CC2R08

Implications of Climate Change for Adaptation by Wastewater and Stormwater Agencies

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Implications of Climate Change For Adaptation by Wastewater and Stormwater Agencies

December 2009

Water Environment Research Foundation
Climate Change Challenge

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ACKNOWLEDGEMENTS

In 2008, Water Environment Research Foundation (WERF) embarked on a five-year Climate Change program (Climate Change Challenge, WERF website, www.werf.org) to understand how the potential impacts of climate change will affect the wastewater and stormwater sector and to provide best practices and tools to assist managers adapt to climate change. This report reflects input and review by the WERF Issue Area Team for Climate Change members who volunteered their time to support the preparation of this report.

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SUMMARY

Climate change presents a much greater degree of uncertainty than is typically encountered in facilities and operations planning. How do you prepare for changes of unknown magnitude on an unknown timeline? There is a great temptation to wait and see if climate science can be improved to provide a better basis for action. But, it would be a mistake to just ignore climate change and resume a business as usual approach to planning. Since it is certain that climate is changing, planning that is based on the assumption of "stationarity" (known climatic variability) is certain to be flawed. Moreover, uncertainties affecting the local conditions that matter most to wastewater and stormwater agencies are not likely to be greatly reduced by further scientific study of global climatic processes. The uncertainty in climate forecasts is magnified many times by the complexities of tracing climate effects through the subsequent hydrologic and environmental processes that produce the changed operating conditions that wastewater and stormwater agencies will have to face.

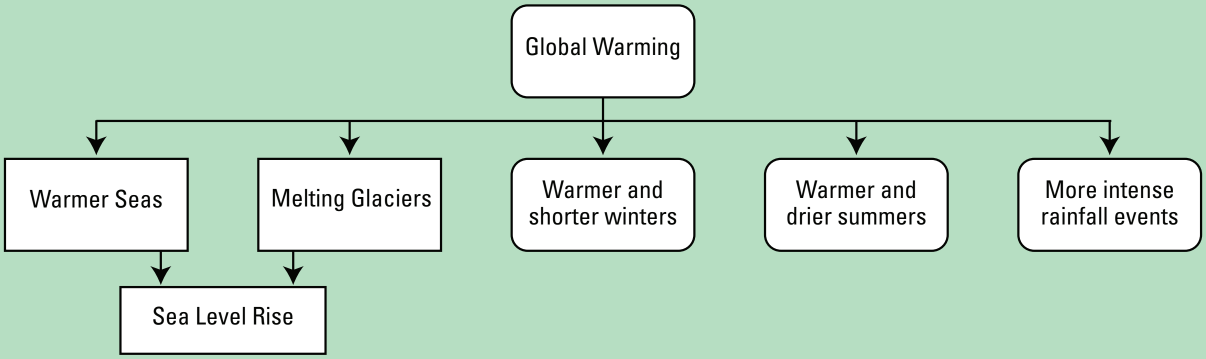
This report offers a way to move forward through a risk management approach. The familiar risk management paradigm consists of three steps: 1) risk identification, 2) risk assessment/characterization, and 3) risk management. The application to climate change adaptation planning is quite unique. It is necessary to first take the problem apart and examine it piece by piece to perform a thorough risk identification analysis. The possible impacts of increasing temperatures are far reaching when all the secondary effects on hydrologic and environmental processes are taken into account. This "deconstruction" of the problem is accomplished with the aid of a number of cause-effect impact tree diagrams that are presented in this Summary. They provide a good overview of the full scope of the problem and a handy means of organizing information about it.

The cause-effect impact tree diagrams represent four major chains of causation that may be expected to result from global warming. First, as temperatures rise, it is expected that sea levels will rise due to warmer ocean temperatures and melting of land ice such as glaciers. Next, warmer overall temperatures are expected to produce two important changes in seasonal conditions over most of the continental United States. Warmer and shorter winters are expected. And, warmer and drier summers are expected in most of North America. Lastly, warming is expected to accelerate and amplify the functioning of the hydrologic cycle to produce, among other things, more intense rainfall events. The cause-effect impact tree diagrams trace through the linkages to show how *climate changes* produced by warming may result in *impacts* on hydrologic and environmental processes that may have *implications* for wastewater and stormwater facilities and operations.

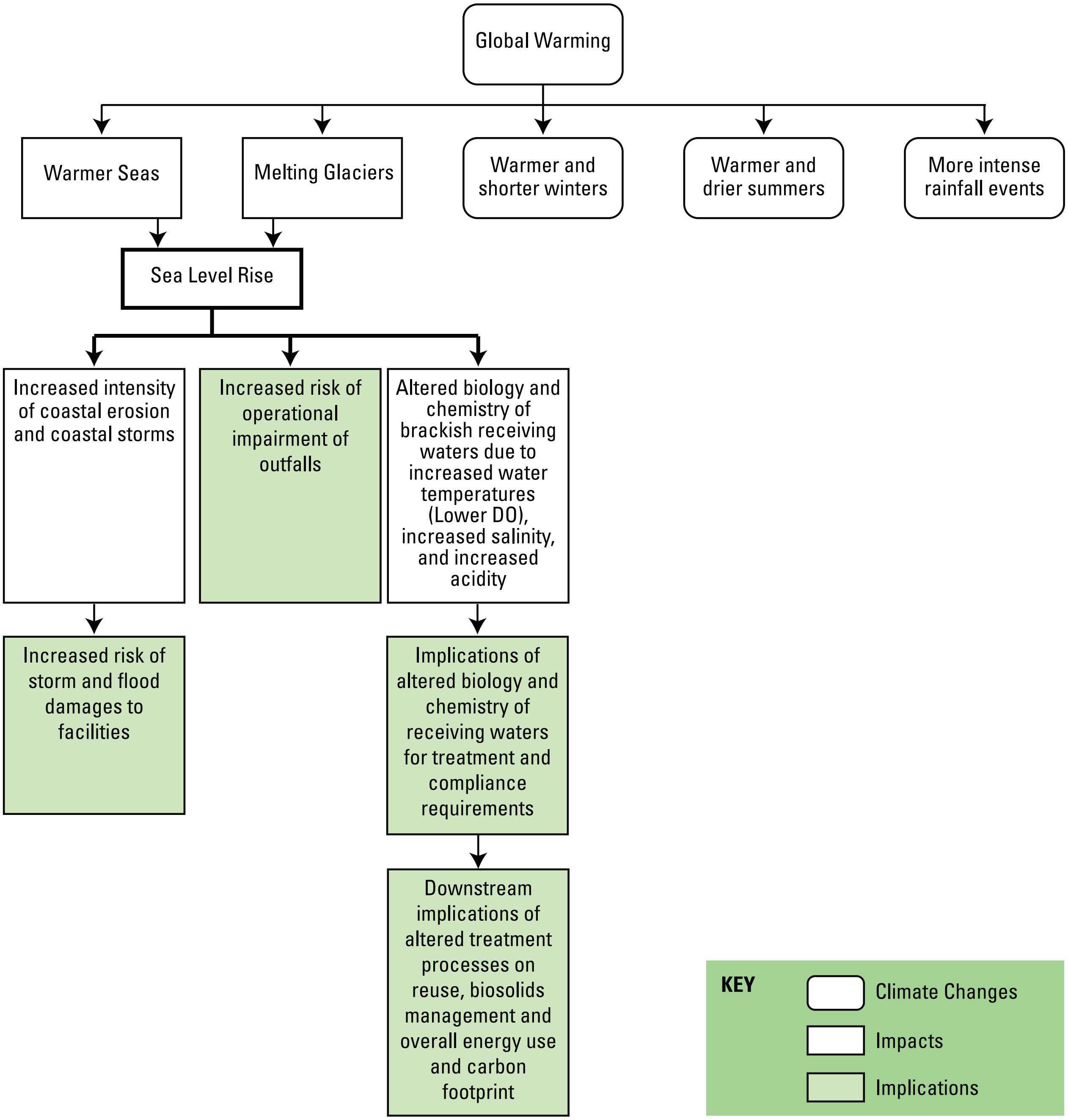
It is important to stress that while these cause-effect impact tree diagrams provide an intuitive and structured approach to risk identification, these are only *potential* risks. The magnitude and timing of these potential downstream effects of global warming remains highly uncertain, as discussed above. A risk characterization step needs to be undertaken to assess what is known and what is not known about the possible magnitude and timing of these *potential* impacts and implications along each of the branches. To assist in making that risk assessment, Sections 2 and 3 of this report provide a background review of the current understanding of climate change at a global level, including forecasts for the continental United States. Section 4 discusses what is known about each of these specific areas of *potential* impacts and implications.

Section 5 illustrates an approach to managing these impacts and implications of climate change through "reconstruction" of the information provided in the cause-effect tree diagrams – bundling individual threats together for analysis in terms of common endpoints relating to major facilities and operations. For example, the cause-effect impact tree diagrams identify a large number of *potential* impacts spawned by global warming that could affect performance requirements for wastewater treatment plants. But these multiple threats are driven by different processes that are understood with varying levels of confidence and are proceeding on differing timelines. From a risk management perspective, it is therefore necessary to evaluate each such "threat bundle" as a package to assess which specific causative influences are likely to be the most critical and to assess adaptation options with a composite rather than a piecemeal approach. This composite understanding is also the appropriate context for consideration of research needs to support adaptation planning. Section 5 defines and analyzes each of the major threat bundles facing wastewater and stormwater agencies in terms of a risk management approach to adaptation planning and then reviews relevant research needs at the end of each discussion.

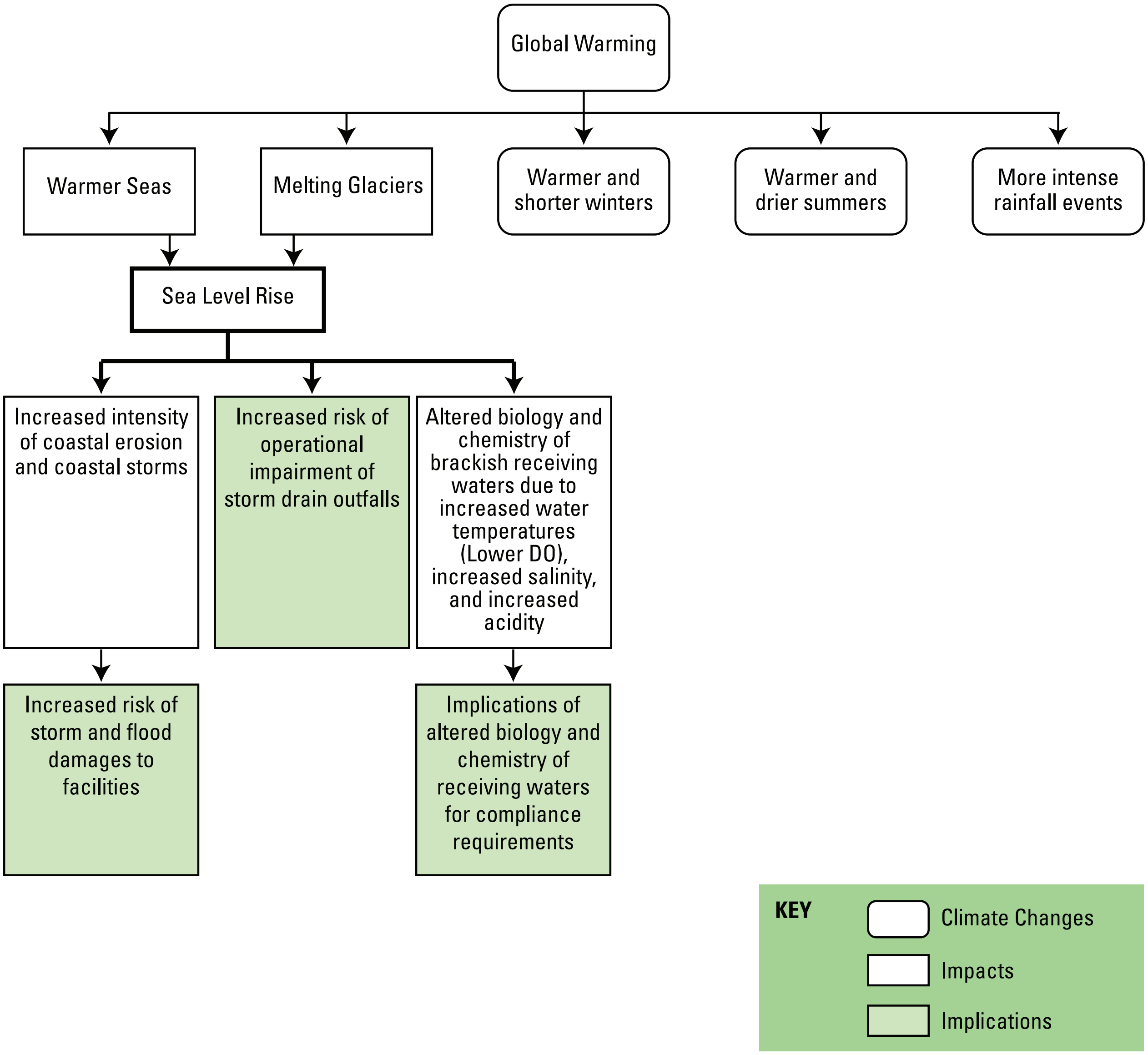
Overview: Major Categories of Climate Change Impacts



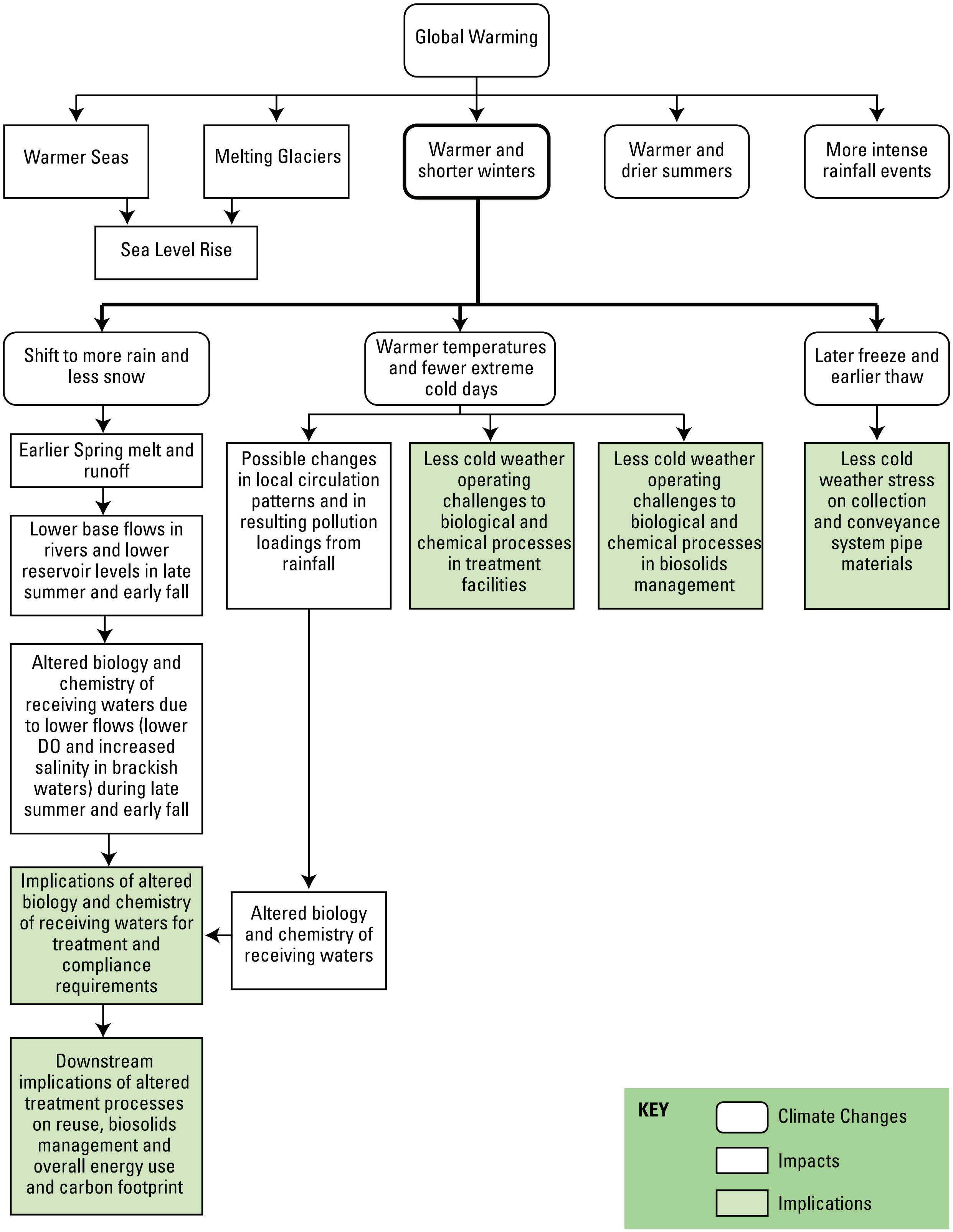
Impacts and Implications of Sea Level Rise for Wastewater Agencies



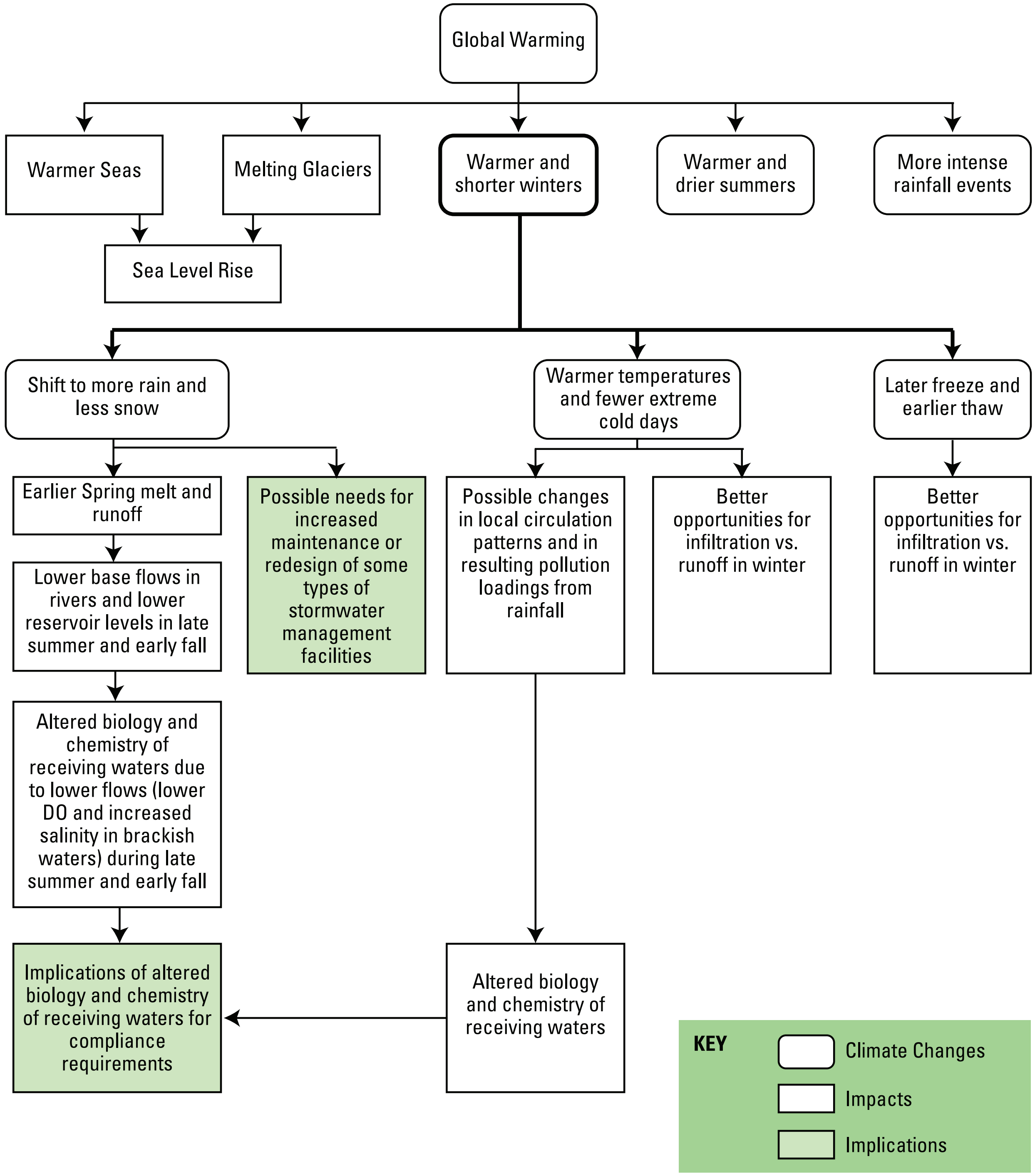
Impacts and Implications of Sea Level Rise for Stormwater Agencies



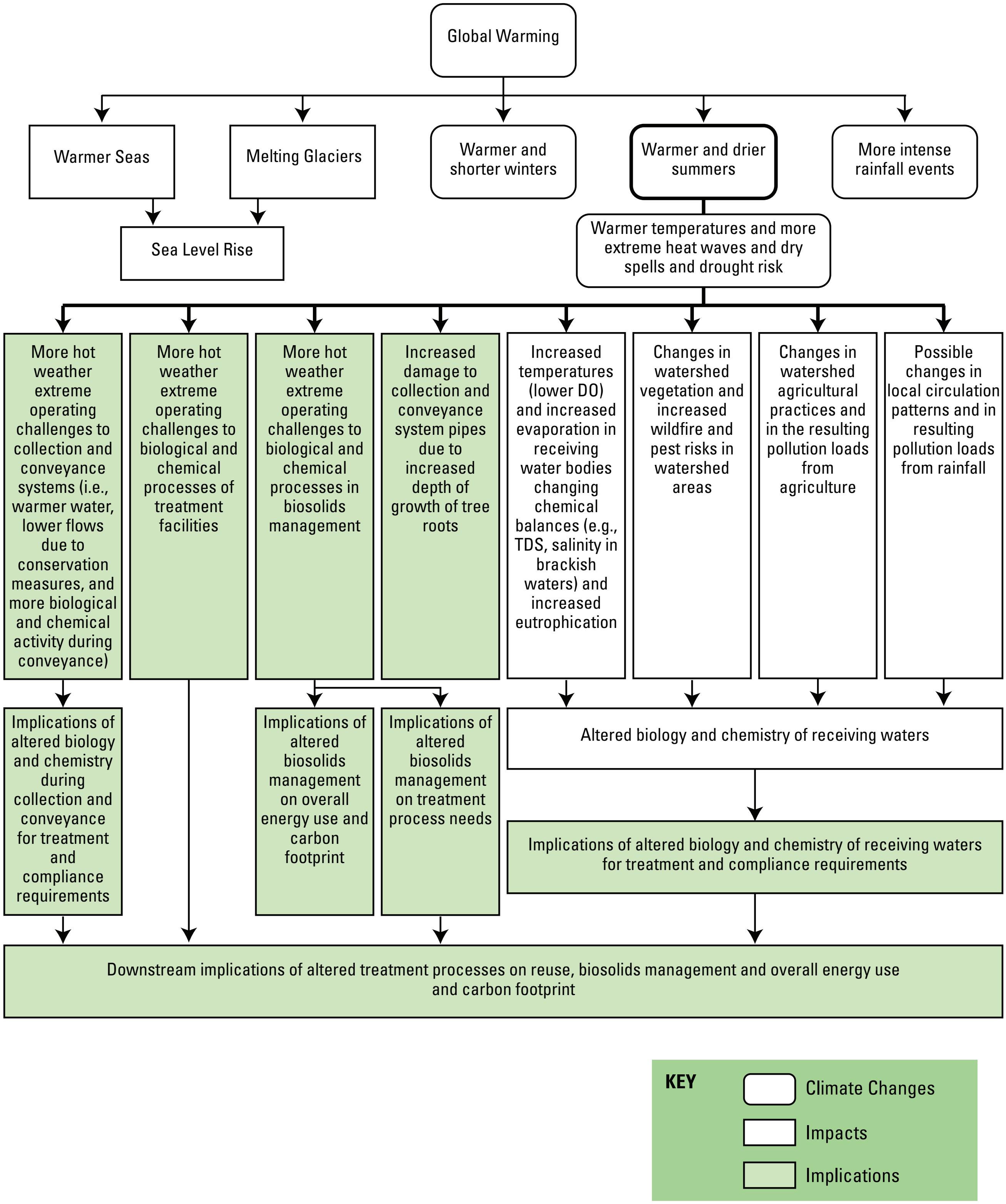
Impacts and Implications of Warmer and Shorter Winters for Wastewater Agencies



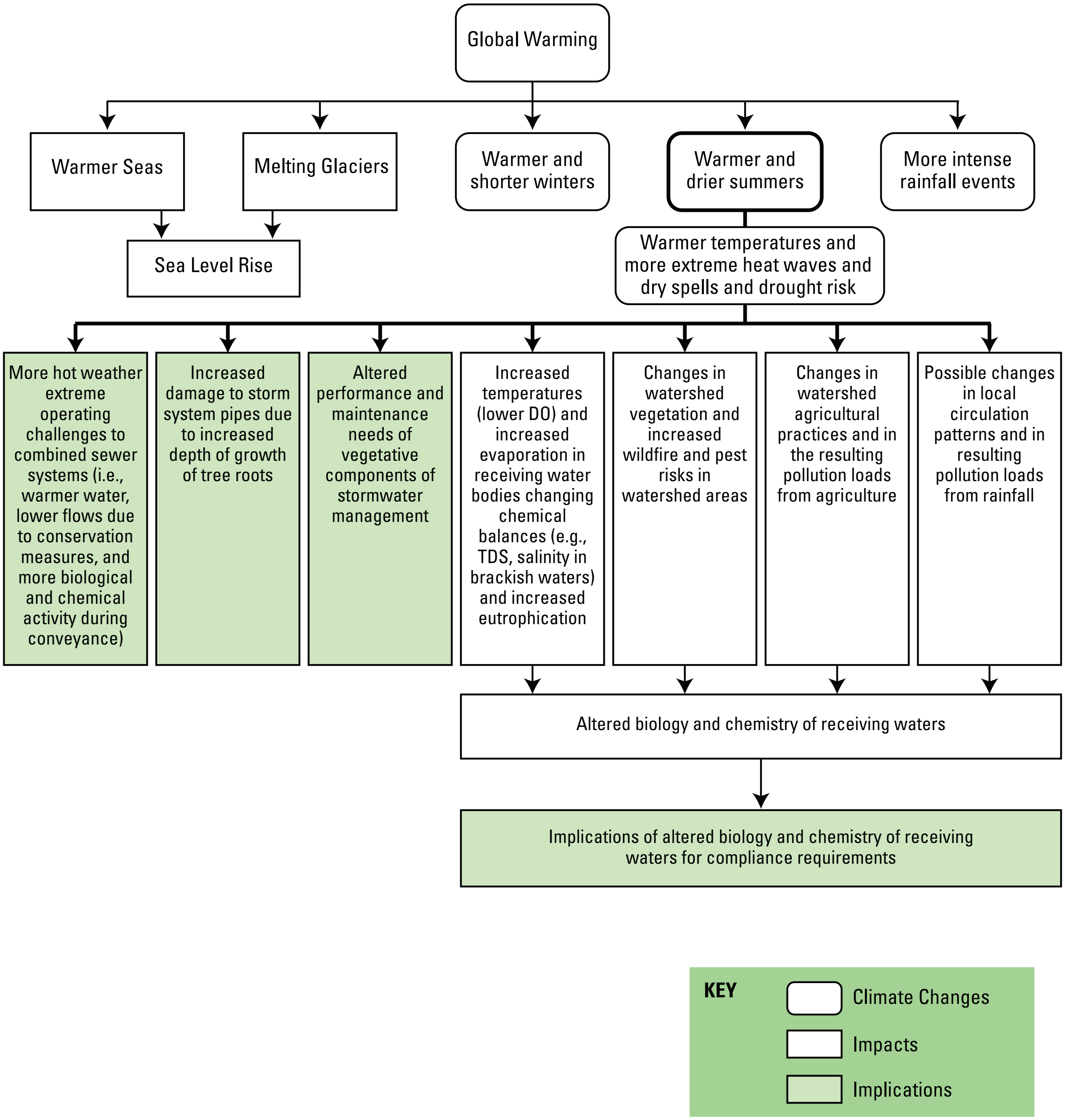
Impacts and Implications of Warmer and Shorter Winters for Stormwater Agencies



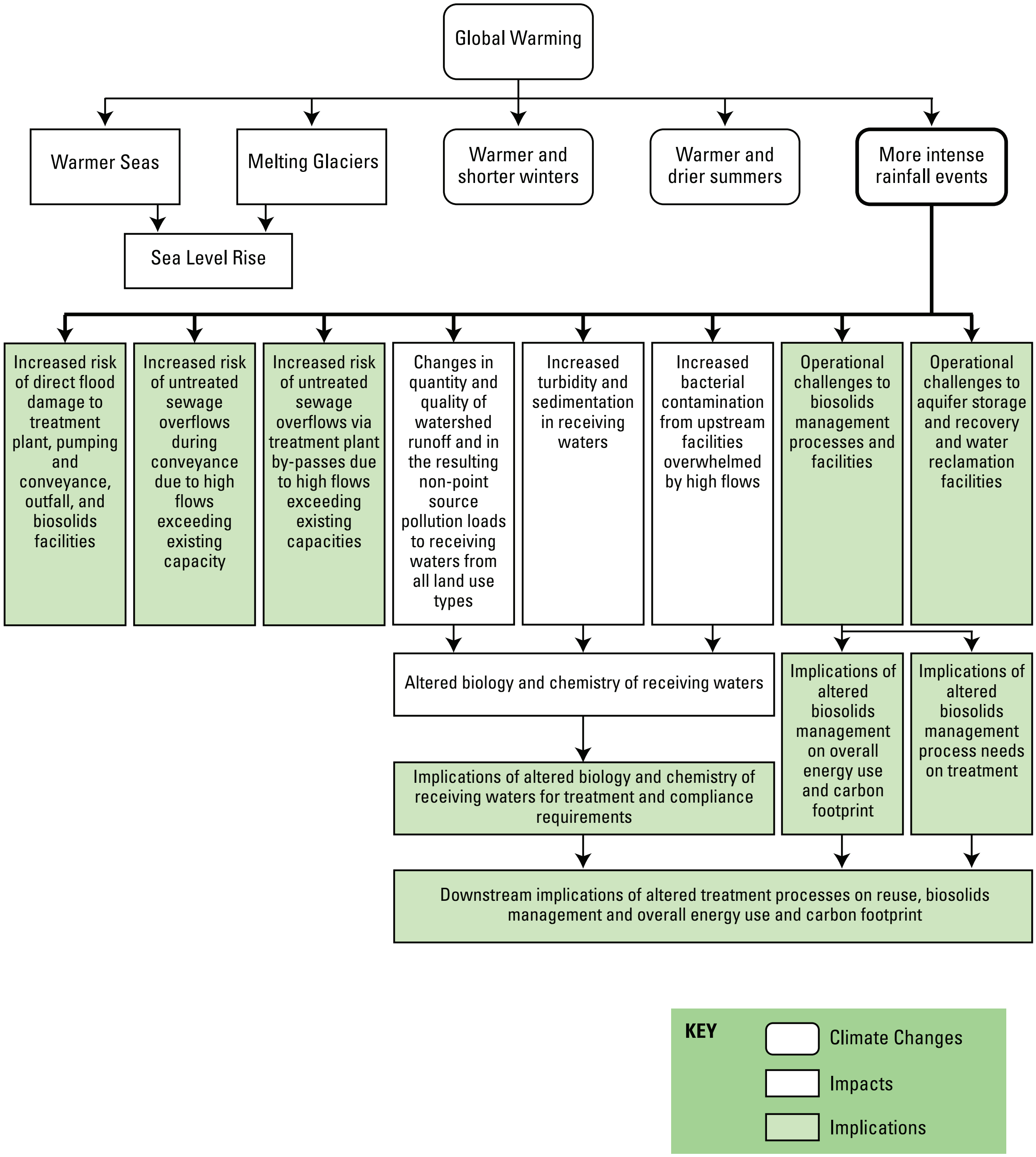
Impacts and Implications of Warmer and Drier Summers for Wastewater Agencies



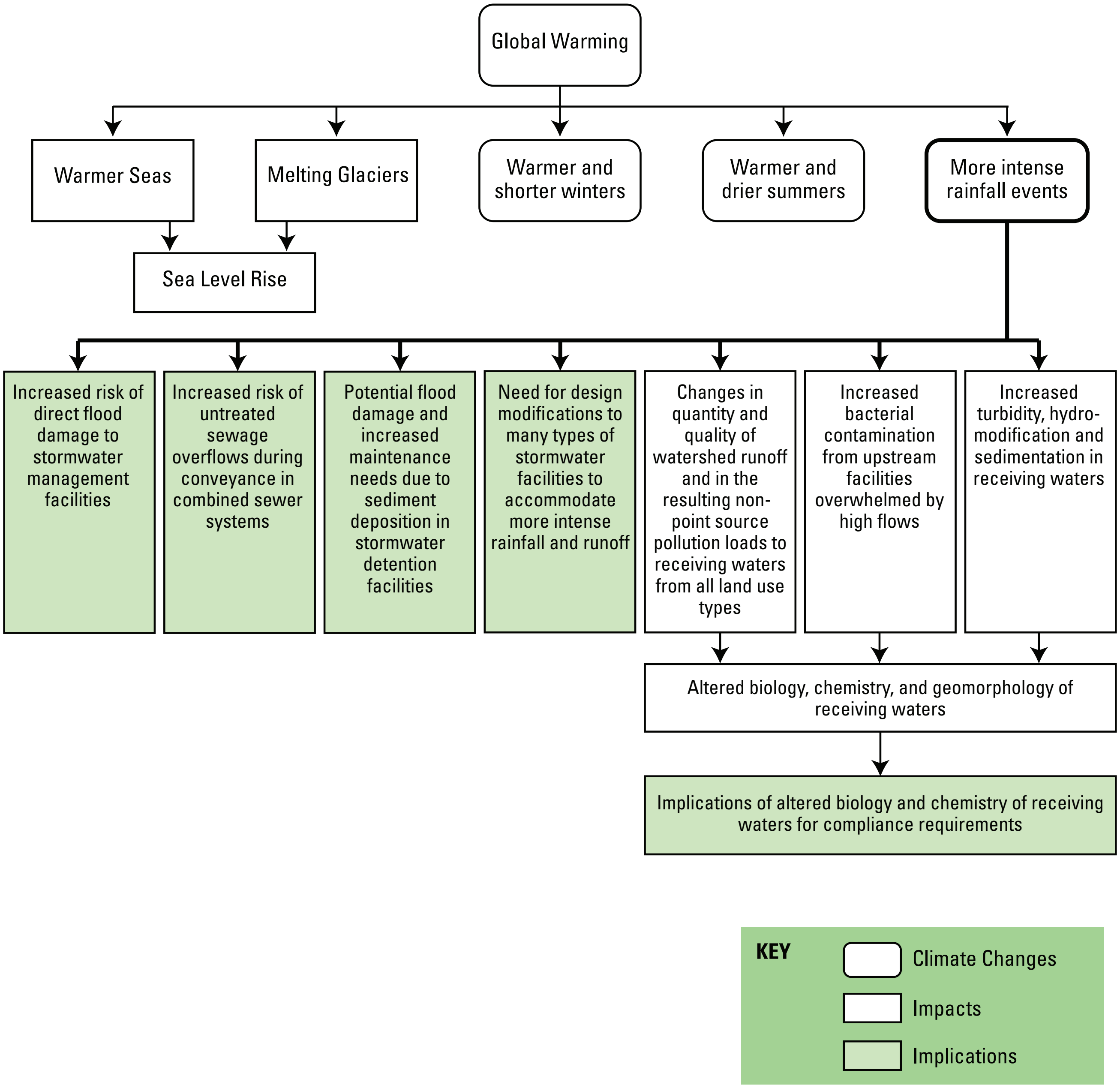
Impacts and Implications of Warmer and Drier Summers for Stormwater Agencies



Impacts and Implications of More Intense Rainfall Events for Wastewater Agencies



Impacts and Implications of More Intense Rainfall Events for Stormwater Agencies



1. INTRODUCTION

The development of this report on the implications of climate change for wastewater and stormwater agencies was recommended in the Water Environment Research Foundation's exploratory team report (WERF, 2008) to help outline a beginning strategy and road map for WERF's Climate Change Challenge. The exploratory team broadly conceived the Climate Change Challenge as described below.

WERF's Climate Change Challenge

Develop value-added research which will provide a solid understanding by wastewater industry management and WERF subscribers of the likely impacts of climate change, including impacts on water quality, wastewater services and costs. The outcome of this challenge will be methods, processes, tools and information for effective planning and operational management of wastewater services to cost-effectively mitigate and adapt to the potential impacts of climate change.

This Challenge will provide information, guidance and tools to the industry to:

- Identify and reduce greenhouse gas emissions
- Understand and minimize impacts to operations due to changing hydrologic and climatic conditions
- Make decisions on capital improvements in the face of climate uncertainty
- Communicate management approaches and their costs to its customers

The first bullet regarding greenhouse gas emissions relates to industry efforts to help with the ***mitigation*** of global warming and resultant climatic impacts. The exploratory team concluded that these energy management and process optimization aspects of addressing climate change are already included in the WERF Optimization Challenge. Hence, they concluded that the focus of WERF research efforts in the Climate Change Challenge needs to be on assisting wastewater and stormwater agencies in ***adaptation*** of their operations and facilities to cope with the impacts of climate change, as represented by the other three bullets above.

This report is therefore designed to identify and characterize climate change impacts to set the stage for defining research needs in support of adaptation. This report does not address the topic of ***mitigation*** through control of greenhouse gas emissions except incidentally where such actions may conflict with ***adaptation*** strategies.

In defining the objectives for this report, WERF's Issue Area Team (IAT) identified a companion need to provide suitable background on climate change. This is intended to help raise the awareness and understanding of climate change and its impacts among industry professionals. It is also intended to provide an authoritative resource for industry professionals to share with stakeholders and governing officials.

The inherent complexity of climate change and the related information overload can be a barrier to engaging in adaptation planning. There is a growing amount of information about climate change. Some presentations are piecemeal and others are overwhelmingly comprehensive. There are many interrelated aspects relating causes and effects; there is a crucial time dimension; and there are large uncertainties that will likely not be resolved in the near term. These complications need to be surmounted to progress into an action phase involving adaptive responses. Accordingly, this report is organized in two parts, as follows.

Organization of Report

Part I (sections 2 and 3) provides a background understanding of climate change. Section 2 describes how the warming effect on the atmosphere is produced by greenhouse gases and reviews major climatic and hydrologic changes projected to result. Section 3 provides a review of the climate models that have been relied upon to support the scientific consensus described in Section 2. While it is important to know something about climate models, it is not important to know everything about these very sophisticated models that run on super computers. Whether continued refinement of these tools can enhance adaptation strategies is an important question relating to research needs. It is, however, a very technical question that has been set aside for purposes of this report. A summary of research prospects in this area has recently been produced by the Water Utility Climate Alliance (WUCA, 2009).

Part II (sections 4 and 5) defines potential impacts and addresses adaptation issues and research needs in the wastewater and stormwater sectors. Despite scientific consensus regarding the main elements of climate change, uncertainties remain about the magnitude and timing of expected impacts. As a result, there is growing awareness that adaptation planning must be approached within a risk management framework, involving familiar steps of: 1) risk identification, 2) risk assessment/characterization, and 3) risk management (adaptation). Part II adopts this approach as described below.

Following the structured approach of the cause-effect tree diagrams presented in the Summary of this report, Section 4 identifies potential impacts of climate change on the operations and infrastructure of wastewater and stormwater agencies. The discussion traces the implications of climate model forecasts and of some trends already apparent in historical data relevant to each category of potential impact.

Section 5 describes a structured approach to adaptation planning following the risk assessment and risk management steps of the risk management paradigm. In the climate arena, this approach is also referred to as a "bottom-up" or threshold approach to adaptation planning. After describing the approach, Section 5 then applies it to the top categories of potential impacts (risks) identified in the Section 4 analysis. These applications are presented as separate subsections that consider for each of the major potential impact categories: 1) the major questions facing wastewater and stormwater agencies in assessing or characterizing the risk; 2) the major adaptation options (risk management strategies) that are apparent; and 3) the obvious places where research might improve the ability to conduct these key steps.

2. CLIMATE CHANGE PROCESSES

Climate refers to the long-term average behavior of weather in a particular location or region. It is also used to describe mean global conditions. Climate is characterized by environmental variables including air temperature, precipitation, wind speed and direction, relative humidity, cloudiness, and the frequency and intensity of storms. The global climate system is a dynamic process that is driven by energy in the form of solar radiation and mediated by the physical characteristics of Earth's surface and atmosphere. The intensity of solar radiation reaching the top of Earth's atmosphere is relatively constant over time, although minor variations occur that are associated with sunspots and other solar phenomena. By contrast, the amount of radiation reaching the Earth's surface is highly uneven, as influenced by latitude and season, by surface characteristics (land cover, snow and ice, oceans and other bodies of water), and by the distribution and density of clouds and aerosols. The uneven heating of surface and overlying atmosphere give rise to the movement of air masses, which both modify, and are modified by the temperature and moisture regimes of the surfaces over which they pass (Bonan, 2002). Some air mass movements, referred to as global circulation patterns, are highly organized and global in scale, and act to redistribute heat from equatorial regions toward higher latitudes. Other, more localized movements underlie what we commonly experience as "weather". Atmospheric moisture plays a key role in the global redistribution of heat, since significant quantities of heat are released when water evaporated over tropical oceans becomes precipitation over temperate regions.

Climate is not static, and exhibits variability at a range of time and spatial scales. Variation at short timescales, such as day-to-day variations in weather, are not considered changes in climate, but rather variation within climate. Some annual- to decadal scale climate variability is internal to the Earth's system, and includes episodic shocks such as volcanic eruptions, and complex ocean-atmosphere interactions such as El Nino-Southern Oscillation (ENSO). At millennial timescales, changes in Earth's orbital dynamics amplified by terrestrial feedback can result in changes in the global radiation budget sufficient to cause Earth's climate to oscillate between ice ages and warm inter-glacial periods (Solomon et al., 2007). More recently, concern has focused on the hypothesis that human actions are having profound consequences on global and regional climate. Since the 1980s, the scientific community has allocated substantial resources to examine this hypothesis. Its findings are summarized by the Inter-Governmental Panel on Climate Change (IPCC) in their Periodic Assessment Reports, by the U.S. Global Change Research Program (USGCRP) through a series of Synthesis and Assessment Products and by a wide range of other peer-reviewed publications and "gray literature". The fourth and most recent IPCC Assessment Report (IPCC, 2007) is unequivocal in its interpretation of the body of scientific evidence: (i) greenhouse gasses (GHG) have accumulated in the atmosphere at levels greatly exceeding those prevailing over the last 650,000 years; (ii) the use of fossil fuels, combined with agriculture and other land use changes are the dominant causes of these GHG increases; and (iii) it is "*extremely likely* that human activities have exerted a substantial net warming influence on climate since 1750" (Solomon et al., 2007).

The primary task of the IPCC is to synthesize the large and growing body of scientific findings related to climate change and present the consensus view on important climatic trends and projections. In order to characterize accurately the relative cohesion of expert belief regarding climate change, the Fourth Assessment Report (IPCC, 2007) has developed specific guidelines for the use of language to convey the strength of scientific consensus. When assessing the *likelihood (probability)* that a particular outcome is true on the basis of statistical evidence, the IPCC uses a likelihood scale. To express the *degree of confidence* that experts have with respect to a specific assertion or hypothesis, the confidence scale is used.

IPCC Likelihood Scale

Likelihood	Definition
Virtually certain	> 99% probability
Extremely likely	> 95% probability
Very likely	> 90% probability
Likely	> 66% probability
More likely than not	> 50% probability
About as likely as not	33% - 66% probability
Unlikely	< 33% probability
Very unlikely	< 10% probability
Exceptionally unlikely	< 1% probability

IPCC Confidence Scale

Confidence level	Definition
Very High Confidence	At least 9 out of 10 chance of being correct
High Confidence	About 8 out of 10 chance
Medium Confidence	About 5 out of 10 chance
Low Confidence	About 2 out of 10 chance
Very Low Confidence	Less than 1 out of 10 chance

The mechanism by which the build-up in the atmosphere of CO_2 and other heat-trapping gasses (GHG) leads to changes in climate is referred to as the *greenhouse effect.* According to physical theory proposed as early as 1896 (S. Arhennius), the greenhouse effect results when the earth's surface, warmed by incoming short-wave solar radiation, re-emits long-wave (infrared) radiation, and this long-wave radiation is partially absorbed by CO_2 and other GHGs in the lower atmosphere, as determined by their molecular structures. Some of this trapped infrared radiation is re-emitted downward, and the greenhouse effect thus results in warming of both the lower atmosphere and the earth's surface. (Loaiciga et al., 1996).

In the absence of changes in the composition of the atmosphere and land cover, the Earth's energy budget reaches an approximate state of thermal equilibrium, radiating as much heat outward from the planet and atmosphere as is received in net terms in the form of solar radiation. Any non-natural change that acts to disturb this equilibrium is referred to as a *radiative forcing*. Positive forcings lead to warming, and negative forcings to cooling. Among GHGs, CO_2, released primarily through the burning of fossil fuels and biomass, is the most significant in terms of its overall contribution to warming. Other important GHGs include methane (CH_4), nitrous oxide (N_2O), various halocarbons and ozone. Water vapor is itself a greenhouse gas, and increasing atmospheric humidity (absolute) may act as a positive feedback, contributing to further warming of the atmosphere. The emission of aerosols, both from natural processes (e.g., sulfate from volcanic eruptions) and through human activities, tend to act, on balance, to reduce warming by absorbing or reflecting incoming short-wave radiation, although the magnitude of the cooling effect of aerosols is currently less than the warming impact of GHGs (Solomon et al., 2007).

Efforts to understand climate change have also focused on the hydrologic cycle. The circulation of moisture-laden air is one of the primary mechanisms of heat redistribution globally. Moisture evaporated from tropical oceans warms the mid-latitudes, and ultimately the polar regions, via latent heat transfer (Laoiciga et al., 1996). Ocean currents are another major mechanism of global heat redistribution. The primary expression in the hydrosphere of increased radiative forcing is an intensification of the hydrologic cycle. Atmospheric cycling of water increases in response to increasing surface- and near surface temperatures through the dependence of atmospheric water-holding capacity on temperature. The Clausius-Clapeyron equation, which describes saturation vapor pressure as a function of air temperature, predicts an increase in atmospheric water-holding capacity of around 7% for each degree (C^0) of warming at current global mean temperatures (Trenberth et al., 2003). As increasing atmospheric moisture demand is reflected in actual evaporation rates, globally-averaged annual precipitation rates should increase as well, as more water is cycled through the atmosphere. Physical theory, climate models and historical data also point to an increase in the frequency and magnitude of extreme or heavy precipitation events, due to increases in both atmospheric water and in energy available to drive convective processes (Trenberth et al., 2003). The dynamics of the global energy and water cycles are depicted in Figure 2-1.

2.1 Global Warming – Temperatures Rising

The primary attribute of climate change as predicted by greenhouse theory is an increase in global mean temperature. Support for the hypothesis of greenhouse warming is provided by careful statistical analysis of systematic climate records available since around 1850, augmented by paleoclimate reconstructions and model simulation studies covering much longer periods. The identification of historical trends in global temperature is complicated by the "noise", or year-to-year variability in this data. Nevertheless, analysis of instrumental records from 1850-2005 indicates that globally-averaged temperatures have increased by 0.76 ºC (+/- 0.19 ºC) over this period, with the most rapid warming occurring in the last 50 years (IPCC, 2007; Bates, et al., 2008). Eleven of the warmest 12 years since 1850 have occurred since 1995. Using the language conventions adopted by the IPCC, the scientific consensus is that "Greenhouse gas forcing has *very likely* caused most of the observed global warming over the last 50 years." These global trends are summarized in Figure 2-2. The steepest increase in global temperatures, equivalent to changes of +0.177 ºC per decade, is seen to have occurred over the last 25 years.

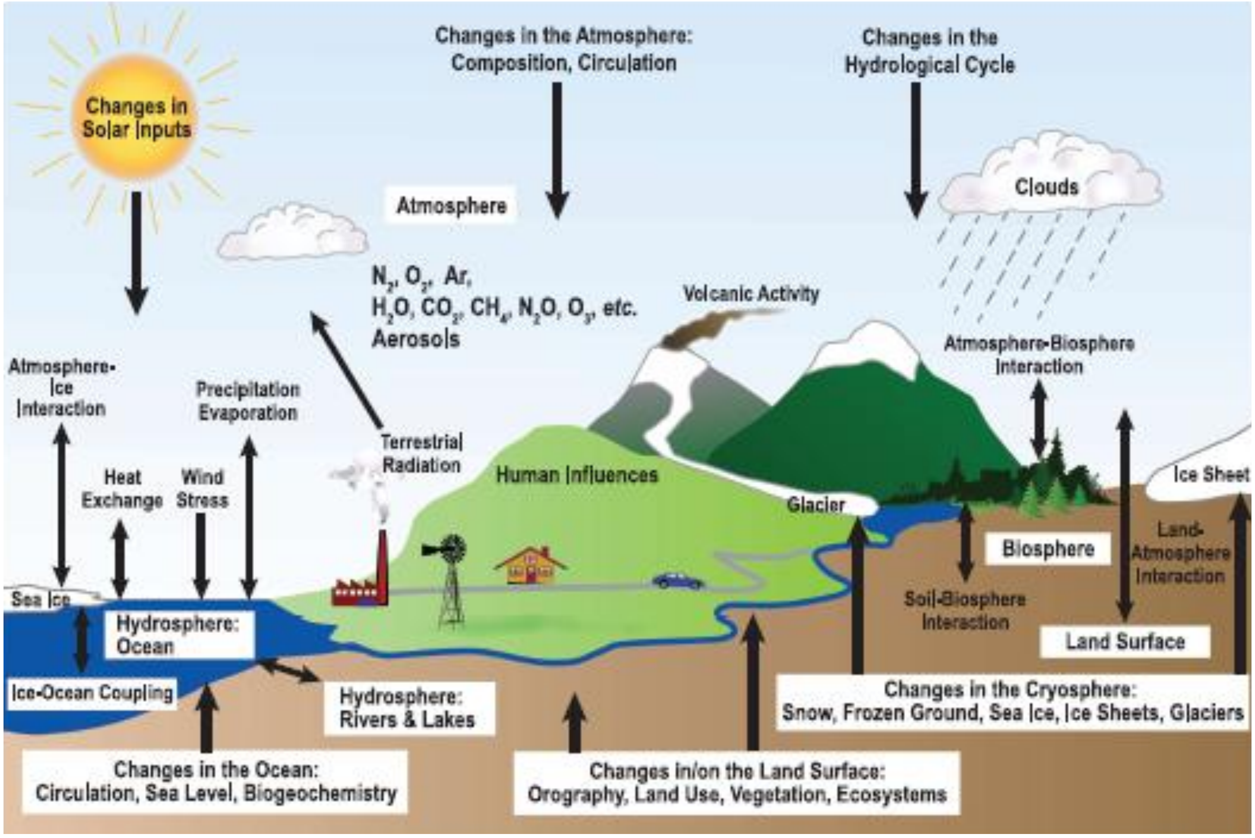


Figure 2-1 – Coupled Global Energy and Water Cycles. Source: Le Treut et al. (2007) p. 104.

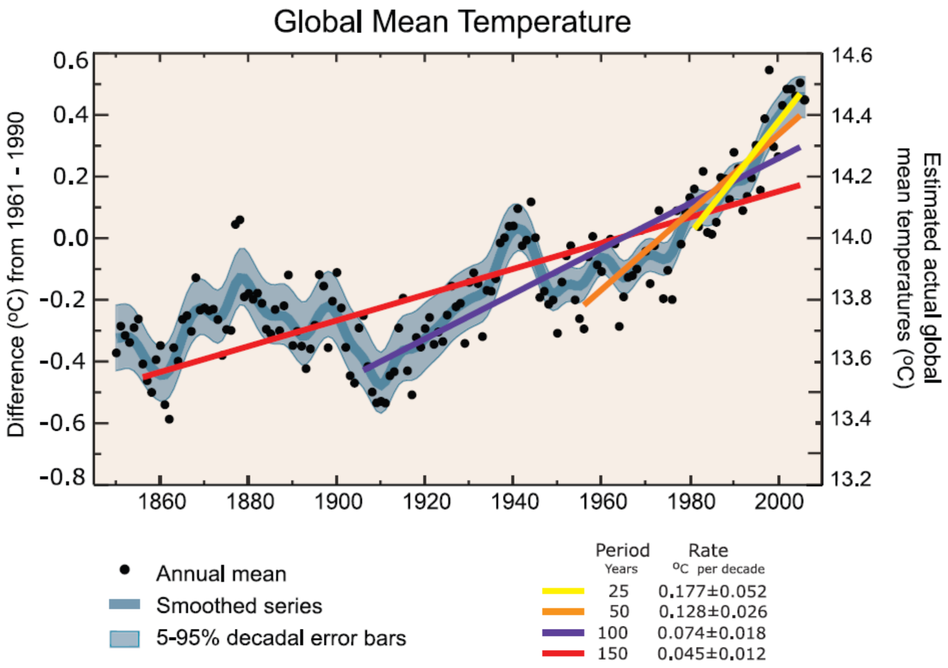


Figure 2-2: Annual Observed Global Mean Temperatures (Trenberth, et al., 2007).

Underlying this general warming trend are significant spatial and temporal patterns. In general, surface temperatures have increased more rapidly over land areas than over oceans. Over the past two decades, the rate of temperature increase over land (+0.27 °C) has increased at twice the rate of increases over water (+0.13 °C). It is also observed that the rate of warming is significantly greater at higher (Northern) latitudes than in the tropics; and within Northerly regions, the rate of increase has been greatest during winter. Temperatures in the Arctic have increased at roughly twice the global rate. In addition, night-time minimum temperatures and daytime maximum temperatures have increased over the last several decades of the 20th Century. However, the evidence indicates that the daily temperature range has not changed significantly over the 1979-2004 period, indicating that minimum and maximum temperatures are increasing at roughly similar rates (IPCC, 2007). Finally, trends in mean temperatures are reflected in the behavior of extremes: the observed number of warm extremes (warmest 10% of days or nights) has increased, and the number of cold extremes (coldest 10% of days or nights) has decreased; in particular the number of cold nights. The duration of heat waves has also increased (Solomon et al., 2007).

Within the United States, temperature increases have also been observed over recent decades at rates exceeding the global average (Figure 2-3). Temperature increases have been most pronounced over the last five decades, and present (1993-2008) U.S. temperatures are on average over 1.1 °C warmer than during the 1961-1979 baseline period. The warming pattern is characterized by longer warm seasons and shorter, less intense cold seasons (Karl et al., 2009). 1998 ranks as the warmest year on record for the U.S.

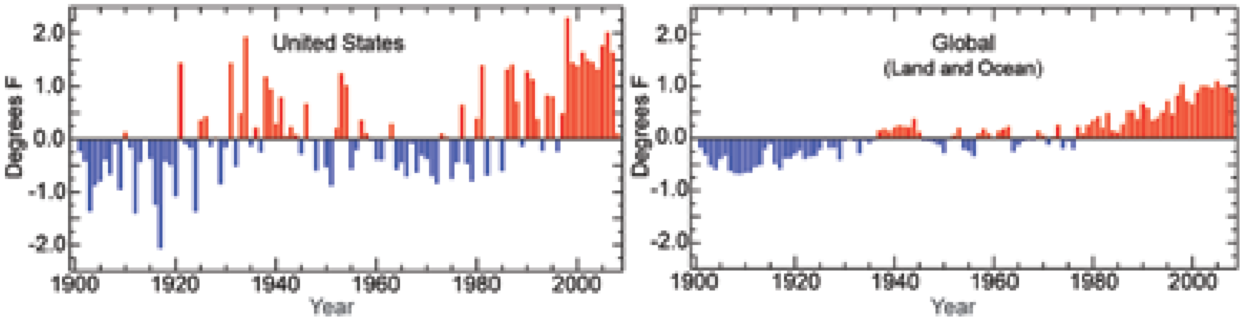


Figure 2-3: Average annual temperatures in the U.S. and globally. Bars indicate departure from 1901-2000 average. Source: Karl et al. (2009) p. 27.

2.2 Climatic and Hydrologic Cycle Implications of Warming

Changes in earth's energy balance ("global warming") are reflected in changes in nearly every aspect of the hydrologic cycle. Increasing air temperatures lead to increases in atmospheric moisture-holding capacity, resulting in higher rates of actual evaporation where water is available. Higher evaporation rates in turn lead to increases in precipitation, and in particular, to increases in high-intensity precipitation events. High-precipitation intensity results in higher rates of runoff, surface erosion and the mobilization of soil and contaminants. In regions where summers are characteristically dry, increased evaporation rates lead to drier soils, reduced groundwater infiltration and base flow. Warming also influences the dynamics of snow and ice: warmer air temperatures mean less winter snowfall and more rainfall in temperate climates; which in turn alter the seasonal pattern of runoff. Warmer air temperatures also lead to warmer water temperatures, which have negative impacts on water quality and habitat suitability. At global scale, sea level rises due to thermal expansion of seawater and the melting of glaciers and ice sheets. Each is discussed below.

2.2.1 Precipitation and Evaporation

Analysis of historical climate data generally supports predictions of increasing average precipitation associated with increasing temperature. Statistical analysis of several global precipitation datasets indicates that annual precipitation over land areas has generally increased over the 20th Century at mid- and upper latitudes (30^{0} N – 85^{0} N) and in the Southern Hemisphere deep tropics, although decreases in precipitation have been observed from 10^{0}S – 30^{0} N, most significantly since the 1960's (Bates et al., 2008). While precipitation has increased on average over these large areas, some areas had decreased precipitation. While many factors potentially contribute to observed changes in precipitation, anthropogenic forcing is estimated to have played a dominant role (Zhang et al., 2007). While average changes in precipitation are important, so too is the pattern of change. An important dimension of changing precipitation patterns is the extent to which heavy, very heavy and extreme rainfall events have increased, both in absolute and in relative terms (Alexander et al., 2006).

Precipitation over the U.S. has also increased by around 5% over the last 50 years. Not all areas became wetter, as Figure 2-4 indicates, with the greatest annual increases occurring in the Northeast and some mid-continental regions while the Southeast and Southwest have become drier. Seasonal shifts in the pattern of precipitation have occurred also, with many regions experiencing increases in winter and spring precipitation, and reductions in summer and fall (Karl et al., 2009). Much of the recent increase in precipitation over the U.S. can be accounted for by an increase in heavy downpours. For example, Groisman et al. (2005) found that while total annual precipitation volumes over the United States increased by 1.2% per decade over the period 1970-1999, the share of annual precipitation associated with extreme events, defined as the upper 0.1% of precipitation events, increased by 14% per decade over this period. In other words, increases in precipitation were not distributed evenly, but tend to come mostly in intense precipitation

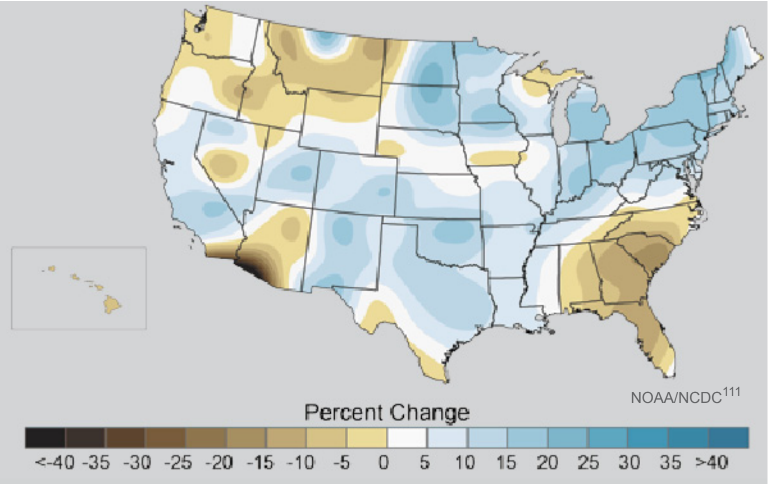


Figure 2-4 – Observed changes in annual average precipitation, 1958-2008. Karl et al. (2009) p. 30.

events. The greatest increases in heavy precipitation events have occurred in the Northeast and Midwest (Kunkel et al., 2008).

Historical trends in evaporation and plant transpiration (collectively called evapo-transpiration, or ET) are more difficult to identify, since relatively few systematic long-term ET time series records exist (Trenberth et al., 2007; Lettenmaier et al., 2008). Although the linkages between increasing temperatures, atmospheric moisture-holding capacity and evaporation are relatively straightforward in physical terms, there are complexities involved in interpreting the impact of climate change on evapo-transpiration. The literature is not clear on whether evaporation has increased. A relatively small number of recent studies in the U.S., India, China and Australia that make use of long-term evaporation pan data conclude that actual evaporation rates have *decreased*. One proposed explanation for this paradox is a reduction in incoming solar radiation due to increases in aerosols associated with air pollution (Trenberth et al., 2007). Alternatively, Brutsaert and Parlange (1998) conjecture that as humidity supplied by the surrounding landscape increases, pan evaporation will decrease (a reverse of the “oasis effect”). Evidence of a temperature-induced *increase* in actual evaporation is provided by Yu and Weller (2007). These researchers utilized satellite remote sensing and atmospheric model re-analysis to estimate trends in evaporation over the ocean surface, where moisture supply is not limited. They estimate that globally averaged ocean latent heat flux (evaporation) has increased by approximately 10% over the 25-year period 1981–2005. This reflects increases in both atmospheric moisture capacity (Clausius-Clapeyron) and sea surface temperature.

Transpiration – the evaporation of water through the leaves of vascular plants – is affected by climate change through another mechanism in addition to temperature increase. Plants that perform photosynthesis take in CO_2 and evaporate water vapor through their stomata, which are microscopic pores on the leaf surface. Higher atmospheric concentrations of CO_2 should allow plants to increase their water use efficiency by operating with more narrow stomatal openings, so that transpiration per unit of biomass could decrease as atmospheric CO_2 levels rise (Ainsworth and Rogers, 2007). This might to some degree offset the impacts of increased temperature on atmospheric water demand. Several studies have attempted to measure the large-scale impacts of increased CO_2 on transpiration by measuring differences over time in continental runoff (Gedney et al., 2006; Piao et al., 2007; Krakauer and Fung, 2008). Each study identified an implied reduction in plant transpiration in response to increased atmospheric CO_2, although these changes were offset by increases in overall leaf area density, and increased atmospheric water demand, depending on the methodology employed in the respective study. As with evaporation, it is not clear how transpiration has changed.

A synthesis of water balance studies of several major North American watersheds (Walter et al., 2004), in which ET was estimated as the residual of precipitation and discharge, concludes that actual ET has *increased* over the last 50 years. Given the mixed results on evaporation and transpiration, it is difficult to determine whether ET as a whole has increased or decreased.

2.2.2 Reduced Snowfall and Snowpack

In Northern, temperate and high-altitude regions, warmer air temperatures are likely to result in shorter, warmer winters. A greater fraction of precipitation will fall as rain rather than as snow, snowpack accumulation will be reduced, and spring snowmelt runoff will occur earlier in the year. Many of these impacts are already apparent, particularly in the Western U.S. Lettenmaier et al. (2008) summarize several studies of western snowpack dynamics. Findings include a reduction in April 1 snow water equivalent (SWE) at over 230 sites, which is particularly apparent at lower elevations (Mote, 2003). Other researchers conclude that the observed trends toward reduced winter snowpack can be attributed primarily to increasing temperatures, as distinct from changes in precipitation (Hamlet et al., 2005). Stewart et al. (2007) have evaluated the timing of spring runoff using center of mass timing (i.e., the date by which 50% of annual runoff has occurred) and identified consistent trends toward earlier runoff in snowpack-dominated western basins. These shifts are of particular concern in the Western U.S. given the general scarcity of water resources and the importance of winter snowpack storage in water resource management.

2.2.3 Changes in Streamflow

Warmer average temperatures are anticipated to alter surface runoff through a variety of mechanisms, the most important of which is increased evapo-transpiration (ET). Changes in the quantity and timing of precipitation (rain and snow) will also influence runoff patterns. Changes in land cover and land use will also alter streamflow patterns, making it difficult to attribute any observed trends to climate change. A number of careful studies have attempted to minimize the potential influence of land use change by restricting analysis to stream gauging records from catchments in which the impacts of human activities are known to be minimal. Lins and Slack (1999, 2005) examined trends in a range of statistics derived from daily flow-duration curves, including annual minimum and maximum flows and the 10%, 30%, median, 70% and 90% quantiles. The number of upward trends (indicating increasing streamflow volume) greatly exceeded the number of negative trends for all but maximum flows. Most of the positive (increasing) trends are found in the Northeastern and Midwestern U.S. Mauget (2003) found similar results: positive trends in streamflow, beginning in the 1970s through the late 1990s and occurring in the Eastern U.S.; and negative trends in the western U.S. commencing in the 1980s.

Many of the changes in climate and hydrology observed within the U.S. over the last several decades are summarized in the U.S. Global Change Research Program summary report (Karl et al., 2009). Table 2.1, prepared by the U.S. Global Change Research Program (2009), summarizes observed 20th Century changes and trends associated with climate and water resources.

Table 2-1 Observed water-related changes during the last century. Karl et. al. (2009) p.43.

Observed Change	Direction of Change	Regions Affected
One- to four week earlier peak stream-flow due to earlier warming-drive snowmelt	Earlier	West, Northwest
Proportion of precipitation falling as snow	Decreasing	West, Northwest
Duration and extent of snow cover	Decreasing	Most of U.S.
Mountain snow water equivalent	Decreasing	West
Annual precipitation	Increasing	Most of U.S.
Annual precipitation	Decreasing	Southwest
Frequency of heavy precipitation events	Increasing	Most of U.S.
Runoff and streamflow	Decreasing	Colorado, Columbia River Basins
Streamflow	Increasing	Most of East
Amount of ice in mountain glaciers	Decreasing	U.S. Western mountains; Alaska
Water temperature of lakes and streams	Increasing	Most of U.S.
Ice cover on lakes and rivers	Decreasing	Great Lakes; Northeast
Periods of drought	Increasing	Parts of West and East
Salinization of surface waters	Increasing	Florida, Louisiana
Widespread thawing of permafrost	Increasing	Alaska

2.2.4 Sea Level Rise (SLR)

Throughout much of recorded human history, sea level has remained relatively static. By contrast, over geologic timespans sea levels have changed dramatically. During the last Glacial Maximum (ca. 20,000 years ago), mean sea level was roughly 400 feet (120 m) below its present elevation, and during the Pliocene warm period (ca. 3 million years ago) it was as much as 80 – 115 feet (25-35 meters) higher than the present level (Rahmstorf, 2007). These large variations reflect two primary mechanisms: thermal expansion of seawater, and the extent of fresh water stored in the Earth's continental glaciers and ice sheets. Each is linked to global and regional temperature regimes. Although relatively precise measurements of sea level globally have only recently been possible with the introduction of satellite altimetry in the early 1990s, global mean sea level can be reconstructed from the 1880s onward. Sea levels have increased since the mid-19th Century, and the IPCC concludes with *high confidence* that the rate of sea level rise has accelerated over this period. Sea level is expected to continue to rise over the 21st Century, although the rate and extent are subject to uncertainty (Hansen, 2007).

3. CLIMATE CHANGE MODELING AND FORECASTING

Physical theory and accumulated historical evidence strongly support the contentions that Earth's climate is already changing, and that human actions are largely responsible. Due to the historical accumulation of greenhouse gasses in the atmosphere, Earth's climate will continue to warm. Since many GHGs, and CO_2 in particular, persist in the atmosphere for decades to centuries, we are "committed" to a certain degree of further climate change even in the absence of new emissions. Although international efforts are underway to reduce GHG emissions, the likely trajectory of global economic development and associated energy use suggests that atmospheric CO_2 levels will increase further before they can be stabilized and eventually reduced. It will be necessary for societies to develop and to implement a range of strategies for adapting to an altered climate. This process is complicated by a range of uncertainties. Among sources of uncertainty are the *unpredictability* of human political and economic behavior, particularly over long timescales, the *structural uncertainty* in our scientific tools and frameworks of analysis, and *value uncertainty* – our lack of knowledge concerning the likely values of important regional environmental variables which, if known, would facilitate adaptive planning (IPCC 2005). Evidence presented in the IPCC (2007) and elsewhere convincingly establishes that "stationarity is dead", although stationarity – "the idea that natural systems fluctuate within an unchanging envelope of variability" (Milly et al., 2008) – has long been the basis for the design of water and related infrastructure. Managers of wastewater and storrmwater management agencies now face a greater challenge. As the climate change research community is striving to overcome the challenges of improving forecasts of global-scale phenomena, water managers require more precise and accurate projections of *regional* climate conditions, which are subject to much greater levels of uncertainty.

The IPCC Task Group on Data and Scenario Support for Impact and Climate Assessment (TGICA) identified five criteria that must be satisfied if regional scenarios are to be used effectively for impact or operational purposes. Scenarios must be (1) consistent with global projections, (2) consistent with physical theory, (3) applicable for impact assessment (i.e., must contain sufficient information to support appropriate decision-making), (4) representative of the range of potential future conditions; and (5) accessible (Carter, 2007, p.26). The IPCC considered a range of approaches to developing regional projections or climate change scenarios for water resources planning and management. These include the use of *synthetic scenarios* (sensitivity analysis); *analogue scenarios* (use of periods in the historical record that contain features consistent with projected climate change); *synthetic weather generators*; and *General Circulation Models* (GCM) and regionally down-scaled GCM outputs. General circulation models are currently the most effective tools for developing projections of future states of the climate, since they embody both the physics of the climate system as currently understood, and have been tested against historical conditions. They are in fact indispensable in understanding and projecting the likely progression of climate over the coming decades and centuries, since the current situation is unique and without precedent in Earth's geological history (Karl et al., 2009).

3.1 Brief Overview of the State of the Art of Climate Change Modeling and Forecasting

A *General Circulation Model* (GCM; also *Global Climate Model*) is a set of computer codes that solve mathematical equations that are based on our scientific understanding of the processes that govern the climate. GCMs are used to simulate the climates of the past and to make projections about future climate change. A model of global scope is required to simulate the climate – and in particular how all its interlocking pieces will react to the changes that humans are causing. A climate model must also be comprehensive enough to cover all the processes that are important on the time scales of the simulations. The current generation of coupled Atmosphere-Ocean General Circulation Models (AOGCMs) are made up of component models of the atmosphere, the oceans, the land surface, and sea-ice. These component models are coupled together, meaning that interaction is permitted among all component models. Versions of these component models have been developed and are continually refined at several major scientific research centers worldwide. From the perspective of water related impact assessment, the atmosphere and land surface components of the GCMs are most important, since performance in those areas is most closely related to the usability of AOGCM outputs for water related decision-making. Nonetheless all components are integral to creating a good simulation of the Earth's climate over the next century.

Climate models that also include a coupled model of the carbon cycle (and other biogeochemical cycles important to climate) are often referred to as *Earth System Models* (ESMs). ESMs explicitly model the uptake and release of carbon dioxide and other greenhouse gases by vegetation and by biological and chemical processes near the surface of the ocean. ESMs are necessary for emissions-driven climate projections where the resulting concentrations of greenhouse gases (GHGs) are calculated in the model rather than being specified as part of an input scenario.

Precipitation, wind, cloudiness, the ocean currents, air and water temperatures – these and other climate variables evolve in time and space governed by physical, chemical and biological processes. The processes included in the climate models are quite varied – from evapo-transpiration to cloud formation, the transport of heat and water vapor by the wind, infiltration of surface water into the soil, turbulent mixing of that air and of the ocean waters and so on. To the climate modeler these all have one thing in common – they can be expressed in terms of mathematical equations derived from a combination of scientific laws, empirical data, and observations. These equations are then converted into computer code along with information about the Earth's geography, such as the distribution of vegetation and soil types, a digital elevation model of topography, and the chemical composition of the atmosphere to form the basis for a climate model.

The variables in a climate model are projected forward at discrete time intervals, or model timesteps. Timesteps can range from a few minutes to an hour, depending on the spatial resolution of the model. As a result, GCMs simulate hourly and daily weather – and climate statistics are computed from climate models just as they are from observations.

Because of the complexity of the mathematical equations in climate models, these equations can only be solved using numerical approximations, even on the most powerful supercomputers. In order to determine the most precise result within this limitation, climate models typically divide the globe—the atmosphere and the oceans—into a grid in the horizontal and vertical, creating so-called "grid boxes" or "*grid cells*". The finer the grid, the higher the spatial resolution, and the more computer power required to run the simulations. The horizontal resolution is typically cited as representative of a component model's overall spatial and temporal resolution. Even this number is only indicative, as the details of the grid (or alternative methods of spatially representing the data) can differ from model to model. The horizontal resolution of AOGCMs has increased over time (Figure 3-1), and the current generation of models, which provides the basis for projections appearing in the latest assessment report (IPCC, 2007), resolve land areas to approximately 110 km on average, although substantial differences in resolution exist across models.

Many climate phenomena, such as thunderstorms, take place at spatial scales smaller than a model grid cell – be it a climate model or a weather model. An approach referred to as *parameterization* is used to account for the total effect of smaller scale processes averaged over the grid cell. Most of the output variables of interest to water managers are calculated in one or more of the model parameterizations. Examples of sub-grid scale processes represented in AOGCMs by parameterization include convective processes in thunderstorms, turbulent transport at the surface-atmosphere boundary layer, and cloud dynamics. Choice of the methods used in parameterization can have a sizable impact on a model's climate simulations. Parameterizations are developed from conceptual models, from empirical relationships based on observations from historical datasets, field experiments and satellites, and from simulations with specialized higher-resolution models. Parameterizations are "universal" in that they are applied the same way in all grid cells. There is not, for example, a separate parameterization of convective rainfall for Iowa and for the Amazon Basin. In the end, however, most parameterizations are highly empirical (CCSP, 2008a).

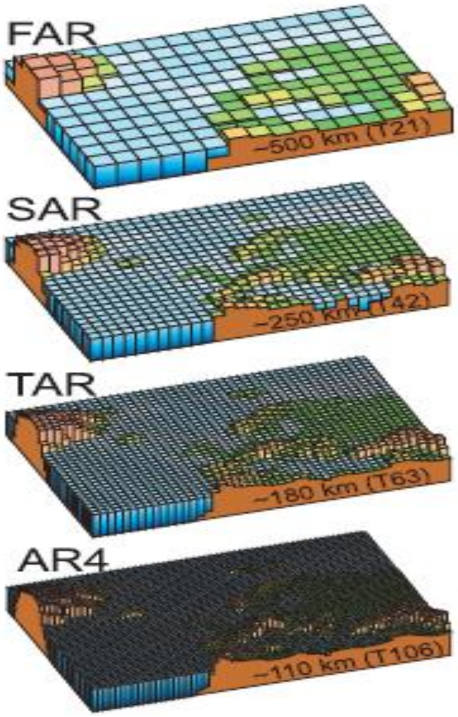


Figure 3-1 Improvements in GCM Horizontal Spatial Resolution. FAR is the first IPCC Assessment Report (1990); SAR is the second assessment report (1995), TAR the third assessment report (2001) and AR4 the fourth and most current assessment report (2007). Source: Le Treut et al., 2007.

3.2 Summary Characterization of Findings

Projections of global climate to 2100 presented in the IPCC's Fourth Assessment Report (IPCC, 2007) represent substantial improvements over projections developed for the Third Assessment Report in 2001 and earlier assessments. These include model adherence to established physical principles, improved spatial resolution and process parameterization, more comprehensive diagnostic testing, and demonstrated skill in reproducing important features of both current and past climates (Solomon et al., 2007). A larger number of improved models contribute to the projections, and the comparative skill of models is now better understood since model predictions have been evaluated against detailed historical climate data, particularly for the recent (1990- 2005) period. As with earlier generations of GCM, confidence remains higher for projections of temperature than for projections of precipitation; and for projections at global and continental-scale relative to regional projections. Although model skill has increased substantially, the ensemble of AOGCMs underlying the Fourth Assessment Report nevertheless generate a range of projections for each future time period, and the dispersion of projected temperature and precipitation estimates widens as the time horizon of simulation increases.

In addition, efforts have been made (through the Coupled Model Intercomparison Project 3) to standardize the assumptions or boundary conditions guiding model simulations. In its Special Report on Emission Scenarios (SRES), the IPCC developed a set of standardized scenarios regarding GHG emissions trajectories (Nakicenovic, 2000). The SRES scenarios, consisting of four basic "families," are based on narrative 'storylines' consisting of coherent assumptions about population growth, economic development, technological advances, policies on interdependency, and commitment to environmental protection. These scenario families can be viewed as equally plausible alternative futures (Bates, et al., 2008). The four broad storylines and associated scenario families are described below and summarized in Figure 3-2. Figure 3-2 also depicts a stabilization scenario, in which GHG emissions are restricted in order to stabilize atmospheric concentrations at 450 ppm.

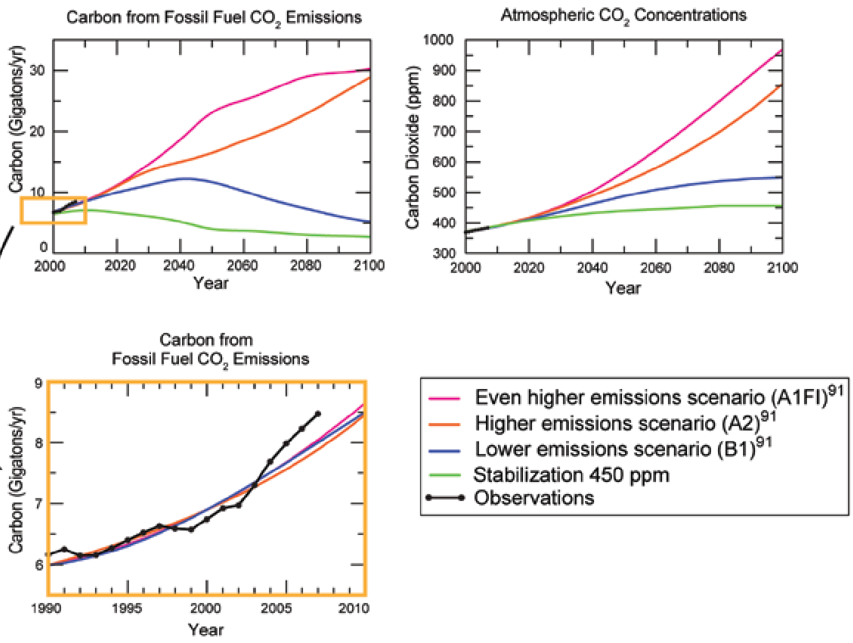


Figure 3-2 - Scenarios of Future Carbon Dioxide Global Emissions and Concentrations. Source: Karl et al. (2009)

A1 storyline and scenario family assumes a world of rapid economic growth with the most growth in developing countries, global population peaking at 9 billion by mid-century and then declining to 8 billion by 2100, and rapid technological development. It has the highest per capita income of the four storylines. This storyline is split into three quite different scenario groups of energy consumption: **A1FI** (the "FI" standing for fossil intensive) assumes high fossil fuel use. Carbon dioxide (CO_2) concentrations would exceed 900 parts per million (ppm) by 2100, the highest of the SRES scenarios. **A1T** (the "T" standing for technology) assumes high development and use of non-fossil fuel energy. CO_2 concentrations would be over 500 ppm by 2100. **A1B** (the "B" standing for balanced) assumes a mix of fossil intensive and non-fossil fuel energy sources. CO_2 concentrations would be about 700 ppm by 2100. *This is the most commonly used scenario in modeling and simulations, although the SRES writing team reached broad agreement that there could be no 'best guess' scenario. In other words, all scenarios are considered to be equally plausible.*

A2 storyline and scenario family assume very high population growth (about 15 billion people by 2100) and slower economic growth and technological development than the other storylines. There is also less convergence in the standard of living and technology between developed and developing countries than the other storylines. It results in the lowest per-capita income of the four storylines. CO_2 concentrations would be over 800 ppm by 2100.

B1 storyline and scenario family assume the same population levels as A1, but with more of a transition to a service- and information-based economy with more clean technologies and less material intensity than A1. CO_2 concentrations are the lowest of the SRES scenarios – over 500 ppm by 2100, but below those for A1T.

B2 storyline and scenario family assume a population of 10 billion by 2100, intermediate levels of economic growth, and less rapid technological development than the A1 and B1 storylines. CO_2 concentrations would be around 600 ppm by 2100.

Figure 3-2 shows actual emissions from 1990 to 2007 in relation to scenario emissions (lower right). Since 2004, actual emissions have in fact exceeded the A1FI "high emissions" scenario levels.

3.3 Summary of current consensus “High Confidence” conclusions – Global Patterns

The consensus is that changes in the global climate system during the 21st century will *very likely* be larger than those observed during the 20th century (IPCC, 2007). (This assumes continued greenhouse gas emissions at or above current rates. SRES scenarios do not include additional climate change mitigation policies above current ones.) Projected global average mean temperature by the end of the 21st century is *likely* to rise by between 1.1 and 6.4°C relative to late 20th Century levels. The wide range in projections of mean surface warming by the late 21st Century reflects (i) the range of assumptions concerning potential GHG emissions (SRES scenarios), (ii) differing estimates of the sensitivity of climate response to changes in atmospheric GHG levels, and (iii) differences in individual model specification. The gray bars on the right side of Figure 3-3 indicate the range of projected global temperatures in 2100 across the six SRES emissions scenarios. For each emissions scenario, the range of projections reflects the range of outputs from various model simulations. Higher emissions scenarios (A1F1 and A2) result in generally higher projections of warming.

Solid lines in Figure 3-3 are multi-model global averages of surface warming (relative to 1980-1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES scenarios. The assessment of the best estimate and likely ranges in the grey bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints.

In the early part of the 21st Century (through around 2030) there is little divergence between emissions scenarios and model projections, and the multi-model consensus indicates global warming of 0.64-0.69 ºC (1.2 ºF) relative to 1980-1999. By mid-century, scenario projections diverge, and projected temperature increases by 2090-2099 strongly reflect the underlying SRES assumptions about GHG emissions. Under low emissions (scenario B1), global temperatures are projected to increase from 1.1 – 2.9 ºC (2-5 ºF), with 1.8 ºC (3.2 ºF) as “best estimate.” By contrast, assuming that GHG emissions follow a higher trajectory, warming is projected at between 2.0 and 5.4 ºC (3.6 and 9.7 ºF), with a best estimate of 3.4 ºC (6 ºF). Under the fossil fuel-intensive development scenario (A1FI), warming is projected in the range 2.4 – 6.4 ºC (4.3 – 11.5 ºF), with a best estimate of 4.0 ºC (7.2 ºF) (Solomon et al., 2007). It is worth contemplating that many

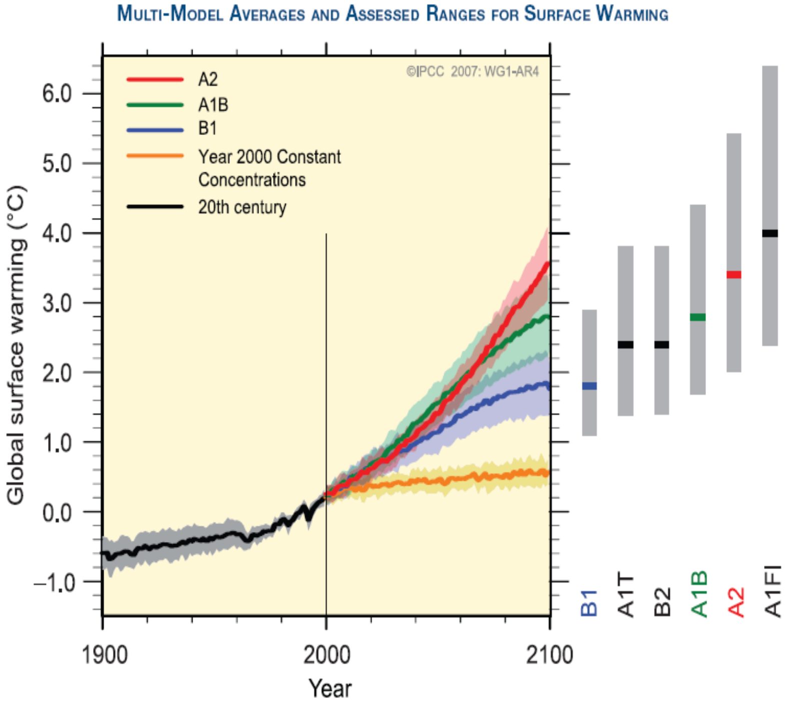


Figure 3-3 Range of Projected Global Temperatures in 2100 Across Six SRES Emissions Scenarios. Source: IPCC, 2007 (Figure SPM.5)

scientists (e.g., Hansen et al., 2006) consider that global temperature increases exceeding 1.0 °C relative to 2000 levels have dangerous implications, particularly with regard to sea level rise.

Warming is not projected to be uniform globally, and the patterns will largely reflect observed warming patterns to date. Specifically, temperature increases will be greater over land than over water; and greater in higher (Northern) latitudes than in tropical regions. Less warming is projected over the Southern oceans and the North Atlantic (Meehl et al., 2007).

Model-generated projections of precipitation are, in general, accepted at somewhat lower confidence than temperature projections. The IPCC concludes that global average precipitation is *very likely* to increase, although there is substantial spatial and temporal variation (IPCC, 2007). As a general pattern, precipitation is projected to increase in high latitudes (*very likely*) and parts of the tropics, and decrease in some subtropical and lower mid-latitude regions (*likely*). Precipitation will likely increase over northern mid- to high latitudes and Antarctica in the winter by the second half of the 21st century. Summer patterns tend to show more drying, particularly in mid-latitudes in the Northern Hemisphere.

A general conclusion, consistent with observed historical trends, is that precipitation intensity and variability are projected to increase. This, in turn, increases the risk of flooding and drought in many regions. Increased rain-generated floods are *very likely*. Analysis of daily GCM outputs indicates an increased number of days without precipitation in many parts of the world (Tebaldi, et al., 2006), and increased extreme drought is *likely*. The duration and intensity of midsummer droughts are likely to increase in interior, mid-continental areas (e.g., Central Asia), although results are inconclusive for other regions. It is *likely* that future tropical cyclones will become more intense, with larger peak wind speeds and heavier precipitation.

Water supplies stored in glaciers and snow cover are projected to decline (*high confidence*). For regions dependent on runoff from snowpack into rivers and lakes, peak runoff is likely to be earlier in the year, with much less snowmelt contributing to streamflow during late spring and summer. Higher temperatures are also likely to cause more precipitation to come as rain rather than snow during the year. When and where it does snow, snowfall amounts could increase in many locations. Glaciers are also projected to continue receding.

Sea level rise (SLR) is projected to continue through the 21st Century, although the rate and extent are subject to uncertainty and controversy (e.g., Hansen, 2007). The IPCC Fourth Assessment Report (IPCC, 2007) bases its projections of sea level rise on the two primary mechanisms identified above – thermal expansion of the oceans and melting of glaciers and ice caps – and concludes that late 21st Century sea levels will be between 0.6 and 2.0 feet higher as compared to the late 20th Century (Solomon 2007). However, these estimates, based largely on General Circulation Model (GCM) simulations, exclude consideration of ice sheet dynamics in Greenland and Antarctica. Studies examining the long-term historical relationship between global temperature and sea level (e.g., Rahmstorf, 2007) conclude that late 21st Century sea levels are more likely to be between 3 and 4 feet above late 20th Century elevations, depending on the emissions scenario assumed.

3.4 Regional Patterns in the United States

The U.S. Global Change Research Program (Karl et. al., 2009) presents summaries of the projected regional impacts of climate change within the U.S. As a general pattern, changes projected for the mid- to late 21st Century extend the regional trends and patterns of change already observed. By late 21st Century, temperatures are projected to increase by between 4.0 and 6.5 °F if a low emissions pathway (B1) is assumed, and between 7 and 11 °F if a high emissions pathway (A2) is assumed. Warming will be highest at higher latitudes, and in mid-continental areas such as the Great Plains and Great Basin. Warming will be more moderate in coastal areas including Western Washington, Oregon and California; and in the coastal Southeast.

Patterns of precipitation in mid- to late 21st century are projected with somewhat less confidence than temperature, although many recently identified trends are anticipated to continue through the coming century. As a general trend, northern areas will become wetter and southern areas drier. Parts of the Southwest in particular are projected to become even drier in coming decades. Figure 3-4 summarizes projected seasonal and regional trends in precipitation. Projections are derived from 15 GCMs from the Coupled Model Intercomparison Project 3. Confidence in winter and spring projections is in general higher than for summer and fall. These projections highlight the strong North-South pattern of variation.

3.5 Major Caveats and Uncertainties

These projections rest explicitly on a number of assumptions embedded within the SRES storylines, and most critically on the assumed trajectory of GHG emissions. Differences in projected climate parameters associated with low emissions (eg., B1) and high emissions (eg., A1FI) scenarios are profound, amounting to up to 4 °F of mean warming over the U.S. by the end of the century.

Projections of climate are the outputs of simulation models, and any weaknesses or uncertainties associated with these models will be reflected in projections. One important caveat concerning the use of GCMs is spatial resolution. Although model horizontal resolution has improved substantially over the last three decades, many important features of regional climate are not resolved or are resolved poorly. These include local convective precipitation, leading models to produce too many days with weak precipitation (defined as less than 10 mm per day) and to under-estimate the overall precipitation from intense events, defined as more than 10 mm per day (Randall et al., 2007). It is important to keep this limitation in view when evaluating various approaches to regional downscaling of GCM outputs. An in-depth review of the state of the art of regional downscaling has recently been produced by the Water Utility Climate Alliance (WUCA, 2009).

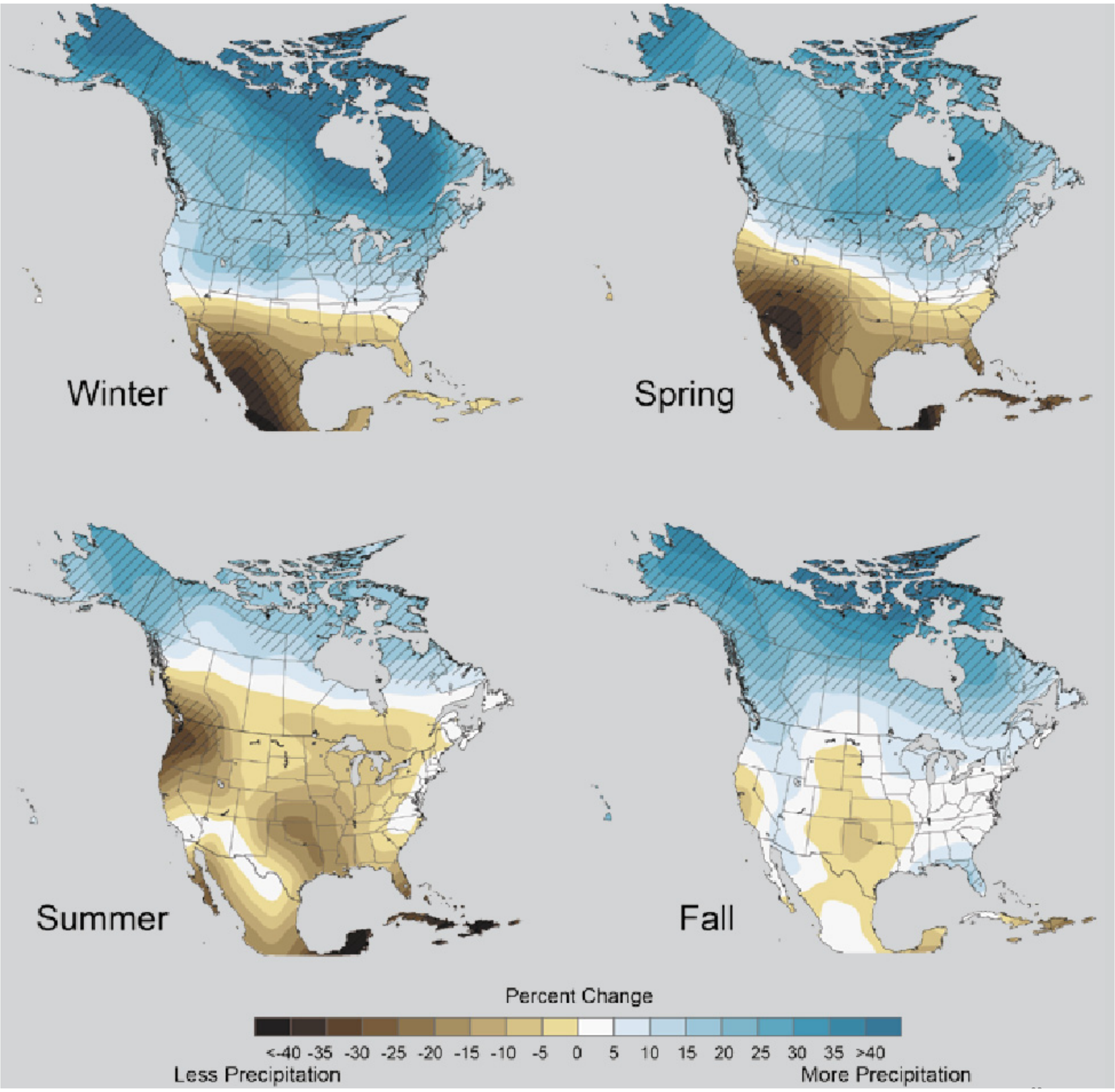
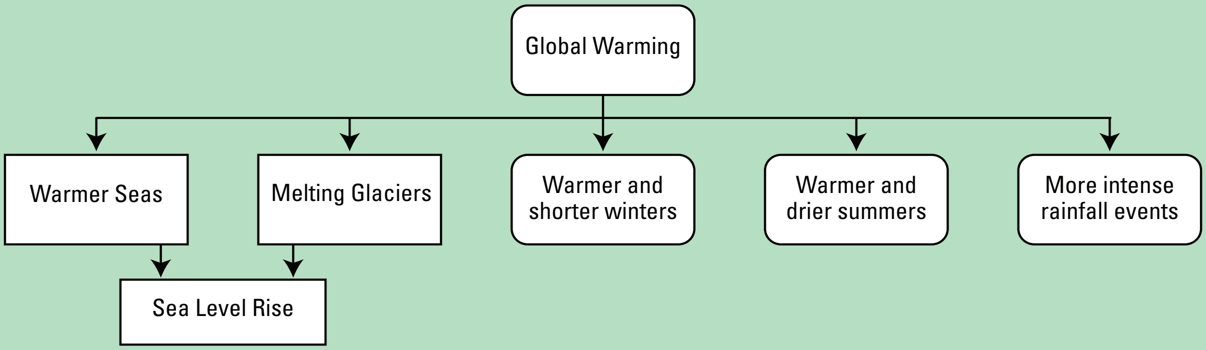


Figure 3-4 Projected seasonal changes in precipitation based on 15 GCMs from the CMIP3. Changes are for 2080-2099 relative to recent historical conditions. Confidence in projections is highest in cross-hatched areas. Source: (Karl et al 2009) p. 31.

4. IMPACTS AND IMPLICATIONS

Although the scientific literature on global climate change and closely related issues is extensive and rapidly expanding, studies that examine the likely, specific impacts of climate change on the facilities and operations of wastewater and stormwater agencies are scarce. This reflects, to some extent, the basic science research agenda of the climate research community. It also reflects, implicitly, the mismatch in spatial and temporal scales between the outputs of climate models and the planning requirements of wastewater and stormwater managers (Xu and Singh, 2004; CCSP, 2008b). Section 4 focuses on risk identification – identifying the key impacts associated with projected climate change and itemizing the implications with respect to the sector. The discussion in this section follows the cause and effect relationships presented diagrammatically in the Summary section of this report.

As discussed in the Summary , there are four major impacts resulting from global warming that are the source of all implications for facilities and operations of wastewater and stormwater agencies, as follows:



Since impacts resulting from sea level rise constitute a unique set of coastal concerns these are discussed in a separate subsection at the beginning. Impacts in the other three categories are then discussed together to avoid repetition since they all derive from climate-induced changes in hydrologic and environmental processes.

4.1 Impact of Global Warming on Sea Levels

The local rate of Sea Level Rise (SLR) will be influenced by the extent to which coastal land is either subsiding or rebounding. Thus, although SLR is a global phenomenon, regional variation in SLR will likely be substantial. Given a two-foot increase in global mean sea level, relative sea levels would rise by 2.3 feet in New York City, 2.9 feet at Hampton Roads, VA and 3.5 ft. at Galveston, Texas (Karl et al., 2009). A two-foot rise is near the lower end of estimates for 2100.

Sea level rise is likely to cause increased coastal erosion and loss of protective coastal features such as barrier islands and wetlands. These effects will render coastal areas more vulnerable to damage from coastal storms. Increasing temperatures may produce an increased intensity of storms that will bring greater storm surge flooding and greater wave heights (CCSP 2009). There is evidence that the intensity of Atlantic hurricanes has increased over the last 30 years. Computer models also confirm that increased temperatures will lead to increased storm intensity. However, it is not known whether this will result in increased frequency of hurricanes (CCSP 2009). Meanwhile, the gradual erosive effects of sea level rise will definitely render coastlines increasingly more vulnerable to storm damage.

4.1.1 Implication: Increased Risk of Coastal Storm Damage and Flooding of Facilities

Sea level rise, particularly in combination with an intensification of both rainfall and/or storm-surge flooding, creates a threat to wastewater treatment facilities and outfalls. Treatment facilities in coastal areas are often located near sea level to facilitate gravity drainage and reduce pumping needs; and outfalls are typically designed to be operational during high tides (NYC DEP 2008). Rainfall flooding of increased intensity may over-tax stormwater sewers, while elevated sea levels may inhibit coastal discharge of stormwater, leading to system backups and localized street and basement flooding. In areas served by combined sewer systems, saline water from storm surges may enter the treatment system and cause damage to equipment and degrade treatment processes (NYC DEP 2008).

Several municipalities and regions have already initiated planning activities to identify wastewater treatment facilities and infrastructure that are vulnerable to the impacts of SLR. New York City (NYC), with 6,600 miles of sewer line, 100 pumping stations and 14 wastewater treatment plants, is particularly vulnerable to SLR. The NYC Department of Environmental Protection (DEP) in conjunction with Hydroqual and others developed a high-resolution Digital Elevation Model (DEM) of the city, including critical wastewater treatment facilities. Scenarios to assess vulnerability were developed based on FEMA estimates of the 100- and 500-year storm surges in combination with projected SLR of 13.8 inches and 16.7 inches by 2080. The analysis identifies several pumping stations and treatment plants at risk by late 21st Century (NYC DEP 2008). King County, Washington has conducted a similar vulnerability assessment focused on 40 wastewater treatment facilities that are located within the vicinity of tidally influenced water bodies (King County, 2008). King County planners identified critical elevations for all potentially exposed wastewater infrastructure, and in collaboration with scientists at the University of Washington. The study concludes that a number of King County wastewater facilities are vulnerable to combined SLR and storm surge by 2050.

Seattle Public Utilities (SPU) used analysis conducted by the University of Washington Climate Impacts Group (UWCIG) to generate an initial assessment of the inundation impacts of sea level rise on SPU's infrastructure. SPU generated three GIS layers for 2050 and 2100 that represent the three sea level rise projections developed by UWCIG, along with a fourth layer that represents storm surge. SPU then identified which of its infrastructure assets are located within the sea level rise and storm surge layers.

The California Climate Change Center (2009) has conducted a study of population, infrastructure and property at risk due to projected climate change throughout California. Wastewater treatment was among sectors examined in detail. As in the other studies cited, digital elevation models and geographic information systems (GIS), in combination with GCM projections of climate and a range of demographic and socio-economic projections form the basis of the study. The study identified 28 wastewater treatment plants as vulnerable to a combination of 1.4 meter SLR in combination with a 100-year flood event. 21 of these facilities are on the San Francisco Bay and the remainder are along the Pacific Coast. The plants have a combined capacity of 530 million gallons per day. Assessed vulnerabilities to treatment plants include damage to pumps and other equipment leading potentially to discharge of untreated sewage into bay and coastal waters; and interference with discharge from coastal outfalls.

4.1.2 Implication: Operating Risks to Submerged or Shoreline Facilities

Coastal storms and associated surges and flooding are not the only risks to clean water infrastructure located in coastal floodplains or submerged offshore locations. Sea level rise (SLR) can also affect the performance of wastewater collection systems and stormwater, sanitary and combined sewer outfalls through changes in the (static) hydraulic head. Several potential problems have been identified to date. Where projected SLR leads to saline intrusion of coastal aquifers, buried pipelines may become exposed to corrosion (NRC, 1987). Where SLR results in higher water tables in coastal floodplains, groundwater infiltration into stormwater and sanitary wastewater collection systems, decreasing available stormwater storage capacity and potentially over-taxing treatment plants (Deyle et al., 2007).

An additional impact is the reduction in sewer discharge from submerged outfall points resulting from the increased hydraulic head caused by SLR. In systems without tidal gates , this can result in backups within the system, and where gates are present can reduce the efficiency of discharge, possibly requiring the installation of larger pumps (and increasing energy use) to compensate for increased hydraulic head (Deyle, et al., 2007). When static SLR increases are overlaid on storm surges and/or seasonal high tides, backups may become more severe, resulting in saltwater damage to sensitive treatment processes as well as causing localized street and basement flooding (NYC DEP 2008).

4.1.3 Implication: Changes in Coastal Receiving Waters and Aquatic Ecosystems

Estuaries are projected to be subject to a range of climate change-related stresses due to their locations at the interface between land and sea (USEPA 2009; Karl et al., 2009). Climate change will result from a range of physical and chemical changes to oceans and ocean waters. These changes include SLR from thermal expansion and the melting of glaciers and ice caps, warming of ocean waters, acidification of ocean waters due to uptake of CO2, and changes in salinity, among other chemical impacts. These changes will have secondary impacts with respect to biotic communities. Warmer waters will promote a shift in species composition, possibly opening the door for many types of invasive species. Coastal storms, including tropical depressions, may also be increasing in strength, thus exacerbating the negative impacts of SLR in exposed regions. Changes in continental climate and hydrology will also impact coastal zones through changes in freshwater discharge patterns, sediment loads and the export of nutrients and other contaminants mobilized from upland sources as a consequence of increased rainfall intensity.

Other factors held equal, rising sea levels will result in elevated water levels and increasing salinity of estuarine waters. These lead in turn to salinization of coastal aquifers, displacement of existing plant and animal communities, and the inundation of coastal wetlands (USEPA 2009). These trends will be worse in regions also experiencing land subsidence, such as the Chesapeake Bay estuary, and will leave these regions increasingly vulnerable to increasingly violent coastal storms. Warmer ocean temperatures encourage the growth of nuisance algae and phytoplankton. U.S. coastal waters have already warmed by up to 2 ºF in many regions, and are projected to increase by another 4-8 ºF by the end of this century (Karl et al., 2009).

Overlaid on these changes are potential impacts reflecting alterations in the land phase of the hydrologic cycle. In some regions where precipitation and overall runoff increase due to climate change, increased estuarine inflows may counteract sea level elevations and temperature increases by decreasing residence time and flushing harmful algae from estuaries, reducing potential eutrophication (Nicholls et al., 2007). By contrast, the primary impacts of land-phase alterations in the hydrologic cycle may include an increasing tendency for freshwater to enter estuaries in flood pulses, but with overall decreases in annual freshwater discharge. Under these circumstances, estuaries will be increasingly vulnerable to eutrophication, as flood pulses introduce increased levels of nutrients and altered water balances increase residence times. These impacts will vary regionally.

For firms and municipalities managing critical infrastructure in coastal floodplains and other areas subject to SLR, three basic long-term strategies have been identified: protect, accommodate or retreat (Nicholls et al., 2007). Strategies to protect areas or infrastructure assets threatened by rising sea level include shoreline-hardening structures such as sea walls, bulkheads and dykes, beach nourishment, and the closure of estuaries. Accommodation strategies include the "flood-proofing" of buildings and coastal zoning to limit the occupation of coastal floodplains. Managed retreat can involve the relocation of critical structures to higher ground. Wastewater and stormwater management agencies with critical infrastructure (including outfalls, pumping stations and collection systems) in coastal zones threatened by SLR should evaluate these and related strategies in the context of routine capital improvement planning.

The USEPA addresses water quality issues in key estuaries through the National Estuary Program (USEPA 2000), which currently extends to 28 estuaries. The National Estuary Program departs in many respects from EPA's regulatory approach under the Clean Water Act in that it supports and engages entire communities sharing important estuaries, and extends beyond specific clean water parameters to encompass broader considerations of ecosystem health, biodiversity, economic integrity and aesthetic values (USEPA, 2009).

4.2 Impacts of Global Warming on Hydrologic and Environmental Processes

The most reliable outputs from climate models are projected long-term changes in average global temperature. Model projections become increasingly less reliable as we move to finer spatial or temporal resolution. However, certain generalizations can be made that hold true for nearly all temperate regions within North America: (i) winters will be shorter and warmer, (ii) summers will be warmer and drier, and (iii) precipitation will occur more frequently in high-intensity events.

The manifestations of warmer and shorter winters depend to some extent on the region we are concerned with. In areas receiving extensive winter precipitation in the form of snowfall, the implications of warmer winters include a shift from snowfall to rainfall (particularly in late Autumn and early Spring), a reduction in total snowpack accumulation and a reduction in the period when snow covers the ground. Regions within the U.S. likely to be affected by this pattern include the Northeast, Midwest, Northern Great Plains, and the Mountain West (Karl et al., 2009). The potential impacts of alterations (reductions) in snowpack are a particular concern in the Western U.S., where water resources are in general more limited and high-altitude snowpack provides a high proportion of usable runoff (Lettenmaier et al., 2008). Warmer winter temperatures and a shift from snow to rain result in earlier spring snowmelt and a shift in the timing of the snowmelt runoff "pulse" to earlier in the year (e.g., Peterson et al., 2008). This, in turn, results in a reduction of runoff in late Summer and early Fall (when annual minimum flows typically occur) and a likely reduction in reservoir storage during critical periods (e.g., Vicuna and Dracup, 2007). A general concern is that many multipurpose storage reservoirs are designed to provide flood protection during the winter and spring and water supply in the summer and fall, as consistent with historical patterns of snowmelt storage and runoff. Under altered flow conditions resulting from climate change, meeting both objectives might become difficult (Roos 2003). The manifestations of warmer, shorter winters also include a trend toward later freeze and earlier thaw dates, and a reduction in the number of extreme cold days.

Reductions in summer-fall minimum flows negatively impact water quality primarily by reducing dilution capacity, resulting in higher concentrations of a range of contaminants (Whitehead et al., 2009). Lower warm-season flows in combination with higher air temperatures lead further to alterations in the chemistry and biology of surface waters. Warmer water contain less dissolved oxygen, resulting in a reduced capacity for self-purification. (Kundzewicz et al., 2007). Since many biological growth processes and chemical reactions are sensitive to temperature, the ecological and chemical balances of surface waters will be altered (Whitehead et al., 2009). Adverse effects on cold water fish species are anticipated and Northern migration of invasive species favoring warmer waters is feared. Algal production is also enhanced in warmer waters, and favors the growth of nuisance species such as blue-green algae (Murdoch et al., 2000; Lettenmaier et al., 2008). In many regions, reduced flows in combination with higher air and water temperatures lead to enhanced evaporation and an increase in salinity in brackish waters. Warmer water temperatures can also result in increased stratification of waters within lakes and reservoirs, associated with reduced dissolved oxygen and anoxic conditions below thermoclines.

Many of the biochemical changes in surface waters associated with warmer temperatures and reductions in flow volume are influenced by ambient levels of nutrients including nitrogen (N) and phosphorus (P). Climate change will alter nutrient loadings via altered patterns of rainfall, surface erosion and runoff, as described below. In addition, warmer air could produce sufficient changes in local or regional air circulation patterns that the nature and extent of nutrient loadings and acid deposition obtained from rainfall could be altered.

Summer temperatures are projected to increase throughout North America. The extent to which increased temperatures are accompanied by reductions in summer precipitation is more regionally variable, as indicated in Figure 3-4. The largest decreases in summer precipitation are projected to occur in the Pacific Northwest, the lower Great Plains and Southern Florida (Karl et al., 2009). Other regions such as the Eastern Seaboard are not projected to experience extensive reductions in precipitation. Changing patterns of rainfall alone will not determine summer moisture conditions, however, since elevated temperatures are likely to result in increased evaporation from soil and surface water bodies, potentially resulting in drier summer conditions even where rainfall changes are not significant.

Warmer, drier summer conditions have a wide range of potential impacts. The effects of reduced summer surface flows due to reduced snowpack and earlier runoff are amplified by warmer summer temperatures, which increase water surface evaporation and induce a range of alterations in water quality. Many water quality changes are anticipated due simply to a reduction in the dilution capacity accompanying reduced flows (Kundzewicz et al., 2007). Where nutrient supplies are available, warmer waters and reduced dilution accelerate the eutrophication process. Higher rates of primary production associated with increased water temperatures have been documented in the Chesapeake Bay estuary (Miller and Harding, 2007) and Hudson River (Howarth et al., 2000).

A second set of impacts reflect the alteration of climate and hydrology on conditions within watershed areas. Impacts include alterations in vegetation, and increased risks of wildfire. Earlier spring thaw and runoff, in combination with elevated CO2 levels, accelerate the production of biomass, providing potential fuel, and extended warm, dry periods later in summer create low moisture conditions conducive to wildfire. In North America, the IPCC (2007) concludes with very high confidence that "…disturbances such as wildfire are...increasing and are likely to intensify in a warmer future with drier soils and longer growing seasons." (Field, et al. 2007, p. 619). Westerling et al., (2006) present evidence that a warming climate is already influencing the frequency and severity of wildfire in the U.S. Comparing frequency and severity of western U.S. wildfires in 1988-2004 relative to the 1970-1987 period, they found a 78-day increase in the length of the fire season, a 400% increase in the number of fires and a 670% increase in burned area. These increases were found to be most strongly associated with increased spring and summer temperatures (which were 1.5 degrees (F) warmer on average during the later period) and with earlier spring snowmelt.

Physical theory, climate models and recent historical evidence predict increases in the frequency and magnitude of extreme or heavy precipitation events. This results from increased atmospheric moisture holding capacity and increased energy available to drive convective processes (Trenberth et al., 2003). Increases in heavy precipitation frequency and intensity are likely to be accompanied by increases in the frequency and severity of rain-generated floods (Bates et al., 2008). Analysis of historical precipitation and flood records generally support these projections. Groisman et al. (2005) found that while total annual precipitation volumes over the United States have increased by 1.2% per decade from 1970-1999, the share of annual precipitation associated with extreme events increased by 14% per decade over the same time period. Milly et al. (2002) found that the frequency of occurrence of floods with return periods greater than 100 years in large basins (> 200,000 km2) has increased substantially over the 20th Century, and analysis of output from Global Climate Models (GCM) suggests that this trend will continue as climate continues to warm. Tebaldi et al. (2006) have analyzed daily outputs from the most recent (AR4) GCM simulations, and have identified positive global trends in heavy precipitation and other variables related to flood production, including number of days with precipitation exceeding 10 mm, maximum 5-day precipitation totals, and fraction of precipitation due to events exceeding the 95th percentile.

Regional impacts of climate change on the frequency and severity of flooding are highly uncertain, due to regional variations in major flood-producing mechanisms. For example, among flood-prone areas of the U.S., the Gulf Coast is regularly exposed to inland flooding associated with tropical depressions; and California to heavy winter-spring snowmelt flooding. The Midwestern U.S. is the nation's most severely flood-affected region on a per capita damages basis, and severe Midwestern floods, such as those occurring in 1993 and 2008, are associated with meridional circulation patterns, by which moist air is continually transported to the region from the Gulf of Mexico (Knox, 2000). Knox (2000) concludes on the basis of paleoflood analysis that these large floods occur more frequently in periods of rapid climate change. Other researchers examining the historical record of discharge patterns in the U.S., including Lins and Cohn (2003), conclude that higher-frequency flood events (the 2- to 10-year flood) are more likely to increase as precipitation increases than are low-frequency events (e.g., the 100-year flood). Perhaps the greatest challenge raised by prospective climate change is that the statistical basis for assessing and designing for flood risk – the use of historical records to estimate the magnitude of design flood events such as the 100-year flood – has been undermined, and no clear alternative presents itself due to uncertainty around future climate (Milly et al., 2008).

Apart from flooding, the increased frequency of high-intensity precipitation events is anticipated to impact surface water quality in a number of ways. Higher-intensity precipitation has a greater capacity to result in the hydro-modification stream and river morphology through the erosion and deposition effects of extreme high flows. More intense rainfall may also be expected erode soils and mobilize a range of contaminants, including pesticides, organic compounds and heavy metals, flushing them into surface waters (Kundzewicz et al., 2007). Suspended sediment loads in surface waters are likely to increase, at least episodically (Whitehead et al., 2009). Greater storm runoff is also implicated in increasing the concentrations of bacteria and pathogenic organisms such as Cryptosporidium and Giardia.

Although it appears paradoxical, the manifestations of climate change are likely to include both lower warm season flows and an increase in high-runoff events, within the same regions and potentially within the same seasons. This combination of extremes is anticipated to exacerbate water quality problems extensively, as intermittent high runoff events wash a range of contaminants into surface water bodies, and low flows result in prolonged detention and increased concentrations (Lettenmaier et al., 2008; Murdoch et al., 2000).

4.2.1 Implication: Changes in Operating Temperatures

Increased temperatures and, especially the risk of increased dry spells and heat waves, will pose challenges in management of odors and corrosion in wastewater conveyance systems. With higher temperatures and lower flows due to water conservation efforts during drought periods, the potential for both hydrogen sulfide odor problems and internal pipe corrosion will both be increased.

Projected increases in air and water temperatures also hold the potential to have both positive and negative impacts on the operation of wastewater treatment facilities. Wastewater treatment involves a number of chemical and biological processes that are temperature-dependent. For example, greater quantities of flocculant are typically required at lower temperatures (Spellman, 2003); and COD, N and P removal are to some degree temperature-sensitive, with efficiency improving with temperature over a range from roughly 5 ºC – 30 ºC (Surampalli and Tiagi, 2004). Thus, increases in ambient temperatures can potentially improve the performance of water treatment plants (Whitehead et al., 2009), particularly in regions where cold winter temperatures currently act as constraints on the efficiency (capacity) of wastewater treatment. Increased water temperatures may help to conserve power by reducing its use in heating digesters (New York City DEP, 2008) Benefits cannot be assumed at much higher temperatures, however, since many important biological treatment processes are inhibited when temperatures reach 42 ºC – 45 ºC (Surampalli and Tiagi, 2004).

Potential gains in efficiency must be weighed against the likely negative impacts of increased water temperatures on the concentration of contaminants and pathogens in wastewater subject to treatment. In general, only limited research has been conducted to date examining the implications of systematically warmer waters on the technical and economic performance of wastewater treatment facilities, although significant impacts are to be expected. For example, increased temperatures will lead to reductions in dissolved oxygen, potentially increasing power requirements to operate aeration equipment (NYC DEP 2008).

4.2.2 Implication: Changes in Flows and Capacity Requirements

Wastewater treatment plants are designed to operate within a range of intake flows and loadings. Designs are developed on the basis of meteorological and hydrological records, specifically the intensity, frequency and duration of precipitation events, and on the specification of the wastewater collection system (e.g., NYC DEP, 2008). It is highly undesirable to have system inflows that fall outside the design parameters: either (i) contaminant concentrations exceed design tolerances (low inflows) or (ii) system capacity is exceeded (high flows). To complicate matters, lengthy reductions in flow, punctuated by intermittent high flows are likely in many regions as climate changes.

A study conducted by the U. S. EPA Office of Research and Development, examines the implications of changes in design low flows on the performance of public wastewater treatment works in the Great Lakes Region of the U.S. (Furlow et al., 2006a), with respect to discharges of BOD. The Clean Water Act requires that all point source discharge sources obtain a National Pollutant Discharge Elimination System (NPDES) permit. If discharges are likely to result in a violation of established water quality standards for a given contaminant, the NPDES permit must contain a water quality based effluent limit (WQBEL) for that pollutant. The 7-day averaging period, 10-year recurrence interval low flow (7Q10) is a design flow used for establishing compliance. If climate change results in reductions in 7Q10 (and therefore assimilative capacity), water quality based effluent limits (WQBEL) for the pollutant would need to be more stringent, and treatment costs would increase correspondingly. Furlow et al. (2006a) found that climate change impacts (as reductions in 7Q10) would result in an increase in the incremental cost of implementing WQBELs summed across all 147 publicly owned treatment works in the study area by an additional $8 million to $97 million per year over the current cost of implementation, equivalent to an average annual cost increase of $54,000 to $660,000 per facility.

In devising a strategy to address climate change, the U.S. EPA Office of Water has predicted that the number of waters recognized as "impaired" is likely to increase, even if pollution levels are stable (USEPA, 2008). This conclusion is not solely based on the effect of low flows, but recognizes that extreme low flows will magnify other adverse effects of climate change such as: warmer waters holding less dissolved oxygen and fostering more algal growth as well as intense rainfall events that increase the loadings of nutrients, pathogens and toxins.

The Total Maximum Daily Load (TMDL) establishment process is required to "take into account critical conditions for streamflow, loading and water quality parameters." Climate change will make rigorous uncertainty analysis even more important for determining the Margin of Safety required in setting TMDLs. The traditional approach of using continuous simulation based on dynamic models using historical data may not reflect more extreme conditions plausible under climate change. Stochastic modeling techniques may make it possible to generate synthetic hydrologic scenarios to simulate climate change impacts for planning purposes (Zhang, 2009). The TMDL and NPDES permit programs will need to adapt by considering the long-range implications for waterbody impairment associated with climate change and make needed revisions to TMDL guidance and WQBELs (Zhang, 2009).

Many older cities, particularly in the Northeast and Upper Midwest of the U.S., rely on combined sewer systems (CSS) to manage both sanitary waste and stormwater removal. When stormwater inflow to the CSS causes the combined flow volume to exceed capacity, a mixture of untreated wastewater and stormwater is often discharged from outfalls directly to surface or coastal waters, generating threats to human and environmental health. These events, termed combined sewer overflows (CSOs), are associated with high-intensity precipitation events. High volume runoff events associated with high-intensity precipitation are projected to increase as a consequence of climate change, and analysis of historical data indicates that the greatest increases in heavy precipitation events to date have occurred in the Northeast (67% increase in heaviest events, 1957-2000) and the Midwest (31% increase) (Karl et al., 2009) which are the regions in which CSS are most common.

The U.S. EPA Office of Water has established a CSO Control Policy requiring communities served by CSS to manage CSOs as consistent with the National Pollutant Discharge Elimination System (NPDES) permitting process. Mitigation practices are designed according to rainfall intensity-duration-frequency relationships that have been established on the basis of historical climate records. As noted with respect to treatment plant design, the climatic stationarity assumption is no longer tenable (Milly et al., 2008) and rainfall events of magnitude sufficient to cause CSO events are likely to occur with a greater frequency. The USEPA Office of Research and Development conducted preliminary simulation studies of the impacts of climate change on

CSOs using GCM projections of increased rainfall intensity (Furlow et al., 2006b). They found that in the Great Lakes region, CSO events would exceed the regulatory benchmark by 38% on average over a range of GCM simulations by 2025-2050. By assuming that event duration and infiltration remain constant over climate change (only intensity increases), design capacity of a CSO storage system can be taken as linearly proportional to precipitation intensity; and the average CSS design capacity would have to increase in direct proportion to rainfall intensity to maintain established water quality goals.

4.2.3 Implication: Increased Risk of Flood Damage to Facilities

Wastewater facilities are typically sited in low-lying areas within watersheds, often within floodplains, at the tail end of gravity collection systems. This creates a vulnerability to flooding, particularly in locations where the magnitudes of floods are increasing relative to historical behavior. Design guidelines for wastewater treatment plants state that treatment plants should be sited and/or protected so that they are fully operational and accessible during a flood having a 25-year recurrence interval (a flood with one in 25 chance of being equaled or exceeded in magnitude in a given year); and plant facilities should be protected against a flood with 100-year recurrence interval (WEF, 2007). Inundation of wastewater treatment plants has been an increasingly frequent occurrence, leading to widespread contamination of surface waters, particularly during major seasonal flooding. Extensive flooding of wastewater treatment plants occurred in the Upper Mississippi River valley during the major flooding of 1993 (NYT, 1993) and again during 2008; and throughout England during 2007 (Whitehead et al., 2009).

Wastewater treatment facilities are typically protected by dikes, levees or floodwalls, and plants are designed for service lives of around 50 years, and the height of levees or floodwalls is set on the basis of systematic historical flood records. Increasing frequency of higher-intensity precipitation events due to climate change implies that (i) the magnitude of a flood having a specified recurrence interval (e.g., 25, 100 years) is likely to increase; alternatively (ii) the recurrence interval of a flood with a given magnitude is likely to decrease. In either event, the vulnerability of wastewater treatment facilities located within floodplains will be higher at some point over the design lifetime than is assumed at the time of design. Wastewater treatment facilities and outfalls located at or below present sea level are also at risk from a combination of increased flooding and sea level rise.

The evidence that large floods are already increasing is mixed. Milly et al. (2002) conclude that the frequency of occurrence of floods with return periods greater than 100 years in large basins (> 200,000 km2) has increased substantially over the 20th Century. Lins and Cohn (2003), examining U.S. hydrologic records, find increases in higher-frequency flood events (the 2- to 10-year flood) and not in the 100-year flood. The frequent occurrence of record-breaking floods in the Upper Midwest – the Mississippi in 1993 and 2008 and the Red River in 1997 and 2009 – tends to lend support to Knox' (2000) observation that great floods accompany a changing climate.

4.2.4 Implication: Parallel Changes in Human Systems – The Built or Managed Environment

Global warming is only one element (albeit an important one) among several broad trends comprising global change. The likely trajectories of other important variables, including population, land use and the level and composition of economic activity, will be no less significant for planning and management by wastewater and stormwater management agencies; and are likewise characterized by high levels of uncertainty. In constructing the reference emissions scenarios (SRES) that underlie the IPCC"s most recent GCM model simulations of climate change, efforts were made to maintain internal consistency, or coherence of each storyline, with respect to assumptions concerning population growth, the nature and pace of economic development,

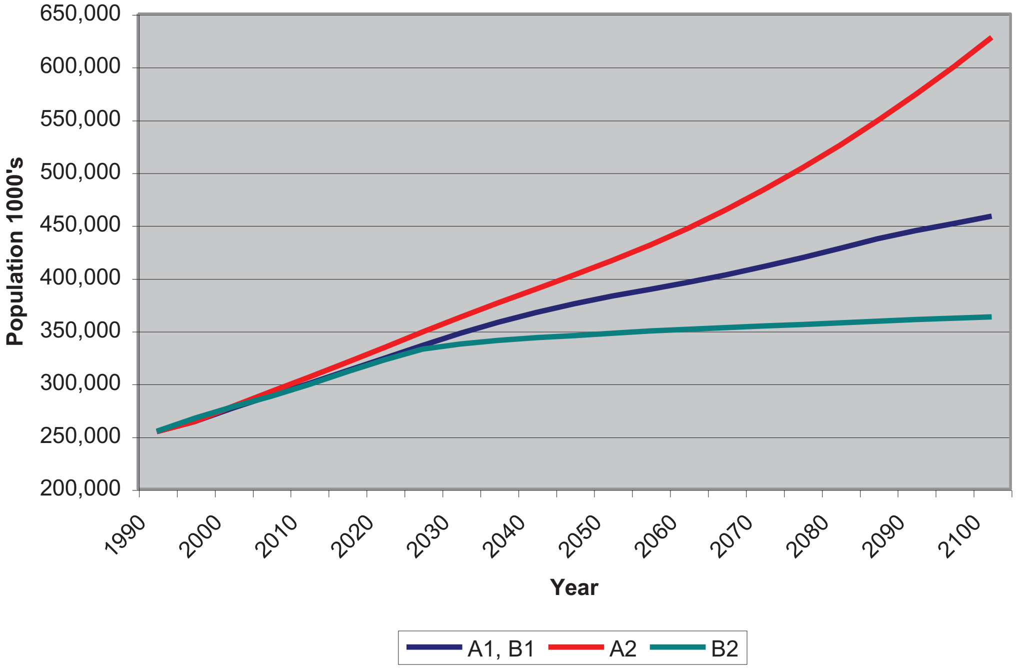


Figure 4-1 Population Projections for the U.S. under Primary SRES Scenarios (CIESIN 2002)

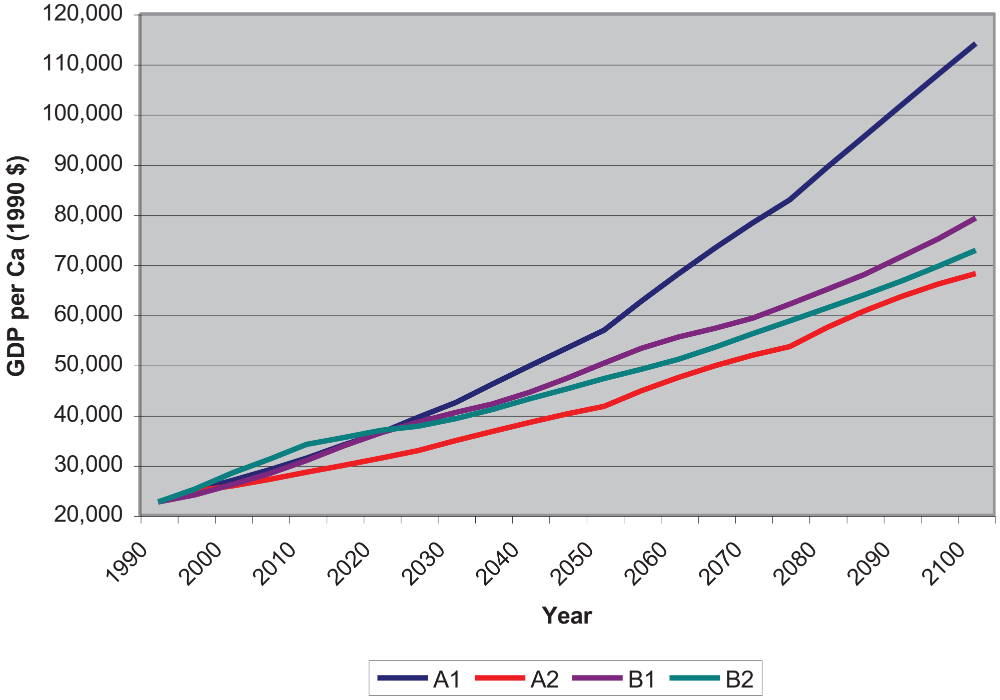


Figure 4-2 Income Projections for the U.S. under Primary SRES Scenarios (CIESIN 2002)

technological innovation and dissemination, and policies and attitudes concerning growth and the environment (Nakicenovic et al., 2000). Each factor considered in constructing the SRES emissions scenarios also has implications for wastewater and stormwater management independent of their impacts on climate.

Figure 4-1 depicts the range of population and income projections for the U.S. as reflected in the primary SRES scenarios (CIESIN, 2002). By mid-21st Century, U.S. population is projected at between 350 million for scenario B2 and 416 million for scenario A2. By 2100, the range of projection has expanded substantially, ranging from just over 360 million (B2) to over 625 million (A2). Although SRES population projections are made at the national level and no regional or state detail is provided, the regional implications of a national population exceeding 600 million are profound. By late 21st century, income assumptions diverge considerably also (Figure 4-2). No probabilities are attached to specific SRES scenarios – they are treated as equally likely visions of the future. Arnell (2004) has noted that by mid-21st Century, differences in the demographic and economic assumptions underlying the SRES scenarios may have a greater impact on regional water resources than differences in the climate scenarios themselves (Bates et al., 2008).

Similar degrees of uncertainty apply to changing patterns of regional settlement, land use and related factors. Of particular concern is the uncertainty concerning future patterns of demand for water. Two observed trends are in apparent contradiction. Economic theory and a considerable body of empirical evidence indicate that in domestic consumption, water is a “normal” economic good, meaning that household demand tends to increase along with household income, although cross-country comparisons of water use and income can lead to the opposite conclusion: as average national income increases, per capita demand decreases as treatment and distribution systems become more technically efficient (Cai and Rosegrant, 2002). Evidence also indicates that household water use is sensitive to temperature, increasing particularly during hot weather (e.g., Balling et al., 2008). By contrast, evidence from the periodic US Geological Survey (USGS) National Water Use Information Program surveys of water use within the U.S., conducted every five years since 1950, indicates that domestic water use within the U.S. peaked around 1980, and has since stabilized even in the face of ongoing increases in population (Lettenmaier et al., 2008). Expanded use of water-saving technologies in both household use and landscape irrigation are believed to be responsible for the decline in per capita usage, among other factors (e.g., NYC DEP 2008). Since per capita consumption in the U.S. is still high by world standards, it is possible that increased future demand driven by growing populations and higher temperatures will be offset at least partially by continued reductions at the per capita level. What is clear is that understanding and realistically projecting demand must accompany attempts to project the behavior of climate.

Climate change may induce an additional set of water quality impacts associated with agriculture. Much of the literature examining the likely impacts of climate change on agriculture has emphasized agricultural productivity in a changing physical environment (e.g., Easterling et al., 2007; Hatfield et al., 2008). It is likely that alterations in growing conditions will have impacts on water quality as a result of farmers’ adaptive responses. Hatfield et al. (2008), summarizing a wide range of published literature, report that increased temperatures and elevated CO2 levels influence nutrient cycling, and often create more favorable conditions for a wide range of weeds and pests. Herbicide and pesticide use may increase in response. As an illustration, Hatfield et al. (2008) note that under current conditions, more insecticide is used in the warmer Southern U.S. than in the cooler North. In one of the few published papers examining the links between climate change, agriculture and water quality, Abler et al. (2001) note that farmers are likely to alter the locations of cultivation, type of crops grown and technologies and management practices used in response to climate change, leading potentially to a range of indirect impacts on water quality. In evaluating the potential impacts of climate change on water quality in the Chesapeake Bay, these authors find that the water quality impact of farmer response to climate change may be either positive (reduced N loadings to surface waters) or negative (increased loadings), and that the impacts of an increase in high-intensity rainfall events considered likely under climate change – leading to increased erosion and export of nutrients and agricultural chemicals to surface waters – may dominate other agricultural impacts of climate change.

4.2.5 Implication: Parallel Changes in Natural Systems

The primary manifestations of climate change – increases in temperatures and alterations in the form, frequency, intensity and total quantity of precipitation – are in turn projected to give rise to a range of changes in natural systems. Many of these changes carry important implications for wastewater and stormwater management agencies, especially as they relate to the parameters of compliance instruments employed in implementation of the Clean Water Act such as NPDES permits, State water quality standards, designated uses for water bodies, reasonable potential analysis, and Total Maximum Daily Loads. Projected changes in the frequency and intensity of rainfall events can alter the effective toxicity of wastewater and stormwater discharges to which aquatic organisms are actually exposed, departing significantly from chronic or acute exposure levels assumed in permitting. In addition, the altered rainfall/runoff regime imposed by climate change has the potential to significantly change the comparative nutrient loadings from point and non-point sources, while also altering sedimentation processes that produce other impacts on water quality and stream morphology. Coupled with higher temperatures, the potential for eutrophication of water bodies will be increased in many places.

Features of natural systems likely to be influenced by climate change include patterns of watershed vegetation, streamflow, groundwater recharge and the integrity of aquatic ecosystems. The levels and seasonal patterns of temperature and precipitation jointly act to determine the fraction of precipitation that results in evaporation and transpiration, runoff, groundwater recharge and changes in soil moisture storage. Maurer et al. (2002) have shown that the runoff ratio (fraction of annual precipitation that becomes runoff) is highly sensitive to elevation in the (drier) western United States, where a small fraction of the total area is responsible for a large fraction of total runoff. The extent of high-altitude snowpack, which is the source of most of this runoff, is sensitive to temperature, particularly in the warmer Sierra Nevada and Cascade mountain ranges. Relatively small changes in temperature can have significant impacts on runoff volume, since they will affect the average snowline (altitude at which precipitation occurs as snow) and the accumulated snow water equivalent (SWE) stored over the winter and released as streamflow in the spring and summer.

Combined evaporation and transpiration (evapo-transpiration, or ET) is typically the most significant term in the hydrologic budget relative to precipitation. In areas of high ET, the ratio of runoff to precipitation is often low. Potential ET is determined largely by atmospheric demand for water, as influenced by air temperature and relative humidity, and by the energy available to evaporate water. Actual evapotranspiration is determined by the interaction of demand and the supply of water available for evaporation. Higher temperatures are predicted to lead to higher rates of potential ET, all other factors held equal, although physical measurements of ET are scarce relative to measurements of temperature, precipitation and runoff. Long-term records from evaporation pans, which provide an indication of potential ET (since water supply is never limited in an experiment) suggest that potential ET over the U.S. may have declined over the last 50 years, although temperatures have increased. Several hypotheses have been proposed to account for this, including "global dimming" – a reduction in net radiation at the earth's surface due to increases in cloud cover and atmospheric aerosols (Lettenmaier et al., 2008). Other studies examining the continental (U.S.) water balance (e.g., Walter et al., 2004) find that actual ET has increased over the last several decades, reflecting increases in precipitation (and hence the supply of water for ET) in addition to increased temperatures.

Groundwater recharge, strongly coupled to spatial and temporal patterns of precipitation and ET, is also assumed to be sensitive to climate change, although at the time of the IPCC Fourth Assessment Report (IPCC, 2007), very little research had been published examining this relationship (Lettenmaier et al., 2008). More recent research by Green et al. (2007) indicates that groundwater recharge rates are highly sensitive not only to changes in climate, but to changes in vegetation characteristics that accompany climate change. These authors conclude that no generic conclusions concerning the response of groundwater recharge to climate change can be made, since this response is tied directly to a specific, local soil-water-vegetation system.

Projected alterations in climate and hydrology lead in turn to changes in terrestrial ecosystems, which both respond to, and act to modify hydroclimatic variables (Lettenmaier, et al., 2008). Among the observed ecosystem changes linked to climate change are alterations in seasonal phenology and primary productivity. Growing seasons, constrained in many regions of the U.S. by the period of continuous frost-free days, have increased since 1948, with the largest changes occurring in the West. The timing of spring "greening" has advanced by 10 to 14 days in the last two decades throughout the Northern Hemisphere. As a partial consequence, forest growth has increased, albeit slowly, in regions where water supply is not limiting. By contrast, in regions such as the U.S. Southwest, drought and water shortage have caused a reduction in forest growth (Lettenmaier et al., 2008). Alterations in watershed hydrologic regimes will also influence water quality, although the direct impact of increasing air temperatures on water temperatures is among the most important influences on water quality. Many biological processes are temperature-dependent, and dissolved oxygen capacity declines with increasing water temperature. Increased nutrient loads delivered to streams as a result of high-intensity precipitation-runoff events also serve to accelerate biological productivity in natural waters. Attributing specific changes in water quality is difficult, however, since other factors, in particular changes in land use and management, may be the dominant sources of change. These and other factors suggest a range of quantitative and qualitative changes in U.S. surface waters accompanying climate change, although the specific implications will vary by location.

5. VULNERABILITY, ADAPTATION AND RESEARCH NEEDS

5.1 Generalized Risk Management Approach to Adaptation Planning

The risk identification step in analyzing climate change is a straightforward exercise. Basic climatic, hydrologic and ecologic principles can be followed to trace the path from climate changes to potential impacts on facilities and operations, as illustrated in the cause-effect diagrams at the outset of this report. The next steps in the risk management paradigm are risk assessment (or characterization) and risk management. In the climate change field, these are often referred to as vulnerability analysis and adaptation analysis.

	Steps In A Risk Management Approach to Adaptation Planning
Risk Identification	What ***climate changes*** are expected over what period of time? What resulting ***impacts*** may be produced in climatic systems, hydrologic systems, terrestrial and aquatic ecosystems, and man-made systems that interface with environmental systems? What are the ***implications*** (i.e., the implied ***consequences***) of these changes in the operating environment on the performance of utility assets and asset systems?
Risk Assessment/ Vulnerability Analysis	What ***threshold*** level of ***consequences*** would be significant enough in terms of the performance of specific assets or asset systems that it would be best to mitigate, avoid or deter such ***consequences*** if possible? What is the ***likelihood***; how soon might you see such a ***threshold*** level of ***consequences***?
Risk Management/ Adaptation	How can a ***threshold*** level of ***consequences*** be avoided or mitigated through adaptive responses? How are short-term adaptation options different from long-term choices and what is the strategic path that leads from one to the other? What is the overall adaptation strategy that leads to mores sustainable infrastructure over the course of this century – the ***sustainable path***?

An essential aspect of applying these time-tested steps in risk management to climate change adaptation is the need for a critical awareness of the time dimension. The impacts and implications of climate change will emerge continually over the next several decades – and centuries. Moreover, they will emerge at differing rates and intensities that will be manifest through a number of direct and indirect mechanisms. Adaptation should not be viewed, therefore as taking individual steps to address discrete risks, but rather as a series of steps to be taken over time to cope with an array of ever-changing risks. Taken together, the successive steps will trace a pathway to the future. This highlights the need for a strategic element in adaptation. As climate change unfolds during the remainder of this century, a central question will be defining the *sustainable path* (Aspen Institute, 2009) that leads from the existing asset configuration to a new one that is *climate ready*.

Some risks may be perceived to be strong enough in the short term that wastewater and stormwater agencies should be already implementing adaptive measures, while other types of risks may be perceived to be so weak over the short term that they may not require significant changes in facilities or operations for decades. The prospect of climate change sometimes evokes a misperception that the sky is falling and leads people to skip right over the risk characterization step and begin evaluating adaptation options as though everything is happening at once. It is prudent to first undertake a vulnerability analysis to assess how soon the impacts may materialize at a strong enough level to present a meaningful threat to existing or planned facilities and operations. In cases where the change processes are initially weaker phenomena that will develop gradually, adaptation will become a long-term undertaking where the responsibility of current managers is limited to laying the right foundation to enable selection and implementation of the best adaptations by future generations of managers.

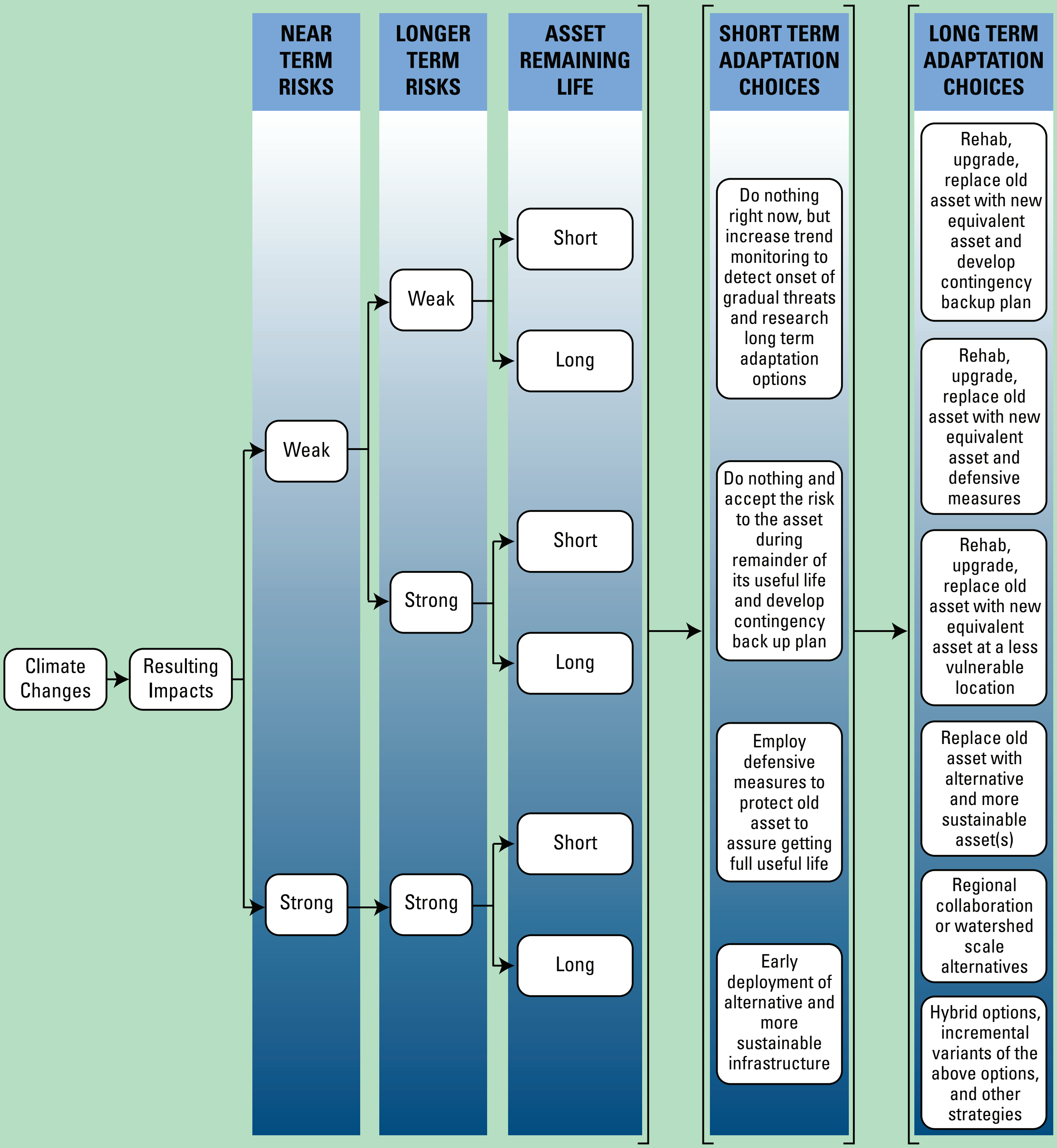
In devising adaptation strategies, it will be important to be mindful of the fact that today's risks are not the same as tomorrow's and today's assets are not the same as tomorrow's. Asset management maximizes the value derived from infrastructure by optimizing asset life cycles in terms of capital and O&M costs. Climate change presents a suite of new variables that may cause re-evaluation of the presumed remaining lives of existing assets. Decisions about the level of upgrade, rehabilitation, maintenance or replacement expenditures necessary to keep assets in service at desired levels of performance may vary depending on whether the remaining useful life of the asset is regarded as short or long – relative to the rate at which climate driven threats to the asset are believed to be advancing.

Climate change certainly involves some strong short-term threats to existing assets that will call for protective measures to *sustain* them. But, the current asset configuration may not be the *most sustainable* choice for the long-term. Future generations may need a different type of infrastructure that is designed from the start to be more sustainable in a changing environment, involving nontraditional types of investments such as decentralized treatment, green infrastructure, watershed buffers and wetlands.

However, asset management is often grounded in the assumption of a stationary climate in which the old asset is simply replaced by a new one. Asset management will have to be broadened to incorporate alternative concepts of infrastructure that may provide more value in a changing environment. In incorporating alternative infrastructure concepts, it is especially necessary to be sensitive to the potential for "path-dependency" in the sequencing of adaptation choices. In some instances, an incremental approach to adaptation might result in an inadvertent commitment to one path over another. For example, in a situation where the climate change signal is initially weak and developing slowly over the long-term, conventional infrastructure may continue to be selected because it continues to perform well in conditions that do not differ markedly from historical climate. But, it could be the case that an alternative infrastructure – perhaps a green infrastructure solution involving vegetation – is what is needed in the long-run. Since vegetation takes time to mature (especially trees), it may not be prudent to wait until the climate change signal is strong before selecting this path, better to use that time letting the trees grow.

In sum, the overall challenge in vulnerability assessment and adaptation is one of using risk management principles to help define the most *sustainable path* for infrastructure that will be best suited to a continually changing operating environment. This is summarized in the following decision tree diagram.

The balance of section 5.1 provides a generic description of the second and third steps in applying the risk management approach to adaptation planning, while taking full account of the importance of the time dimension in order to fully explore all possible pathways to a sustainable, climate ready future. Section 5.2 applies the method to the major categories of climate change induced risks identified and discussed in prior chapters and draws conclusions regarding priorities for early attention by wastewater and stormwater agencies as well as priorities for research to improve the information basis for assessing risks.


Finding the Sustainable Path in Adaptation Planning

SHORT TERM ADAPTATION CHOICES

- Do nothing right now, but increase trend monitoring to detect onset of gradual threats and research long term adaptation options
- Do nothing and accept the risk to the asset during remainder of its useful life and develop contingency back up plan
- Employ defensive measures to protect old asset to assure getting full useful life
- Early deployment of alternative and more sustainable infrastructure

LONG TERM ADAPTATION CHOICES

- Rehab, upgrade, replace old asset with new equivalent asset and develop contingency backup plan
- Rehab, upgrade, replace old asset with new equivalent asset and defensive measures
- Rehab, upgrade, replace old asset with new equivalent asset at a less vulnerable location
- Replace old asset with alternative and more sustainable asset(s)
- Regional collaboration or watershed scale alternatives
- Hybrid options, incremental variants of the above options, and other strategies

Source: Stratus Consulting Inc.

5.1.1 Vulnerability Analysis (Risk Assessment/Characterization)

The level of uncertainty involved in predicting climate change impacts is much greater than that normally encountered in facility and operations planning. This degree of uncertainty may lead many to choose to ignore climate change in their planning. But that would be a mistake because climate is changing. One thing that we can say with certainty is that the future climate will not be the same as the past. This has generated the catch phrase: "stationarity is dead."

But in the presence of such uncertainty, how is it possible to know how and when to adapt? The planning approach recommended in much of the climate adaptation literature is broadly referred to as a "bottom-up" analysis (or *threshold* approach). It relies on system managers' knowledge of their operations. This is especially useful because there is a wide array of practical consequences of climate change that cannot be predicted by climate models. The best information the models provide is long term changes in mean climate. It may be that changes in extreme events in the next ten years are far more important for planning now. There is experience with extreme events. Vulnerability analysis begins by asking a very practical question:

"What *threshold* level of change in the combination of climatic, hydrologic and environmental parameters would constitute a significant challenge – an unacceptable failure risk – to existing or planned facilities and operations?"

Working from the "bottom-up," this approach is anchored in existing or planned facilities and operations with which there is good staff knowledge of performance characteristics and the tolerances of these systems to extreme operating conditions. A *threshold* level of challenge can be defined that would produce a level of failure in critical components or systems that is unacceptable. (Episodes of noncompliance with EPA regulations certainly qualify as threshold events, but the concept of climate-induced critical failures is also much broader.) This threshold determination can be accomplished on the basis of staff knowledge alone, without having to have a climatologist in the room at all. Clearly, avoiding this critical level of failure or mitigating the consequences of such failure should be the objective of adaptation planning.

Once the potential risks to specific assets or asset systems are characterized in terms of a critical threshold, the next question in vulnerability analysis is the likelihood of such threshold events within planning horizons or other meaningful time frames.

"What is the likelihood of seeing a *threshold* level of change in the combination of climatic, hydrologic and environmental parameters that would constitute a significant challenge – an unacceptable failure risk – to existing or planned facilities and operations within capital planning or other time horizons?"

This is where climate change science needs to be drawn upon. Outputs from climate science need to be consulted to assess what is known about changes in climatic and environmental conditions that could produce situations that exceed the defined thresholds. Both the likelihood of occurrence and timing need to be addressed. Answers will most likely not be definitive. There are so many uncertainties about climate change that responsible scientists at best can identify ranges of changes, not make specific predictions.

Although this step can be daunting, it is not prudent to simply freeze planning decisions until better predictive tools become available. Developing better predictions of climatic changes as a first step in vulnerability analysis has been termed the "top-down" approach to vulnerability analysis in the climate literature. An overview assessment of the state of the art of the top down climate modeling tools has recently been completed by the Water Utility Climate Alliance (WUCA, 2009). While there is promise for somewhat better information, it will take considerable time to develop. Many adaptation decisions should be made sooner and the level of improvement possible in forecasting will still leave decision makers facing a much greater degree of uncertainty than what is customary under the conventional assumption of stationary (or, known) climatic variation.

5.1.2 Adaptation Analysis (Risk Management)

While assessing the likely timing of a *threshold* level of impact can be difficult, adaptation decisions might be made tractable by distinguishing between the short term and the long term responses to a given threat. It is logical to ask not only:

"How can the consequences of an anticipated *threshold* level of impact be avoided or mitigated through adaptive responses?" But also: "How are short term adaptation options different from longer term choices and what is the strategic path that leads from one to the other?"

In other words: What is the overall adaptation strategy that leads to more sustainable infrastructure over the course of this century – the *sustainable path*?

A popular rule of thumb encourages that the guiding principles of adaptation should be: flexibility, flexibility and flexibility. This has both short- and long-term connotations. Large, fixed capital commitments are more risky in a changing climate due to the increased uncertainties in the operating environment that may alter the planned useful life and lifecycle cost of such facilities and hence diminish the value derived. Moreover, capital is a limited resource. Placing big bets on what turns out to be the wrong infrastructure and leaving the next generation with large debts on the books might make it difficult to afford the right infrastructure later.

Staged implementation of smaller increments of capital additions has been suggested as a strategy for conserving capital and keeping options open to move in a different direction if climate change effects make it unfavorable to build additional increments. A caution has been raised, however, that due to the gradual nature of some of these change processes, incremental decision making can inadvertently lead down the path of building more conventional infrastructure grounded in assumptions of stationary climate when the path to building a more sustainable infrastructure may lie in a different direction.

Many short-term adaptive measures involve improving the reliability, redundancy and resilience in facilities and operations. Especially when these options consist of low-or-no capital cost items and low-or-no carbon footprint items, they fall into a category called "low regrets' or "no regrets" adaptations. Many such improvements in reliability are probably justified under current climate conditions. Climate change just provides one more reason not to hesitate with implementation. These adaptations can be readily justified as extending the useful life and value derived from existing assets, even in light of the uncertainties.

Changes in extreme events, for example, may not be gradual but could strike at any time. It is important to recognize that climate change includes long-term changes from greenhouse gases, but also climate variability. Another critical time dimension that should enter into the overall adaptation strategy is the remaining useful life of the current asset systems. If a new plant has just been erected by the sea, defensive facilities may be considered to protect the new asset from increased risk of storm damage. But if the seaside plant is older and in need of replacement, alternative plant sites or decentralized treatment might be alternative adaptation strategies to eliminate rather than mitigate vulnerability to storm surge.

In contrast, there are many climate change effects that will increase gradually as a function of temperature rise. For these effects, trend monitoring and incorporation into long-term asset planning may be adequate adaptations for now. It should also be acknowledged, however, that certain types of more sustainable future infrastructure – in particular green (or vegetative) infrastructure – may be best implemented gradually over a period of several decades, thus requiring an early start. And, yet another strategy that water management agencies can adopt in advance is to begin working more closely with one another and with local land use planners to consider collaborative adaptations at a watershed or regional scale to enhance their collective flexibility to meet change.

5.1.3 Research Needs (The Role of Better Information in Risk Management)

A risk management framework for adaptation planning is an ideal prelude to consideration of research needs. The approach described above involves explicit characterization of the consequences of various types of critical failure scenarios. It also involves explicit treatment of uncertainties affecting the likelihood and timing of such failures. The risk management approach makes it very clear what is at stake and what unknowns will likely determine the outcome. The approach thereby informs decision makers about the relative importance of the areas of uncertainty. After setting a problem up in this manner and assessing decision options with current information, the final step in risk management is always to ask:

“What additional information might be obtained to reduce the uncertainty – or, risk? Is it possible to better understand: the potential likelihood and timing of the threshold events, or the potential cost and effectiveness of alternative adaptation options?” In other words, what is the potential value of better information – the potential benefit of some additional research to enable better decisions?

The remainder of Section 5, applies the above described risk management approach to vulnerability analysis and adaptation planning for the major categories of potential climate change impacts on wastewater and stormwater agencies as identified in the Summary and Section 4 of this report. The discussion of each potential impact area provides a systematic way of summarizing the key strategic questions about vulnerability analysis and adaptation analysis. This flows logically to consideration of research needs at the end of each section. The research needs discussion for each area includes cross referencing to specific research proposals that were put forward in a joint water industry research needs workshop convened by the Water Research Foundation (WRF), the Water Environment Research Foundation (WERF) and the UK Water Institute for Research (UKWIR) in early 2008 (WRF, 2008). Profiles of these research proposals are reproduced in Tables 5-2 to 5-6 at the end of the section, re-sorted according to five major categories of adaptation defined below. It was found that the prior workshop covered most of the obvious areas of potential research needs, leaving only a few obvious gaps (e.g., sea level rise). Otherwise, these ideas cover the topic fairly well, capturing the major areas where additional research might help agencies in vulnerability analysis and adaptation planning. The next steps would involve refinement of these nominated research projects to develop more concrete proposals tied more specifically to benefits in adaptation strategy development. Hopefully, the analysis in this section will serve to make those benefits clear through the cross-referencing to risk management.

5.2 Major Adaptation Challenges Facing Wastewater and Stormwater Agencies

The discussion in Section 4 provides an overall risk identification analysis for wastewater and stormwater agencies, reviewing the spectrum of climatic, hydrologic and environmental changes that result from global warming and identifying implications for the sector. There are primarily four causative influences:

- Sea Level Rise
- Warmer and Shorter Winters
- Warmer and Drier Summers
- More Intense Rainfall Events

The cause-effect diagrams presented in the Summary of this report indicate a large number of impacts that result from these four sources of causation. As mentioned in the Summary, however, it is unwise to approach adaptation one variable at a time because different climate change processes might affect a number of related variables. Table 5-1 offers a more practical summary, collapsing the detailed cause-effect diagrams (useful for risk identification) into a set of related "bundles" of climate change-induced threats. The columns in Table 5-1 represent five major categories of identified risks to facilities and operations that require vulnerability and adaptation analysis (i.e., risk management). In the rest of Section 5, each column is discussed individually in terms of vulnerability analysis, adaptation analysis, and research needs to meet the "threat bundles" presented by the four major causative influences – indicated by key intersections with the rows in Table 5-1.

Table 5-1 Major Categories of Climate Change Impacts

	Increased Flood Risk to Plants & Other Facilities	Increased Risk of Impaired Coastal Outfall Operations	Altered Receiving Water Quality	Challenges to Collection & Conveyance System Operations	Challenges to Treatment Processes, Biosolids Facilities & Reuse Plants
Sea Level Rise	●	●	●		
Warmer & Shorter Winters			●		
Warmer & Drier Summers			●	●	●
More Intense Rainfall Events	●		●	●	●

5.2.1 Increased Flood Risk to Plants and Other Facilities

Risk Identification. Many treatment plants and other wastewater and stormwater facilities have historically been located near major waterways for obvious reasons related to gravity flow. Such proximity gives rise to a concern for increased flooding of these facilities in the presence of a changing climate. As shown in Table 5-1, the increased risk of flood damage arises from two climate change influences – sea level rise and more intense rainfall events. These should be treated as separate adaptation issues except, of course, in the case of facilities located near the mouth of a large river on the coast where both risks may come into play. In addition, coastal erosion and loss of natural protective features such as barrier islands and wetlands is already progressing at alarming rates and is expected to continue as sea levels rise.

Risk Assessment/Characterization (Vulnerability Analysis). What would represent a *threshold* level of flood damage to treatment plants, pumping stations or detention and drainage facilities that are vulnerable to these flood risks? What would be an unacceptable failure risk? Certainly damage at a level that causes a treatment plant to be knocked out of service for any period of time would qualify as a critical failure. Such a level of failure could cause broad environmental and public health damages. A lesser failure threshold might be conceived as a marginal degree of damage, sufficient to perhaps cause an episode of noncompliance, but more readily recoverable. Damage to collection and conveyance or drainage and detention facilities may or may not represent acceptable risk, but will surely increase maintenance needs.

What is the likelihood of seeing such *threshold* levels of flood damage within typical capital planning or other planning horizons?

Coastal erosion and increased flood risk from coastal storms are products of sea level rise. Sea level rise is expected to be gradual but the rate of change is uncertain (and a key reason is the potential contribution of melting of major glaciers in Greenland and Antarctica). Coastal storm intensity is also projected to increase gradually as a function of sea level rise, but there is a natural stochastic element in such phenomena that make it possible to see much stronger storms sooner than expected.

The same observations apply to increased flood risk produced by the increasing trend towards more intense rainfall events. Here too, there is a natural stochastic element that makes it possible to see larger floods sooner than expected. In fact, precipitation intensity has increased and there are indications that increased flooding has already been in evidence across the United States, based on trends in recorded streamflows.

Risk Management (Adaptation Analysis). How can these increased risks of flood damage be met with adaptive responses? Regarding increased flood risk in general, it is a logical starting point for adaptation to undertake a review of emergency response plans to be better prepared for whatever the future holds. With respect to storm damage and coastal erosion from sea level rise, a review of protective measures to address the threat from erosive forces and storm surges during coastal storms may be warranted. This can include structural as well as non-structural approaches such as restoring wetlands in the vicinity of a plant or other facility.

Along rivers and flood plains, conventional flood control methods may become more critical in the short term as rainfall and runoff events continue to intensify. This includes both onsite defensive structures such as levees as well as upstream control facilities such as reservoirs. In addition, it is worthwhile to expand the long-term emphasis on non-structural approaches such as watershed scale land use planning and smart growth strategies, focused on reducing the amount of impervious area and encouraging a switch to green infrastructure where appropriate to dampen the compound impacts of climate change and growing populations on flood risks.

In the longer term plant replacement cycle, options might need to be expanded to incorporate elevation of key facilities, although this entails a carbon cost for pumping and there is a natural limit to this strategy – ultimately, wastewater treatment plants cannot be designed to look like drilling rigs. Relocation to upland sites or consideration of decentralized treatment options versus large downstream regional plants may come into play.

Research Needs

- An obvious first priority research need in this area is improved assessment/characterization of increased flood risks to existing facilities and operations. As discussed in Section 4, a number of coastal utilities have begun using GIS tools together with relevant climate data resources to develop more definitive assessments of the vulnerability of seaside facilities. There is certainly more room to further develop this area of practice and planning tools. WERF has recently proposed a state-of-the-art review of tools and techniques in this area to assess opportunities for improvement (Table 5-2, Project 1).

- A general call has been raised for a comprehensive project to characterize climate change impacts on infrastructure systems with the intent of attempting to quantify the range of potential magnitudes involved (Table 5-2, Project 2). While very challenging for many types of climate impacts, assessment of flooding risks from the effects of sea level rise and from more intense rainfall events may be more tractable targets for such vulnerability analysis.

- Vulnerability analysis for flood risks might also be improved by a proposal to undertake collaborative regional development of hydrological models at a watershed scale (Table 5-2, Project 3). The potential to improve opportunities for sustainable adaptations to climate change impacts through cooperative watershed approaches has also been identified as a useful research topic (Table 5-2, Project 4).

- Another research suggestion relevant to this category of climate impacts is a proposal to assemble case studies of utility experiences coping with extreme events to identify the key lessons learned from these experiences that can be useful to others in devising response plans as interim adaptive measures (Table 5-2, Project 5).

- Several research projects have been proposed that would involve re-evaluating the use of dams and reservoirs in light of climate change for multiple purposes of water supply, ambient water quality management (especially during low flows) and flood control (Table 5-2, Project 6 and Table 5-2, Project 7.

- In Circular 1165-2-211, the US Army Corps of Engineers provides guidance on incorporating sea level rise in civil works programs. Something similar would be appropriate on incorporating changes in precipitation intensity into design standards, encompassing also non-structural approaches.

Table 5-2. Research Proposals Relevant to Increased Flood Risk to Plants and Other Facilities

Number	Title	Objective(s)
1	State-of-the-Art Survey of Tools and Techniques for Assessing Vulnerability of Coastal Facilities and Operations to Sea Level Rise. (Note: this proposed project was not part of the prior research needs workshop, but has been added to this list to plug an important gap).	This project recognizes that many coastal wastewater and stormwater agencies are already well underway in evaluating the vulnerability of facilities and operations to sea level rise. The project would develop detailed case studies of the methods (including GIS tools) and data (including weather data and data on storm surge, etc.) being used to develop these analyses. A synthesis document would then be prepared identifying gaps and additional needs in tool development, data development and data access with a focus on improving the quality and relevance of analytical outputs to decision makers.

2	Characterizing Climate Change Impacts on Infrastructure Systems	The objective of this project is to characterize climate change impacts on infrastructure systems by: Identifying a portfolio of potential environmental impacts due to anticipated climate change conditions Identifying specific material and system changes such as frost impacts, geotechnical changes, variation in groundwater level, temperature effects, soil changes, etc. that may be affected by climate change Quantifying the range and magnitude of potential changes Identifying how these environmental changes will impact infrastructure (water supply, wastewater, and stormwater systems).
3	Collaborative Regional Watershed Scale Hydrological Models for Climate Change Analysis	This project will use historical and modeling analysis methods to link climate change, watershed changes, and water resource changes. The project will also critically analyze regional hydrological vulnerability assessments of climate change, including a review of economics of scale, and an analysis of cooperative and consistent regional modeling through literature review, surveys and case study analysis.
4	Assessing Cooperative Watershed-Scale Opportunities for Adapting to Climate Change	The objective of this project is to identify opportunities for water utility engagement in cooperative, multi-user water and land use planning to deal with the hydrologic changes and related watershed changes anticipated to arise as a result of climate change.
5	Case Studies on Extreme Events and Infrastructure Interdependencies under Climate Change Conditions	The objective of this project is to: Identify and gather experience on how extreme climate change events have affected water, wastewater, and stormwater infrastructure systems. Determine "lessons learned" from that experience that can assist in managing climate change effects on infrastructure systems in the future. Determine "lessons learned" from the interdependencies of water, wastewater, and stormwater infrastructure on other infrastructure systems – e.g., electric power, transportation, and communication – under extreme conditions comparable to those of potential climate change scenarios.
6	Analysis of Reservoir Operations Under Climate Change	This project will critically analyze reservoir operations under a new climate regime. The project will also evaluate the range of climate change impacts on larger storage projects and how these impacts will play out in light of current rule curves based on past hydrological data; and study and develop different and more flexible ways to operate and maintain reservoirs to address these impacts.
7	Managing Large-Scale and Old Infrastructure Under New Climate Conditions	This project will identify methods to manage major existing infrastructure, such as dams, transmission mains, and diversion structures, to adapt to climate change.

Adapted from: WRF, WERF, UKWIR, *Water Industry Climate Change Research Needs Workshop, Denver, CO., 2008.*

5.2.2 Increased Risk of Impaired Coastal Outfall Operations

Risk Identification. Sea level rise will change the hydraulics under which many types of outfalls and stormwater conveyance facilities were designed to operate. The functioning of combined sewer systems – and of expensive modifications to combined sewer systems in coastal cities – is a particular concern in conjunction with the prospect of larger stormwater flows as a result of increased rainfall intensity.

Risk Assessment/Characterization (Vulnerability Analysis) What would represent a *threshold* level of damage from improper outfall operation in coastal locations that are vulnerable to these risks? What would be unacceptable failure risks?

If outfall structures are unable to release discharges as fast as flows are entering at the other end of the pipes, flooding in streets and dwellings may result. Sewage back-ups and overflows pose additional risks in combined sewer systems. These are clearly failure scenarios to be avoided.

In addition to the risk of back-ups and overflows, there is the potential that an unlucky combination of wind, tidal and storm surge patterns could cause saline water to invade collection and conveyance systems. This risk might grow as sea levels rise. Not only is salt water corrosive to piping systems, but if it enters the wastewater treatment plant, it can cause great disruption of biological and chemical treatment processes.

When might you expect to see a *threshold* level of impairment of coastal outfall operations?

Operational impairment of coastal outfalls is expected to be a direct result of sea level rise. While the rise in sea levels is projected to be a gradual phenomenon, there is the possibility of more sudden changes due to faster melting of land ice in Greenland and Antarctica. Coastal storm intensity is also projected to increase gradually as a function of sea level rise, but there is a natural stochastic element in such phenomena that make it possible to see much stronger storms sooner than expected.

Risk Management (Adaptation Analysis). How can you meet the increased risk of impaired coastal outfall operations with adaptive strategies?

Despite the gradual nature of the trend in sea level rise, the stochastic nature of storm events makes it prudent to initiate efforts to mitigate anticipated adverse impacts on coastal outfall performance. This is somewhat easier to engage since the costs of getting started are relatively modest. In the case of New York City and King County, Washington, both initiated their efforts with careful planning exercises to locate their outfalls using GIS tools and relate these locations to digital elevation data and storm surge data to evaluate the nature of the threat from the sea. Operational experiences with outfall performance under critical conditions was also examined in order to identify and prioritize the most vulnerable locations at which to begin applying adaptive measures, such as gates to prevent salt water inflow to the system. As always, where combined sewer systems are involved, the adaptive response might also include a redoubling of the commitment to green infrastructure and reduction of impervious surfaces as a means of diverting stormwater flows from the overloaded system.

Beyond the immediate priorities, the problem poses a number of planning challenges. Adaptation can include an array of defensive measures early in the century, leading perhaps to a re-configured coastal infrastructure during the next major replacement cycle. It goes without saying that such rearrangements of facilities will also change the carbon footprint of the resulting facilities. As many similarities as there are in the coastal setting, the examples to date also indicate that solutions are likely to be highly site specific.

Research Needs.

- An obvious first priority research need in this area is improved assessment/characterization of increased risks to coastal outfall operations. As discussed in Section 4, a number of coastal utilities have begun using GIS tools together with relevant climate data resources to develop more definitive assessments of the vulnerability of seaside facilities. There is certainly more room to further develop this area of practice and planning tools. WERF has recently proposed a state-of-the-art review of tools and techniques in this area to assess opportunities for improvement (Table 5-3, Project 1).

- Another research suggestion relevant to this category of climate impacts is a proposal to assemble case studies of utility experiences coping with extreme events to identify the key lessons learned from these experiences that can be useful to others in devising response plans as interim adaptive measures (Table 5-3, Project 2).

- Longer term, it has been suggested more broadly that research is needed on the question of planning new infrastructure systems that can be more resilient to impacts of climate change (Table 5-3, Project 3). WERF's current project on decentralized stormwater controls for urban retrofit and combined sewer overflow controls is an example.

- In Circular 1165-2-211, the US Army Corps of Engineers provides guidance on incorporating sea level rise in civil works programs. Something similar would be appropriate on incorporating changes in precipitation intensity into design standards, encompassing also non-structural approaches.

Table 5-3. Research Proposals Relevant to Increased Risk of Impaired Coastal Outfall Operations

Number	Title	Objective(s)
1	State-of-the-Art Survey of Tools and Techniques for Assessing Vulnerability of Coastal Facilities and Operations to Sea Level Rise. (Note: this proposed project was not part of the prior research needs workshop, but has been added to this list to plug an important gap).	This project recognizes that many coastal wastewater and stormwarer agencies are already well underway in evaluating the vulnerability of facilities and operations to sea level rise. The project would develop detailed case studies of the methods (including GIS tools) and data (including weather data and data on storm surge, etc.) being used to develop these analyses. A synthesis document would then be prepared identifying gaps and additional needs in tool development, data development and data access with a focus on improving the quality and relevance of analytical outputs to decision makers.
2	Case Studies on Extreme Events and Infrastructure Interdependencies under Climate Change Conditions	The objective of this project is to: Identify and gather experience on how extreme climate change events have affected water, wastewater, and stormwater infrastructure systems. Determine "lessons learned" from experience that can assist in managing climate change effects on infrastructure systems in future. Determine "lessons learned" from the interdependencies of water, wastewater, and stormwater infrastructure on other infrastructure systems – e.g., electric power, transportation, and communication – under extreme conditions comparable to those of potential climate change scenarios.
3	Planning New Water, Wastewater, and Stormwater Systems for a Future with Climate Change	The objective of this project is to provide a framework for planning new water infrastructure (potable, waste, storm and reused) with resilience to effects from climate change.

Adapted from: WRF, WERF, UKWIR, *Water Industry Climate Change Research Needs Workshop, Denver, CO., 2008.*

5.2.3 Altered Receiving Water Quality

Risk Identification. As illustrated in Table 5-1, everything resulting from climate change will contribute to baseline changes in receiving water quality which can have enormous significance for the wastewater and stormwater agencies, relating directly to regulatory compliance issues. At the most elemental level, the global increase in air temperatures will produce increased water temperatures and lower dissolved oxygen. Estuarine waters will become warmer as well as more saline due to sea level rise and also more acidic due to CO_2 absorption. Generally warmer air during both winter and summer seasons may produce local or regional variations in air circulation patterns that will, in turn, produce changes in pollutant loadings contained in rainfall (e.g., nutrients, acidity, etc.).

Warmer and shorter winters will result in smaller snowpacks, earlier spring melt and less groundwater recharge, producing lower base flows in many rivers during the late summer and fall. Warmer and drier summers will further increase the risk of extreme heat waves and drought conditions in many regions of the country, altering water temperatures and concentrations of water quality parameters during extreme low flow conditions.

Warmer and drier summers will also contribute to increased eutrophication of surface water bodies. This effect can be magnified by climate induced changes in watershed conditions. The changes in temperature and rainfall are likely to produce changes in natural vegetative cover that could have effects on water yield and quality. The risk of wildfire is known to increase under warmer and drier conditions and wildfires can be a major source of nutrient and sediment loads that can be sustained for years following an event. Finally, agricultural and irrigation practices are likely to adapt also, producing a different pattern of non-point pollution loadings.

More intense rainfall events are troubling because of the compliance challenges associated with wet weather flows through treatment plants and because of consent decree requirements governing the control of overflows from combined sewer systems. However, these direct compliance challenges of more intense rainfall – discussed under 5.2.4, below – also affect wastewater and stormwater agencies indirectly to the extent that the same problems occurring upstream of their location can alter the receiving water quality at their downstream location.

Risk Assessment/Characterization (Vulnerability Analysis). What would represent a *threshold* level of climate-induced deterioration in receiving water quality? What would impose an unacceptable failure risk on existing wastewater and stormwater management facilities sufficient to impair their ability to sustain regulatory compliance or meet water quality goals?

The Clean Water Act strives to attain and sustain water quality goals in the receiving waters of a wastewater or stormwater agency. As described above, there are so many climate induced threats to baseline water quality, it is conceivable that adverse trends might eventually cause the regulatory process to respond in some manner. It may be temperature, or dissolved oxygen, or bacteria, or nutrients – or compounded effects due to low base flows and high wet weather flows. It may be that state water quality standards will eventually have to be revisited to make a realistic appraisal of the attainability of designated uses in a changing climate. Alternatively, the regulatory process could require upgraded performance from existing wastewater and stormwater facilities via tighter NPDES or MS4 permit requirements or TMDLs in order to hold the line on ambient water quality. As discussed further, below, that is not to say that more effort would not also be required of non-point sources, but the critical threshold for existing wastewater and stormwater facilities would be the point at which regulators would be forced to require expensive modifications.

When might you expect to see a *threshold* level of deterioration in receiving water quality such that regulators might be compelled to require expensive modifications of existing wastewater and stormwater facilities in order to offset climate-induced adverse trends in ambient water quality?

The spectrum of potential adverse effects of climate change on receiving water quality is so broad as to be truly daunting in its complexity. It will be very difficult to detect and attribute changes in baseline water quality to – in this instance – mostly gradual climatic, hydrologic and ecologic changes as well as climate induced changes in anthropogenic activities that affect water quality (land use, agriculture and forestry). It will indeed be difficult to say when this critical threshold level of impact has been reached – due to climate change.

Risk Management (Adaptation Analysis). How can you adapt to meet the threat of a *threshold* level of climate-induced deterioration in receiving water quality that would result in new regulatory requirements for costly upgrades to existing wastewater and stormwater facilities?

Because this is more likely to be a gradual change process for most phenomena, there is time to improve knowledge before adaptive responses are compelled by circumstances. The need for research extends beyond the US EPA, WERF and other nationwide basic research sources, however. Every wastewater and stormwater agency should consider the question of potential climate-induced impacts on receiving water quality and identify their own research needs to assist them in gaining a preview of the future through watershed monitoring and modeling that will better enable them to anticipate a critical threshold level of change in receiving water quality. Watershed scale cost sharing among water supply, wastewater and stormwater agencies might help break the cost of this particular adaptive strategy.

In many instances, the attainability of use designations established for water bodies under state water quality standards was never fully scrutinized under assumptions of stationary climate. With the broad array of threats to receiving water that could conceivably arise in a changing climate, these foundation issues in the establishment of water quality standards may be impossible to ignore. Active involvement of State and EPA regulators and watershed stakeholders in the design and implementation of enhanced monitoring and related research will be key to all parties concerned in evaluating the possibilities for changes in the regulatory program. It is conceivable that different regulatory approaches will be more appropriate to a changing future, involving more reliance on such techniques as watershed based permitting, trading and other innovations. It is also conceivable that in some areas of gradual change, the main responsibility of the current generation of water professionals will be development of trend data to support later adaptations in facilities, operations and regulatory institutions.

A second step in adapting to meet this threat is to carefully re-examine the remaining useful life and planned rehabilitation / replacement cycle for all facilities that can conceivably be affected by this threat. Given the anticipated gradual nature of the threat, it is possible that the changes required can be efficiently integrated into normal asset management and capital planning processes and that the extra expense of unplanned modifications can be avoided. The wet weather issues stemming from increased rainfall intensity may be the exception in places where it appears this change is already underway.

Finally, in adapting to meet this challenge wastewater and stormwater agencies need to recognize that this threat – as defined above – is based on a business-as-usual extrapolation. But the future does not have to simply replicate a past in which every wastewater and stormwater agency works alone and fends for itself. It is possible to conceive of an alternative future based on watershed scale collaboration, involving not only regulated point sources, but non-point sources and other influences totally outside the regulatory regime such as land use planning authorities and other interested stakeholders. By expanding the system boundary in this manner, the range of possible adaptive strategies may be expanded to the benefit of all concerned.

Research Needs.

- To begin the process of coping with the threat to receiving water quality, a research project was proposed to identify the key ecosystem and water quality parameters that should be tracked to measure and record water quality and aquatic ecosystem changes induced by climate change (Table 5-4, Project 1).

- A related project has been proposed to develop a comprehensive set of water quality parameters to be incorporated in water quality monitoring contained in the WATERS Network to provide a national database with which to track climate change impacts (Table 5-4, Project 2).

- In view of the many aspects of climate change that may impact nutrient loadings, a research project was proposed to study the potential secondary impacts on the nature and extent of algal blooms (Table 5-4, Project 3).

- An initial analysis was proposed to survey the prospective impacts of climate change on aquatic ecosystems from the perspective of the potential need to adjust designated uses accordingly (Table 5-4, Project 4).

- A multi-dimensional analysis of adaptation opportunities that may exist through holistic watershed collaboration has been proposed to bring considerations of hydrology, land use, water quality, and aquatic biota under one umbrella to evaluate adaptation in the most holistic manner (Table 5-4, Project 5). This holistic watershed context is especially important since it would be too limited to base adaptation strategy on water quality and aquatic ecosystem impacts, for example, without taking account of potentially significant changes in hydrology affecting such variables as base flows, peak flows, and reservoir operations.

- A broad analysis has been proposed to consider the need for adaptation and institutional transformation by a regulatory process that was developed under the assumption of stationary climate. The analysis would endeavor to consider all the ways the regulatory processes influence both adaptation and carbon footprint, as well as the interrelationships between these potentially conflicting goals. The objective would be to plot a new more sustainable course for regulation (Table 5-4, Project 6).

Table 5-4. Research Proposals Relevant to Altered Receiving Water Quality

Number	Title	Objective(s)
1	Identification of Water Quality and Ecosystem Monitoring Parameters to Assess Climate Change Impacts	The objective of this project is to identify water quality and ecosystem monitoring parameters to assess climate change impacts and develop standardized impact metrics, monitoring protocols, and reporting structures (databases) for tracking, assessing, and reporting climate change impacts on aquatic ecosystems at the local, regional, and national levels.
2	Data Collection and Monitoring Workshop	The objective of this project is to conduct a workshop with the professional practice community (including utilities, consultants regulators and academics) to participate in the development of the WATERS Network as a tool for collection and evaluation of data related to identifying the water quality impacts of climate change.
3	Impact of Climate Change on the ecology of Algal Blooms	The objective of this project is to develop models to predict changes in algal growth, algal speciation, and the frequency of algal blooms related to changes in ambient water quality due to climate change. From these predictions, the potential adverse impacts of algal ecology shifts can be interpreted into anticipated impacts on water treatment, focusing on toxins, and taste and odor problems. Finally the study would define public health risks from exposure to algae impacted waters.
4	Evaluation of the potential impacts of climate change upon aquatic ecosystems and designated uses	The objective of this project is to evaluate the potential for predicted climate changes to significantly alter the characteristics of the aquatic ecosystem and associated communities of aquatic species. For those alterations deemed significant, assess the effect upon water and wastewater utility functions and develop guidance to incorporate these effects into utility operation and management protocols. In Phase 2, identify the relevant designated beneficial uses and how anticipated changes in the aquatic ecosystem may drive the need to refine the designated use for those alterations in aquatic ecosystems which are deemed significant.
5	Assessing Cooperative Watershed-Scale Opportunities for Adapting to Climate Change	The objective of this project is to identify opportunities for water utility engagement in cooperative, multi-user water and land use planning to deal with the types of hydrologic changes and related watershed-level changes anticipated to arise as a result of climate change.

6	Climate Change: a Case for Smart Regulation	The objectives of this project are to: Gain recognition by agencies, regulators, and government that current environmental law is not climate proof and is driving poor carbon behavior Undertake broad qualitative analysis of regulatory frameworks to identify areas where carbon emissions are being driven for marginal benefit Identify barriers to water utilities following ‘good carbon behavior and climate change – e.g. investing in carbon reduction, investing in low carbon technologies etc Identify legal and regulatory barriers to ‘good adaptation’ – e.g. policy that allows building on flood plains, development where resources are threatened. Identify areas of legislation that needs to be more forward thinking – drives a long term approach and recognizes that climate change will occur in the lifetime of a statute or policy Undertake specific case studies to illustrate the way in which specific legislation drives carbon – water, wastewater and sludge Provide sound evidence that will support environmental regulation that recognizes ‘net environmental benefit’ – i.e. balances the local improvements with the global carbon cost

Adapted from: WRF, WERF, UKWIR, *Water Industry Climate Change Research Needs Workshop, Denver, CO., 2008.*

5.2.4 Challenges to Collection and Conveyance System Operations

Risk Identification. Table 5-1 indicates climate-induced challenges to collections and conveyance system operations will likely result from both the dry spells associated with warmer and drier summers as well as from more intense precipitation events when it does rain. These are two different impacts involving totally different mechanisms, but resulting in increased stresses on the same pipe infrastructure systems.

Risk Assessment/Characterization (Vulnerability Analysis). What would represent a *threshold* level of climate-induced impact on collections and conveyance system operations that would produce an unacceptable level of failure risk?

As temperatures continue to rise over the century, warmer and drier summers are predicted in almost all parts of the country. Even many areas projected to receive more rainfall overall are projected to be drier in summer. Many places will also be subject to increase drought risk and risk of more intense heat waves and dry spells. The net effect could be damaging to pipe infrastructure. Water conservation efforts could greatly reduce flows in sewers designed to carry higher volumes. The additional air space and longer dwell time in the piping system could create greater opportunities for septic odor problems and for pipe corrosion due to formation of hydrogen sulfide and sulfuric acid. In addition, more frequent and extreme dry spells could stimulate the growth of deeper root systems causing increased penetration and blockage of sewers.

The acceleration of the hydrologic cycle caused by warmer temperatures will produce more intense rainfall events. This trend is already apparent in precipitation records. If such extreme rainfall events follow extreme dry spells, there may be accumulations of material in some pipes that could cause local back ups and/or surge loadings to treatment facilities. Agreements with industrial sources may be affected by such anomalies that were not anticipated when arrangements were established to accept industrial flows. With or without pretreatment, industrial flows were probably accepted on the basis of the flow regimes in the conveyance system that exist under current climate. Altered flow regimes may upset those arrangements.

Although most wastewater and stormwater flows by gravity, pump stations are a critical part of the conveyance infrastructure. There is clear threat to the performance of this infrastructure if flows are either much smaller or much greater than estimated when the pumping facilities were designed under assumptions of stationary climate. Overflows, backups and equipment damage could result.

In addition, there is a concern that an increasing trend towards more intense precipitation was not recognized and taken into account in the design of many remedial programs developed to address combined sewer overflows and sanitary sewer overflows. If the planned corrective measures are under designed, then the significant expenditures entailed could result in less improvement in water quality than anticipated.

When might these *threshold* levels of climate-induced impact be expected to appear in the operations of collections and conveyance infrastructure?

Although both of these effects are already in evidence, the increased incidence of both dry spells and more intense rainfall events are generally regarded as gradual changes. However, both of these phenomena are subject to stochastic influences that could produce events that are more extreme than expected. Despite these factors, the threshold levels of impact required to produce serious damage to pipe infrastructure or sustained violations will probably take time to become manifest. For the most part, these are impacts for which there is time to deploy an adaptive response.

Risk Management (Adaptation Analysis). How can you adapt to meet *threshold* levels of climate-induced challenges to collections and conveyance systems from abnormally low or abnormally high flows?

The increased threat to the physical integrity of pipe infrastructure from both corrosive action and tree roots suggests that augmentation of the inspection and maintenance elements of the asset management program would be an excellent “no regrets” adaptation. In consideration of the potential problems caused by deposition of materials during extreme low flows, enhanced maintenance and cleaning programs may be justified from another important perspective.

The increased threat of sewage overflows during extreme rainfall events will first require careful study to evaluate how much buffer is believed to exist to absorb high flow events without triggering violations. The question then becomes one of how much of that capacity could be lost to climate-induced rainfall intensity and how it can best be recovered. It is conceivable that, under the right conditions, the long term answer may lie in green infrastructure strategies designed to reduce runoff and prevent it from entering combined sewers or leaky sewers. As more and more green infrastructure is added to such a program year after year, it may be capable of keeping up with the gradually increasing rainfall intensity phenomenon over the course of time.

Research Needs.

- A general project was proposed to characterize climate change impacts on infrastructure systems with the intent of attempting to quantify the range of potential magnitudes involved (Table 5-5, Project 1). Assessment of the above impacts on conveyance systems may be a tractable target for such vulnerability analysis since the experience with extreme events under current climate can lend insights into the future.

- A follow-up to the above project was proposed to develop new design and operating parameters to help make infrastructure systems more resilient to the impacts of climate change (Table 5-5, Project 2). This may also be a tractable target with regard to conveyance systems.

- Another research suggestion relevant to this category of climate impacts is a proposal to assemble case studies of utility experiences coping with extreme events to identify the key lessons learned from these experiences that can be useful to others in devising response plans as interim adaptive measures (Table 5- 5, Project 3).

Table 5-5. Research Proposals Relevant to Challenges to Collection and Conveyance Systems

Number	Title	Objective(s)
1	Characterizing Climate Change Impacts on Infrastructure Systems	The objective of this project is to characterize climate change impacts on infrastructure systems by: Identifying a portfolio of potential environmental impacts due to anticipated climate change conditions Identifying specific material and system changes such as frost impacts, geotechnical changes, variation in groundwater level, temperature effects, soil changes, etc. that may be affected by climate change Quantifying the range and magnitude of potential changes Identifying how these environmental changes will impact infrastructure (water supply, wastewater, and stormwater systems)
2	Design and Operation of Water Systems for Resilience to Climate Change	This project will be based on the climate change impacts and effects as defined by the project, "Characterizing Climate Change Impacts on Infrastructure" by providing guidance on the design of systems to provide resilience to climate change. Any design necessitates a consideration of the asset to be provided along with how it will be operated and maintained. The project will Provide framework of options and method to evaluate change in: Planning and design Operations and maintenance Management practices Develop a guidance manual that will include examples for specific utility guidance. Create an outreach plan and conduct for maximum industry wide dissemination.
3	Case Studies on Extreme Events and Infrastructure Interdependencies under Climate Change Conditions	The objective of this project is to: Identify and gather experience on how extreme climate change events have affected water, wastewater, and stormwater infrastructure systems. Determine "lessons learned" from that experience that can assist in managing climate change effects on infrastructure systems in the future. Determine "lessons learned" from the interdependencies of water, wastewater, and stormwater infrastructure on other infrastructure systems – e.g., electric power, transportation, and communication – under extreme conditions comparable to those of potential climate change scenarios.

Adapted from: WRF, WERF, UKWIR, *Water Industry Climate Change Research Needs Workshop, Denver, CO., 2008.*

5.2.5 Challenges to Wastewater Treatment, Biosolids and Reuse Operations

Risk Identification. As shown in Table 5-1, treatment, biosolids and reuse operations will also be impacted by the odd combination of warmer and drier summers – carrying the risk of more extreme heat waves, dry spells and drought risk – together with increased wet weather operating challenges caused by more intense rainfall events. Both types of extremes are capable of presenting a broad range of process operating challenges with complex effects. Climate change delivers both.

Risk Assessment/Characterization (Vulnerability Analysis). What would represent critical *threshold* levels of key influent and operating parameters during extreme dry weather conditions and extreme wet weather conditions – threatening process failure in the absence of adaptive responses?

Wastewater treatment plants, biosolids management facilities and reuse treatment plants are all designed on the basis of an assumed range of flow rates, temperatures, and biological and chemical influent characteristics. Some types of processes are more tolerant of variations in these parameters than others. Going forward under climate change, it must be taken as a given that there will be an increasingly wide operating challenge presented by variability in the influent stream. In addition, the natural relationship between operating temperatures and oxygen transfer efficiency could affect treatment and biosolids processes, disturbing process control and potentially producing anaerobic conditions and odor control issues.

During extended dry spells and drought periods a much stronger and smaller waste stream is to be expected as a result of likely implementation of conservation measures. But when it rains, the intensity of rainfall and runoff might produce initial surge loadings from material deposited in conveyance facilities followed by excessive volumes of dilute waste at extraordinary flow rates. It may be necessary to swing rapidly from one operating mode to the other, increasing the risk of operating errors. As conditions progress, it may become clear that either a treatment plant or biosolids processing facility or land disposal site or reuse facility designed under historic climate assumptions is not suited to these extreme operating modes without adaptation. Land disposal of biosolids and odor control facilities may be particularly challenged by rapid shifts between wet and dry conditions that will also affect soils, vegetation and insect pests.

All of the above issues have implications for industrial sources as well. Direct dischargers will face all the same challenges in their treatment processes. Industrial sources contributing wastes (with or without pretreatment) to municipal wastewater systems may find that the additional operating challenges at the municipal plant have repercussions in terms of future arrangements regarding the timing and strength of their allowed waste flows into the system.

When might these erratic changes in operating conditions be expected to present a critical *threshold* level of challenge to treatment, biosolids and reuse facilities?

The increased incidence of both dry spells and more intense rainfall events is already in evidence and will likely increase as temperatures increase. However, both of these phenomena are subject to stochastic influences that could produce events that are more extreme sooner than expected. Despite these factors, the threshold levels of impact required to produce serious process operations difficulties will probably take time to become manifest. For the most part, these are impacts for which there is time to deploy an adaptive response.

Risk Management (Adaptation Analysis). How can you adapt to meet *threshold* levels of climate-induced challenges to treatment plants, biosolids facilities or reuse plants from abnormally hot and dry or abnormally wet weather?

A vulnerability analysis of treatment, biosolids and reuse facilities is a good way to determine adaptation needs. Examining the existing design and operations, it is prudent to look at all the key parameters to see if there are weaknesses in the process concept that would be stressed by sudden shifts between extreme operating conditions and then identifying operating practices and perhaps plant modifications to meet these challenges. Because these impacts are expected to arise gradually over time, there may be an opportunity to fold capital modifications into routine rehabilitation/replacement cycles rather than identifying them as additional capital demands.

Significantly, there are at least three major sets of constraints that will have a bearing on the extent of flexibility available in modifying the operations of treatment facilities. First it is apparent from previous discussion of the challenges presented from changes in receiving water quality that the extreme variation between wet and dry inflows to a plant discussed here are only one part of the overall performance challenge to be faced; the receiving water quality that drives treatment standards will be simultaneously impacted by the same extreme phenomena. A second set of constraints is imposed by the fact that process changes in wastewater treatment may change the character of the outputs that are provided to downstream biosolids and reuse facilities. Too much change in the nature of the treated products may create the subsequent need for changes in these downstream processes. Finally, wastewater treatment and biosolids processes have been the center of much attention regarding the minimization of green house gas (GHG) emissions. Process changes to meet water quality objectives as adaptations to climate change must be factored into these quite complex process optimizations that have single-mindedly targeted GHG reductions because the two goals may conflict in a number of places.

Research Needs

- A general project was proposed to characterize climate change impacts on infrastructure systems with the intent of attempting to quantify the range of potential magnitudes involved (Table 5-6, Project 1). Assessment of the above impacts on treatment processes, biosolids processing, land disposal and reuse processes may be a tractable target for such vulnerability analysis.

- A follow-up to the above project was proposed to develop new design and operating parameters to help make infrastructure systems more resilient to the impacts of climate change (Table 5-6, Project 2). This may also be a tractable target with regard to these engineered processes.

- Several significant research projects have been proposed to make a comprehensive – cradle-to-grave – assessment of the opportunities for optimization of wastewater treatment and resource recovery processes of biosolids management and reuse to thoroughly investigate potential trade-offs between greenhouse gas emissions and process performance (Table 5-6, Projects 3, 4, 5, 6 and 7). These projects would be made complete by adding a third dimension of potential trade-offs relating to potential constraints imposed by GHG reduction strategies on flexibility for adaptation. Process optimization should not be approached under assumptions of stationary climate.

Table 5-6. Research Proposals Relevant to Challenges to Wastewater Treatment, Biosolids and Reuse		
Number	**Title**	**Objective(s)**
1	Characterizing Climate Change Impacts on Infrastructure Systems	The objective of this project is to characterize climate change impacts on infrastructure systems by: Identifying a portfolio of potential environmental impacts due to anticipated climate change conditions Identifying specific material and system changes such as frost impacts, geotechnical changes, variation in groundwater level, temperature effects, soil changes, etc. that may be affected by climate change Quantifying the range and magnitude of potential changes Identifying how these environmental changes will impact infrastructure (water supply, wastewater, and stormwater systems)
2	Design and Operation of Water Systems for Resilience to Climate Change	This project will be based on the climate change impacts and effects as defined by the project, "Characterizing Climate Change Impacts on Infrastructure" by providing guidance on the design of systems to provide resilience to climate change. Any design necessitates a consideration of the asset to be provided along with how it will be operated and maintained. The project will provide framework of options and method to evaluate changes in: Planning and design Operations and maintenance Management practices Develop a guidance manual that will include examples for specific utility guidance. Create an outreach plan and conduct for maximum industry wide dissemination.
3	Cradle-to-grave wastewater process optimization for resource recovery and greenhouse gas emission reduction in a carbon constrained world	The objectives of this project are to: Identify pathways to most efficiently recover resources and create new products throughout the treatment train. Focus on nutrient and energy recovery and optimization of resource recovery, including ammonia and phosphorus Evaluate the tradeoffs of traditional processes vs. processes to maximize resource recovery Identify best practices for process optimization through case studies Conduct pilot studies to measure the tradeoffs between various process options.
4	Green certification program for water and wastewater utilities	The objective of this project is to: Investigate the feasibility of developing a green (energy and environment) certification program for the water and wastewater utility sector Develop a framework for the certification program and recommended rating criteria Document similar programs in other sectors and the potential nexus with other certification programs.

5	Advancing process optimization in the water industry to include energy efficiency and control greenhouse gas emissions	The objective of this project is to: Document the relationships between optimized distribution system practices and GHGe and provide linkages to GHGe reductions. Adapt the existing Energy and Water Quality Management System (EWQMS) software to include elements of GHGe control, pressure management, leakage control, reservoir management, and pump station efficiency. Develop pilot demonstration projects that document energy savings and GHGe reductions by applying the modified EWQMS protocols.
6	Energy management planning decision support for water and wastewater systems	This project will develop and pilot a decision support tool for water and wastewater utilities that evaluates operational, economic, social and environmental tradeoffs associated with energy management planning and carbon footprint reduction. The project emphasis will be on energy demand side management, resource recovery, renewable energy options, and water demand management.
7	A comprehensive guidance document to help utilities develop integrated water, energy, and environmental resource planning strategies in a challenging climate of global warming	The objectives of project are to: Identify various successful measures used by both energy and water utilities to reduce energy and water consumption and greenhouse gas emissions (GHGe). Test measures used by one industry to attain targets in other industry; evaluate costs to achieve the same benefits. Evaluate economics of technically feasible measures for cross-cutting applications. Recommend economically feasible measures to both the energy and water sectors for reducing energy and water consumption and GHGe.

Adapted from: WRF, WERF, UKWIR, *Water Industry Climate Change Research Needs Workshop, Denver, CO., 2008.*

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Library of Congress Catalog Card Number: 2009940246

Printed in the United States of America

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