Details of the case studies are presented in LaRoche and Webb (1987) and Waddell and Blaylock (1987) for the Charleston and Fort Walton Beach studies, respectively.)

LaRoche and Webb (1987) and Waddell and Blaylock (1987) estimated the increase in flooding, specified the best option for upgrading the drainage system to its performance standard, and estimated the cost of the necessary improvements for each of the three scenarios. These estimates indicate the cost of sea level rise if it is anticipated correctly. To measure the cost of failing to accurately anticipate sea level rise, the authors also estimated the costs of designing for the wrong scenario and late retrofitting the system for the scenario that does unfold.

The results for the Charleston study indicate that the city should probably incorporate sea level rise into it planned improvements for the Grove Street watershed. LaRoche and Webb estimate that the cost of retrofitting the system in 2025 would be 10 times as great as the cost of designing the system today for an additional 30-cm (1-ft) rise in sea level. Waddell and Blaylock, however, concluded that the best way to address the impacts on the Gap Creek watershed in Fort Walton Beach would be to floodproof the houses, which could be accomplished effectively the responding to sea level rise as it occurs.

Charleston's Grove Street watershed has ground elevations ranging from 1.5 to 4 m (5 to 13 ft) above mean sea level. The current design tidal elevation is 1.3 m (4.36 ft), based on spring high tide. With an average surface slope of ½% and medium-to-high density development, flooding occurs frequently. LaRoche and Webb report that stormwater runoff is discharged through a 3-ft-by3.5-ft (0.92- x 1.07-m) box culvert, with pipe conduit laterals extending along each street. All of the existing drainage facilities are undersized for the city's design criteria of a 5-yr rainstorm.

Based on analysis used for Charleston's proposed master drainage plan, LaRoche and Webb designed a drainage system that would be adequate for a 10-yr storm, they deemed that criteria more typical of most urban drainage basins. Because this system would follow a different route to the river, pipe sizes are not directly comparable. Nevertheless, the larger pipe sizes, ranging from 5 ft by 8 ft (1.5 x 2.4 m) to 9 ft by 12 ft (2.7 x 3.7 m), indicate a substantial increase in capacity. LaRoche and Webb estimated that the system would be 35% deficient by 2025 and 100% deficient by 2075 if sea level rises as projected.

LaRoche and Webb considered several designs for projected sea level rise. Because the area is densely developed and real estate values are high, they concluded that retention basins would not be feasible. Given the high capital and operating costs for pumping stations, the concluded that larger pipes would be the best way to design for year 2025 conditions for all scenarios. By 2075, however, gravity drainage would no longer be feasible and levees with pumping stations would be required.

LaRoche and Webb estimated that a system designed for today's sea level would cost $4,810,000 (in 1985 dollars), but that if sea level rises as projected, an additional $2,400,000 will be required to upgrade the system by 2025. However, the cost of designing the system for the projected 2025 sea level would be $5,070,000, only $260,000 greater. LaRoche and Webb also estimate that designing the system for projected sea level rise and a 10% increase in precipitation would cost $5,280,000 (increasing project cost about 10%) while a later retrofit would cost an additional $3,300,000.

The Gap Creek watershed, in the heart of Fort Walton Beach, Florida, has elevations ranging from 0.6 to 11.3 m (2 to 37 ft) about mean sea level. Although the tidal range is less than 30 cm (1 ft), storm surges from hurricanes occasionally raise water levels 1.5 to 3 m (5 to 10 ft). About 50% of the watershed's 810 ha (2,000 acres) are undeveloped, with 35% residential and 15% commercial/residential.

The county's current design criteria for flood protection is the 25-yr rainfall [29 cm (11.25 in.) in 24 hours] with no storm surge. Because the 25-year storm actually includes a 1.7-, (5.7 ft) storm surge, such a storm would undoubtedly cause extensive flooding. In theory, it would probably have been better to design for a combined rainfall and storm surge with a return period of 5 to 10 years; the current criteria probably overprotect areas vulnerable to rainstorms compared with those subject to storm surge. As a practical matter, however, the criteria enabled the drainage planners to concentrate on a type of flooding that can be controlled by gravity drainage, instead of diverting resources to protecting against storm surge, which would require flood walls.

The 25-yr rainfall criteria is already satisfied by improvements that have been implemented in the last several years, including open ditches, separate storm sewers, detention basins, and new outfall structures. However, the county also plans to implement additional improvements, including additional retention or detention facilities; selective dredging; removal of debris, undergrowth, and fences that increase hydraulic roughness; and floodproofing of the most vulnerable homes.

Waddell and Blaylock estimated the potential flooding that would result under each of the scenarios if the drainage system were designed for either current conditions or a 30-cm (1-ft) rise in sea level by 2025. They estimated that a 30-cm rise in sea level would cause flooding in more than 50 homes during the design storm, with 11 houses being flooded with 0.92 m (3 ft) of water. A 30-cm rise accompanied by 10% more rainfall would result in 12 houses being flooded with 1.2 m (4 ft) of water. If the system were designed for a 30-cm rise, however, no flooding would occur with a 30-cm rise in sea level; and only four houses would be flooded with 30 cm of water if rainfall increased as well. Although the necessary design changes would cost $555,000, they would prevent over $1,000,000 in damages during the design storm.

Table 1 shows the damages that would result from the design conditions by 2025 if the system were designed for current conditions or for projected sea level rise. If sea level rises, the design storm would cause $1,161,000 in damages. These damages can be avoided if the system is upgraded for projected sea level at a cost of $555,000. Unlike the Charleston situation, the retrofit cost is equal to the cost of upgrading the system in the original design.

This finding is an important difference between the two case studies. Charleston's system relies on a single approach, drainage pipes, which can be built to any number of possible sizes. Fort Walton Beach, on the other hand, relies on numerous components, each of which can be implemented over time as the system is upgraded. The cost of adding additional components is not influenced by the other components also adopted. A second important reason is that Charleston is considering a complete overhaul, whereas Fort Walton Beach has already implemented modifications to meet the current design criteria.

Table 1
Fort Walton Beach Drainage System

Scenario (1)	Cost of Designing for Scenario ($) (2)	Damages from design storm if designed for current Conditions ($) (3)	Damages from Design storm if designed for Projected 2025 Sea level ($) (4)	Additional cost of Upgrade by 2025 if designed today for current Conditions ($) (5)	Additional cost of upgrade by 2025 if designed today for Projected 2025 sea level (6)
Current conditions	0	0	0	0	0
Sea level rise[b]	555,000	1,161,000	0	555,000	0
Sea level rise[b] and precipitation increase[c]	670,000	1,266,000	25,000	670,000	115,000

[a]The initial cost of construction would exceed the cost of designing for current conditions by approximately $555,000.
[b]Projected 30-cm rise in sea level.
[c]Hypothetical 10% increase in precipitation.

IMPLICATIONS FOR TODAY'S DECISIONS

The Charleston case study shows that urban coastal communities that plan to overhaul or build coastal drainage facilities can consider the risk of future sea level rise and climate change like any other risk. It is possible to insure the Grove Street watershed against the potential future retrofit cost of $2,410,000 that would be required as a result of a 30-cm (1-ft) rise in sea level by spending an additional $260,000 today ($5,070,000 minus $4,810,000) to improve the system. Whether or not this insurance is worth buying depends on one's assessment of the probability of the sea rising or precipitation increasing.

Unlike the probability of a storm, there is no historical data with which to forecast the probability of sea level rise or climate change. Nevertheless, one can estimate how likely sea level rise and climate change would have to be to warrant investing extra resources so that the system can handle future conditions.

Table 2 displays the fiscal requirements for the Charleston area assuming that the system improvements take place in 1990. The table considers the impact if sea level does or does not rise for each of three possible decisions: (1) ignore sea level rise; (2) design for sea level rise but let the intended beneficiaries (taxpayers in 2025) pay the extra cost; and (3) design for sea level rise and pay the cost today. Because the latter two options differ only in the method of financing, we will compare only the first two options.

Table 2
Fiscal Requirements: 1990 and 2025

	COST ($)		
		2025	
Option (1)	1990 (2)	If sea level rises (3)	If sea level does not rise (4)
Ignore sea level rise	4,810,000	2,410,000	0
Build for sea level rise, borrow $260,000	4,810,000	731,000	731,000
Build and pay for sea level rise	5,070,000	0	0

If the community decides to design for future sea level rise and borrow the extra $260,000, by 2025 this debt will have grown due to interest costs. Although interest and inflation rates cannot be precisely predicted, the writers assume here that the municipal bond rate will be, on average, 3% above the rate of inflation, which is consistent with long-term averages in the past. Thus, the debt would grow to $731,000 by 2025.

As guardians of the fiscal interests of future taxpayers, public officials can view the design decision as choosing between leaving future generations with the *risk* of a $2,410,000 retrofit or leaving them with a *certain* debt repayment of $731,000. If sea level rise has a probability of greater than 30% the expected cost will be less if the system is designed for future sea level rise. Although no one has estimated the probability of future sea level rise, the fact that all three assessments have concluded that a substantial rise will take place suggests that a probability of 30% is not excessive.

This analysis does not incorporate all of the benefits of anticipating sea level rise. The benefits captured here only relate to the reduced cost of maintaining the ability of the drainage system to meet its design objectives. In addition to this benefit, increasing the capacity of the system in 1985 will provide benefits between 1985 and 2025 in terms of improved system performance in situations when the design conditions are exceeded. For example, between 1985 and 2025 several storms that are more severe than the 10-yr design storm would be expected, resulting in flooding if the system is built for current sea level. If the system were upgraded today to meet the expected 2025 sea-level-rise conditions, less flooding would occur during such storms. Perhaps most importantly, the analysis excludes nonconstruction of overhauling the system twice, such as the nuisance of having a street blocked and the cost of studies and political debate necessary to allocate sufficient resources to overhaul a drainage system.

CONCLUSION

Four panels of the National Academy of Sciences have concluded that in the coming decades, a global warming due to the greenhouse effect is likely to cause sea level to rise and precipitation patterns to change (Charney, et al. 1979; Smagorinski, et al. 1982; Nierenberg, et al. 1983; Meier, et al. 1985). Such consequences would have important implications for numerous activities by civil engineers and resource planners. Nevertheless, professionals have been reluctant to consider the consequences because the impacts are decades in the future and projections are much less certain than one would like. This paper shows that in some cases, the long-range and uncertain nature of these impacts no longer is sufficient reason to avoid detailed analysis of the implications.

Some deign decisions are sufficiently sensitive to the 1-ft rise in sea level projected in the next 40 years to warrant modifications in spite of the uncertainties. In cases like the Grove Street watershed in Charleston, the potential retrofit costs of failing to consider sea level rise far exceed the additional cost of designing for future conditions. In other cases, such as Fort Walton Beach, it is still cost-effective to wait and upgrade the system if and when it becomes necessary. Only if these impacts are assessed as part of the design process will it be possible for communities to take timely measures and thereby avoid costly retrofits.

By comparing the consequences of different designs for different outcomes for future sea level rise and rainfall, and factoring in their own judgement about the probability of each, civil engineers can develop designs that are less vulnerable to unpredictable shifts in sea level or climate. No one knows how many other coastal communities must make decisions in the near future that depend on the risk of future sea level rise. But in view of the substantial future costs that could be avoided by cost-effective design modifications today, it would be prudent for all master drainage studies in coastal areas to assess the implications of future sea level rise and climate change.

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