Climate Change's Impact on the Design of Water, Wastewater, and Stormwater Infrastructure

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Abstract. The climate is dynamic and constantly changing; it is projected to change more rapidly through the next 50 to 100 years. These predicted changes, while uncertain, are likely to increase failures of water, wastewater, and stormwater infrastructure due to extreme events if changes are not made during the planning and design of improvements and modifications required as systems reach the end of their useful lives. This study briefly outlines actual climatic changes that have occurred and recently published predicted changes. It looks at the impacts these changes will have on water, wastewater, and stormwater infrastructure and provides recommendations to assist engineers and owners who are working to address these impacts. In addition, cautions are provided relating to evaluating and using current climate data, models, and studies for planning and design purposes. While societal and socioeconomic factors also impact the design of water, wastewater, and stormwater infrastructure, this study only summarily covers those impacts associated with climate change.

1. Introduction

Engineers and owners are currently planning and designing improvements to water, wastewater, and stormwater infrastructure throughout the world. The majority of infrastructure in the United States (U.S.) was designed and installed over 30 years ago and has reached or is about to reach the end of its design and/or useful life. Currently, the American Society of Civil Engineers (ASCE) estimates that just over $30 billion annually is needed to fix the water and wastewater portions of the infrastructure in the U.S. (ASCE 2009). They also estimate that at least 20 years of investment at this level will be required to replace failing infrastructure.

In the past, engineers and owners assumed the climatic parameters that impacted extreme events were stationary (Chow et al, 1988: Garrett, 2008), or could be assumed to be stationary for the useful life of the infrastructure. Therefore, data collected in the past was sufficient to construct a simple model of the constraints that would impact the planning and design of water infrastructure (The term water infrastructure will be used herein to indicate the infrastructure associated with water, wastewater and stormwater systems). However, recent studies (UCCSP 2008; Schneider and O'Gorman 2007; DeGaetano 2009) have shown that not only has the past climate not been stationary over the useful life of water projects, but it is predicted that the impacts of a warming climate will increasingly accelerate climate changes.

This study will outline the impact that a dynamic climate has had on the observed climatic record in the recent past and the predicted changes that are expected in the climate over the next 50 to 100 years. Once these have been outlined, it will address the impact that each change may have on water infrastructure and, thereby, the planning and design of

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water infrastructure projects. Conclusions and recommendations are provided to advise engineers and owners who are planning or designing water system improvements.

2. The Climate's Impact on Design

An engineer designs systems to meet the objectives of the owners, users, and other stakeholders within the constraints on the system. These constraints range from the physical lay of the land, to the climate, and to the regulatory system. The engineer's main goal is to design a system that meets the objectives set forth by the project team. In addition, they seek to reduce the risk or frequency of failure to an acceptable level socially or legally, such as designing a wastewater treatment plant to be operational during a 100-year flood event.

Climatic constraints on the planning and design include:

- Temperature – The temperature range in which design elements operate is important. In particular extremes in cold and heat are integral design considerations. Extreme cold can cause design elements to freeze and fail while extreme heat can cause them to overheat. In addition, heat can cause users to request additional water supplies for irrigation, recreation, or industrial cooling—depleting the water supply.
- Precipitation
    - High Precipitation – If an area experiences extreme amounts of intense or high precipitation, flooding or other failure modes such as system overloading can occur if not considered during design.
    - Low Precipitation or drought – When precipitation is low additional demand on water resources is normal. If an area is prone to drought this must be figured into the design of water infrastructure in order to prevent a failure in supply or conveyance.
- Severe Weather Events – The occurrence of severe weather events throughout the year can be an important design considerations. These extreme events bring additional constraints such as high winds which impact exposed structures and lightning which can damage electronic and controls equipment and structures.

In the past, engineers and owners have assumed that climate extremes were stationary through time (Garrett, 2008; Chow et. al, 1988) meaning that there was no trend through time in the number, frequency, or magnitude of extreme events. Therefore, engineers could use limited temporal data to understand the climatic constraints on a system. The limited data was often published in manuals (SCS, 1961) and used to provide guidance for local regulations. Engineers believed that these data and the associated calculations would provide an acceptable risk of failure within the useful life of the system.

As time has progressed, systems have been left in service far beyond their design life and are approaching the end of their useful life. Current research into climate extremes has indicated that extreme events have changed both in frequency and intensity since the design and installation of most of the water infrastructure within the U.S..

3. Current Climatic Observations

The U.S. Climate Change Science Program (USCCSP) has recently published *Weather and Climate Extremes in a Changing Climate (USCCSP, 2008)* which followed the Intergovernmental Panel on Climate Change's (IPC) Synthesis Report on the climate

(IPCC, 2007). Each report discusses the changes in weather and climate extremes observed over the last approximately 50 years in the U.S. and the world, respectively. In general terms each study concluded:

- In most locations globally, extreme cold days, cold nights, and frost days have become less frequent, while extreme hot days and warm nights have increased. In particular, the number of heat waves has increased since 1950 even though the heat waves of the great depression of the 1930's remain the most severe in the U.S. since historic records have been kept.
- Heavy precipitation has become more frequent and intense over several decades as discussed in detail below.
- There is a regional trend in the southwestern and western U.S., and other drought prone areas to increased and prolonged drought.
- It is likely that hurricanes as measured by the Power Index have increased in intensity, frequency and duration, however there is no evidence that they are increasingly making landfall.
- There does not appear to be a change in the number or intensity of convective storms to date.

In a recent more detailed study of precipitation extremes by Arthur T. DeGaetano, a statistical analysis of changes in precipitation was completed (DeGaetano, 2009) by region in the U.S.. The analysis indicates that the majority of the U.S.'s storm intervals calculated using data from 1950 to 1979 have reduced all return intervals by 20%. That means that 2-yr, 50-yr and 100-yr intervals calculated from the 1950's to 1970's would have return intervals equal to 1.8-yr, 40-yr, and 80-yr respectively if calculated using all the data available through 2009. In general, since 1980 the return interval has decreased by 0.75% per year. Using a rolling 30-year average to determine the changes, some regions have seen a 40% reduction in return interval from the 1950 to 1979 data. What would have been considered a 100-yr storm during design in 1950 now would only be considered a 60-yr storm in 2009 increasing the likelihood of system failure during intense rainfall.

4. Climate Change Predictions

Predicting climate change relies on using global climate models that have been calibrated using information from the past climate cycles (Burroughs, 2007). These models contain uncertainty but provide a glimpse into what the future may hold. Resent studies by the IPC and the USCCSP have indicated that in the future there will be a shift in extremes as shown in Figure 1.

In a general sense the studies indicate:

- Future changes in extreme temperatures will generally follow an increase in the average temperature.
    - There will be more abnormally hot days and nights, with a more frequent and intense heat waves.
    - There will be fewer cold days and nights.
    - The number of frost free days will continue to increase.
- Droughts will become more frequent in the locations that are currently drought prone. Higher air temperatures will increase water evaporation increasing drought frequency and severity.

- Precipitation is likely to become less frequent but more intense. The average amount of rainfall will not likely decrease in most regions but the amount of extreme intense precipitation will increase.
- There is likely to be more frequent intense storms.

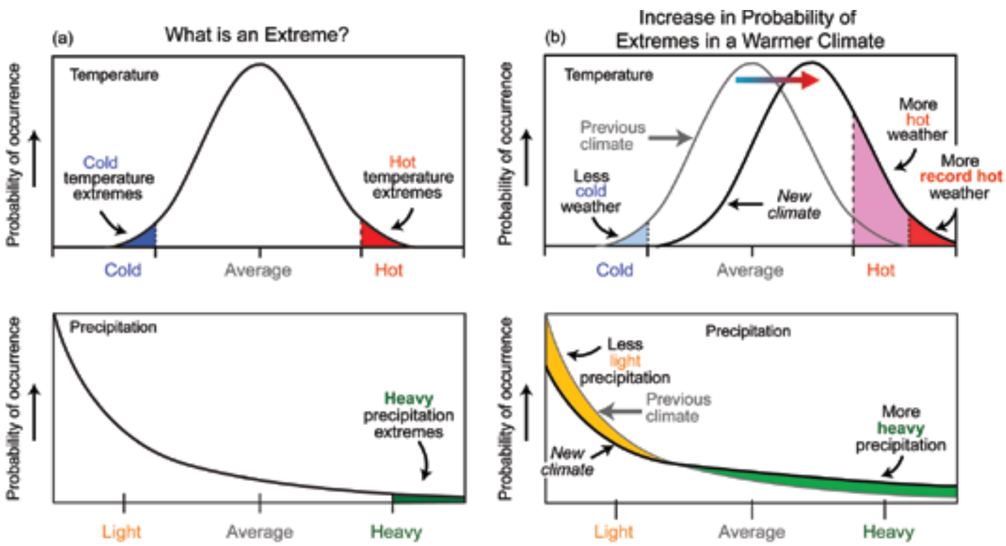

Figure 1 - Example of Climate Changes Impact on Temperature and Precipitation Probabilities (Courtesy of USCCSP 2008)

In particular, a recent study used global circulation models (GCMs) to compare the current rate of change in extreme precipitation to that expected in a warmed climate (DeGaetano, 2009). DeGaetano indicated past extreme precipitation trends as described in Section 3.0 match the predictions of the calibrated GCMs. He concludes that these trends are likely to continue to in the future.

GCMs consistently consider the 20-year return frequency storm and they predict that a 20-year return frequency storm as determined in 2000 will have a decreased return frequency of 7-13 years by 2090. If one were to extend the current extreme precipitation trends of a 0.75% per year decrease in overall storm return periods to the data, a 20-year return frequency storm in 2000 would be a 7-year return frequency in 2090 (DeGaetano, 2009). Therefore, if the trend continues as predicted, a 100-year design storm from in the early 1980's would have a predicted return frequency of approximate 70-years in 2020, a significant change.

5. Infrastructure Impacts

All of the trends and predicted changes described in Sections 3.0 and 4.0 impact the parameters used by engineers in the design of water infrastructure. This section will outline impacts each of the trends and predictions described will have on water, wastewater, and stormwater infrastructure. In addition elements engineers should consider during the design of infrastructure replacement or improvement will be discussed. Political and social impacts associated with the infrastructure changes needed, will also be outlined.

5.1 Water Infrastructure and Design Issues

Water infrastructure usually consists of water supply facilities such as storage reservoirs or tanks, treatment facilities and distribution systems. Each component is impacted by the usage of water within the system. Climate change is predicted to increase the frequency and intensity of heat waves and droughts. Droughts decrease water storage and potentially increase water demand as has been demonstrated by the most recent droughts in Australia (Landers, 2009). Conservation measures are the most widely instituted measure to help reduce water demand and conserve supplies.

However, as growth in drought prone areas continues, additional water supplies will be required and additional storage facilities may need to be built. In Australia (Landers, 2009) and other locations, one supply that is being exploited is wastewater effluent. Wastewater treatment plant effluent or re-use water is treated and disinfected for a number of uses such as cooling water and irrigation which reduce demand on the primary supply used for drinking water. The technology also exists to treat wastewater effluent to drinking water standards for direct re-use as potable water; however, the public needs to be educated and plant safety features demonstrated to get past the "yuck" factor (Metcalf and Eddie, 2003 & 2007).

Engineers need to work with local climatologists and hydrologists to determine the frequency and severity of droughts that may be experienced in a particular location. Once determined, an estimation of how much conservation can be expected for the project needs to be obtained. Then engineers can determine whether additional water storage or new water sources are needed to meet increased demands for a particular community or region. They also need to evaluate whether significant changes to flooding or wind loads have occurred, or are predicted to occur that will impact proposed infrastructure.

Another issue engineers need to evaluate while designing water treatment facilities is climate change's impact to the overall water quality, not just its quantity. If water quality is predicted to change, contingencies within the treatment system may need to be provided to allow the continued use of the source water and to prevent water treatment plant failure. In particular, in arid regions water sources may increase in salinity requiring extensive and expensive treatment such as reverse osmosis or other desalination processes.

5.2 Wastewater Infrastructure and Design Issues

Most wastewater infrastructure consists of transmission facilities, treatment facilities, and discharge bodies. The impacts to the wastewater infrastructure can be categorized as:

1. Impacts indirectly associated with climate change such as the decrease in water usage associate with water conservation; and
2. Impacts directly associated with climate change on the infrastructure.

Indirect impacts associated with climate change are primarily attributed to impacts associated with water infrastructure. Reduced water usage decreases water that flows into the wastewater transmission and treatment systems of the community thereby decreasing the overall water volume but not the waste load. The increased wastewater strength results in increased sewer cleaning and increased system corrosion (WEF, 1998a). The wastewater's viscosity will increase and flushing of the system will not occur as easily. Wastewater treatment plants will have the same contaminant loading rates at a reduced water volume creating potential hydraulic and corrosion issues that will need to be evaluated. In addition, wastewater treatment facilities may feed water re-use plants that require predetermined effluent quality which will impact the design of the proposed improvements or replacement.

Direct impacts associated with climate change are mainly associated with the increase frequency of intense rainfall. Rainfall infiltrates into sewer systems through cracks, poorly constructed or corroded manholes, and direct connections. Sewers are not hydraulically designed to convey large quantities of inflow. This causes the sewer to become hydraulically overloaded during intense rainfall and allows raw sewage to flow into receiving waters and homes as it escapes the sewer system. This is called a sanitary sewer overflow (SSO). As intense rainfall increases, SSOs will also increase resulting in impacted receiving waters and system users. As engineers work with communities to combat SSOs, they should contact the local climatologist to determine the overall impact of climate change on the current hydrology and the predicted change to determine appropriate design rainfall events.

Another direct impact is associated with decreases in base flow of the waters which receive the wastewater treatment plant effluent. Climate change in drought prone areas will likely reduce the stream and river base flows. Base flow is used to determine the effluent parameters required to be achieved by the wastewater treatment plant (WEF, 1998b), therefore, as the base flow decreases, effluent requirements will become more stringent and may require that the treatment plants install additional treatment facilities to meet the requirements. Engineers should determine changes in climatic parameters with the local climatologist as they are designing wastewater treatment facilities and working with regulating agencies to determine the predicted impacts including any decrease in stream or river base flow predicted.

5.3 Stormwater Infrastructure and Design Issues

Stormwater infrastructure directly impacts the public. Its role is to reduce the impact that runoff can have in an urban environment by removing runoff from structures and other infrastructure such as roads.

The increased frequency of intense rainfall will likely increase the risk of stormwater infrastructure failure. This infrastructure consists of both engineered infrastructure as well as natural streams and drainages, each are impacted by increase runoff intensity.

Engineers use local hydrology and regulations to design pipes, channels, and other infrastructure to reduce the risk of impact to an acceptable level. For instance, roadways may be designed to have one lane open during a storm event with an annual exceedance probability of 10-years. The so called 10-yr event is not stationary such that if the design was completed in the 1970's or 80's, as many suburban subdivision were, these roads may now have an unacceptable risk of failure and may flood more frequently than designed.

The increased frequency of intense rainfall can impact the natural drainage systems within the stormwater system. Increased peak flows create increased erosion, decrease stream stability, and impact overall stream ecology. Currently, engineers are working with ecologists and geomorphologists in many locations to improve the natural drainage system ecology (Columbia, 2007). If these professionals do not account for climate changes, they may not meet the goals of their projects through time as climate change impacts the existing designs.

5.4 Political and Societal Issues

Water infrastructure primarily impacts society by providing potable water, treating wastewater, reducing flooding and loss of life. However, infrastructure comes at a cost. Climate dynamics will impact society as follows:

- Increased financial cost of improving or replacing infrastructure;
- Changes in behavior required such as water conservation; and
- The need for increased education.

One of the major issues associated with these impacts is that society generally supports the needed changes and increased costs when they are faced with the consequences of drought or other pressing climatic condition. However, as these consequences ease the support generally decreases as well. This was documented recently in Australia, when the severe drought impacted daily life. Public support for infrastructure projects was high as the negative consequences of the sustained drought continued. However, as the drought eased and rain returned, public support decreased for the projects as did support for continued conservation (Landers, 2009). Engineers will need to work with professionals and policy makers to educate the public to overcome this tendency. It will not be possible to start and stop projects on a whim but long range planning and investment will be needed to meet the impacts that are predicted. Engineers and municipalities will need to work with residents to help them understand why changes are needed and why they need to accept re-use or other technology, in order to have sustainability.

6. Cautions

Engineers must show caution in using the conclusions of the studies of the climate and climatic extremes in general. The following outlines aspects an engineer should consider when using the results of these studies.

- In general, scientists and engineers are very good as seeing patterns and trends in data even when they do not exist (Wunch, 2007), therefore, what a scientist sees and describes mathematically or statistically may not be real. An engineer should always use caution and common sense when using or evaluating the results of studies and their conclusions for planning or design purposes.
- Climatic extremes are by definition extreme and as such the sample sizes for the data are usually small thereby increasing the uncertainty of methods used for evaluation (Garrett and Muller, 2008).
- Climatic extremes appear to be correlated (Bunde, 2007) thereby extreme events appear to cluster in a record, such that when one extreme event occurs the probability of having another extreme event is increased. The pattern of increasing extreme events may therefore be a normal variation and not a result of a changing climate.
- The climate is a dynamic system that changes through time and therefore climate extremes are not stationary. Garrett and Muller (2008) show that if a record is not stationary and has nonstationary variance the number of extreme events observed is higher than what would be expected with a stationary record. DeGaetano (2009) shows that climate extremes have not been stationary over the last 50 years.
- Global climate models used to evaluate future climate scenarios are limited in time and space (Palmer, et. al, 2008) and forecasting climate responses have

uncertainty due to the model and computing limitations (Rind, 2008; Schneider and O'Gorman, 2007). However, they have a key place in helping scientists and engineers evaluate the climate in the future and make educated planning decisions (Yin and Branstator, 2007; Rind 2008).

An engineer must be aware that science is continuing to evolve as large amounts of research resources are being expended by governments and private agencies throughout the world to more fully understand the issues associated with climate variability. An engineer must remain focused on the latest research in statistics, hydrology, and climatology as it impacts design of water infrastructure.

7. Conclusions/Recommendations:

The climate constantly changes and it is predicted to change more rapidly over the next 50 to 100 years. The predicted changes, while uncertain, will likely increase the rate of infrastructure design failures if not addressed during the planning and design phases of a project. In addition, investment in modifications necessary to infrastructure may be significant and public support may wane through time as conditions change.

In particular, the following changes and impacts have occurred or are expected:

- Systems designed using design storms in the 1950's through the 1970's are generally undersized. The design storms used during those periods have a decreased recurrence interval of approximately 20% and some regions may be as high as 40% such that a 100-yr design storm used during the planning or design of water infrastructure during the 1950's to 1970's would now likely occur with a return interval of 60- or 80- years depending on its location.
- It is expected that the return period of storms will continue to decrease through time at a rate of approximately 0.75% per year such that by the end of a 50 year design life a 20-yr storm would have a return interval of approximately 12-years. This will lead existing stormwater and sewer systems to fail more regularly if modifications are not made to the system. In addition, peak stream flows for these events will increase stream degradation with increased stream erosion, incising, and negative ecological consequences.
- Many regions, such as the western and southwestern United States, will experience a decrease in base stream flows and increase in the frequency and severity of droughts. This will lead to the need for more advanced treatment processes for wastewater treatment plants, for increased water re-use, and for additional water supply development in these regions.
- The frequency and intensity of heat spells will increase while the frequency and intensity of cold spells will decrease. Water supply will be reduced in regions that rely upon snow melt for water. Global water demand will continue to increase if no other measures are implemented to reduce demand through conservation or other measures. Increased demand will require significant investment in alternative water supplies such as reverse osmosis, desalination, and direct/indirect potable water re-use.
- An increase in the strength of both convective and extra tropical storms is predicted with increased frequency and strength of extreme wind events. This increase will increase the risk of failure for exposed structural elements of the

water, wastewater, and stormwater infrastructure such as treatment buildings, etc.

These impacts require the owner and the engineer to work together to determine what is an acceptable risk to the community that the infrastructure serves. Using the regional and local climate models an engineer can design to the predicted conditions, however, this may not be politically acceptable or reasonable. In addition, it is likely that through time, regulations will be adopted that force changes based on the predicted changes particularly in the wastewater effluent requirements.

It is recommended that an engineer consider the following recommendations when designing water, wastewater, and stormwater infrastructure:

- Evaluate the past hydrology trends using partial-series maximum precipitation techniques to evaluated the current trends in the design area. This will allow the engineer to determine if there is a significant trend or trends that must be addressed during design.
- Review the appropriate published climate model predictions. Many state climatologist or other agencies have sponsored studies that have been or are being completed. These studies will outline the overall magnitude of the predicted climate shifts that can be expected in the projects region.
- Determine the modified risk of failure that the project may experience if predictions come true and the current methods for design are implemented without any modifications for the predicted values. Outline the impacts of system failure to the owner and society if a failure were to occur. Include the cost to repair the system and restore any damages that may have occurred.
- Determine the impact to the project if the system were to be designed utilizing the predicted values versus not using the values.
- Discuss issues with the owner at the beginning of the project to determine their perspective and to determine any issues with which the stake holders are particularly concerned. For instance, is the community worried about having an adequate water supply within the near term that will require a significant commitment, is it a long term issue that can be dealt with a little at a time, or is it not a real issue in the scheme of other social factors impacting the community?
- Work with communities, education specialists, and policy makers to implement sound policies associated with water usage, supply, and infrastructure.
- Assist communities to educate their citizens on why conservation and other practices will be needed, and how it can be done.
- Assist regions to work with large water users such as agricultural users to institute conservation practices.
- Conduct research to help mitigate the impacts of climate change on water infrastructure.
- Work with education and research specialists to determine how to reduce social barriers to direct reuse of wastewater treatment plant effluent as drinking water as needed in some inland drought prone locations.

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