Water Resources Adaptation to Global Changes: Risk Management through Sustainable Infrastructure Planning and Management

Y. Jeffrey Yang, Ph.D., P.E., D.WRE,
Daniel J. Murray, P.E.
James A. Goodrich, Ph.D.

U.S. Environmental Protection Agency, National Risk Management Research Laboratory,
Water Supply and Water Resources Division
26W. Martin Luther King Dr., Cincinnati, Ohio 45268, U.S.A.

ABSTRACT

Global changes due to cyclic and long-term climatic variations, demographic changes and economic development, have impacts on the quality and quantity of potable and irrigation source waters. Internal and external climatic forcings, for example, redistribute precipitation seasonally and spatially in the temperate contiguous United States. This change is expressed in hydrologic periodicity, dry and wet period switching frequency, and the maximum rainfall intensity. Spatially, the long-term change is shown by increased precipitation in the eastern U.S., flash floods in the lower Mississippi / Gulf Mexico basin, and intensified droughts in the Great Plain and Southwestern states, and southern California. In Florida and other coastal areas, greater degrees of salt water intrusion to productive aquifers could materialize due to predicted rise in sea levels. Data mining of historical hydrologic data has shown the existence of these regional patterns. The results are in general agreement with the published general circulation model outputs. In addition, water usage has changed with time and water demand has been redistributed spatially as population centers shifted in the past decades.

Quantitative impact analysis focusing on water availability and demand changes is important to risk management and adaptive infrastructure development at various watershed scales. In this approach, adaptive engineering techniques and management methods can be proposed for each relatively homogeneous hydrologic region. Examples include water reuse in the water-stressed Florida, the Great Plain states and California, salt-water intrusion mitigation in Florida and coastal areas, flash floods and storm water quality management in the eastern U.S and lower Mississippi / Gulf Mexico basin. These results are discussed to highlight the importance of engineering factors (e.g., design storms, groundwater level control) in adaptation for sustainable water infrastructure planning and management.

Key words: global climate change, water infrastructure adaptation, hydrological response, source water quality, water treatment

INTRODUCTION

The Intergovernmental Panel on Climate Change reports (IPCC, 2001) and numerous publications (Dore, 2005; Fowler et al., 2007) have cited global climate change as one of the leading environmental challenges that human societies face today. Its manifestations in air circulation and global temperature have been extensively studied (IPCC, 2001; USGCRP, 2001 and references therein). In hydrologic responses to climate change, global sea level rise due to less dense warmed sea water and changes in deep oceanic circulations (Rahmstorf, 2007; Meehl et al., 2005) have been simulated under assumed sea water warming scenarios. The consequence is negative impacts on land uses in the low flight coastal areas and potential impairment of costal hydrological and ecological systems (USGCRP, 2001; IPCC, 2001). Changes in continental hydrology are less understood, yet proven to be more complex responding to a set of external and internal climatic forcings, regional climatic conditions, and land feedbacks (Fowler et al., 2007; Dore, 2005). The complexity and location variations can be exacerbated in watershed and local scales. It is the hydrological changes in such scales, however, that can affect the services of a built environment including drinking water, storm water, and wastewater infrastructures and thus are of significance to planning agencies and water resources practitioners in risk management and adaptation to global climate changes.

Pielke et al. (2007) argued on the basis of delayed response in hydrological systems that even if the atmospheric CO_2 level is reversed, the system inertia is likely to drive the atmospheric and hydrological changes into the foreseeable future. In the contiguous United States, the likely future change is expected to include the increase in storm intensity, more precipitation in the Northeast, lengthened drought and water shortage in the southwest, southern California, Florida and southeastern states (USGCRP, 2001). These predictions, most generated by general circulation models (GCM), provide an overall assessment of the large-scale future hydrological conditions using simplified atmospheric and hydrological representations (McKenney et al., 2006). They often serve as a boundary condition in watershed basin scale downscaling of hydrological models (Fowler et al., 2007). Alternatively, one can examine the past hydrological records instead of relying on model predictions, and uses statistical modeling methods to predict future hydrological changes. This approach can yield results in local scales at the expense of long-term predictability, a disadvantage that is commonly addressed by combing predictive climate modeling in a hybrid approach.

A holistic nationwide investigation using the hybrid approach is under way at the U.S.EPA National Risk Management Research laboratory to predict future hydrological changes. The program uses spatial and temporal analysis of the historical precipitation, temperature, wind, earthquake, hurricanes and other natural phenomena to decode the hydrological systems. Predictive capability is extended by combining modeling results with remote sensing and the statistical analysis. The objective is to generate reliable predictions of future hydrological and water quality conditions in local scales relevant to planning and management agencies, further to identify natural variations for water resources adaptation, and thus to increase the resilience of water infrastructure services. In this analysis, the future climate-related hydrological changes, demographic and economic developments are considered

simultaneously. Their impacts on the balance between water availability and demand to the water and food security, water infrastructure sustainability, and adequate water supply are quantified to the extent possible based on which risk imposed by future climate changes can be managed.

This paper describes the selected preliminary results produced in the nation-wide climate change adaptation studies. It focuses on methodologies for numerical characterization of periodicity in hydrological systems and their applications in detection and quantification of hydrologic trends and variations, based on which implications on hydrological design basis of water infrastructures will be discussed. In addition, the paper will highlight the other two major categories of hydrological impacts in the U.S. and discuss in general the potential adaptation

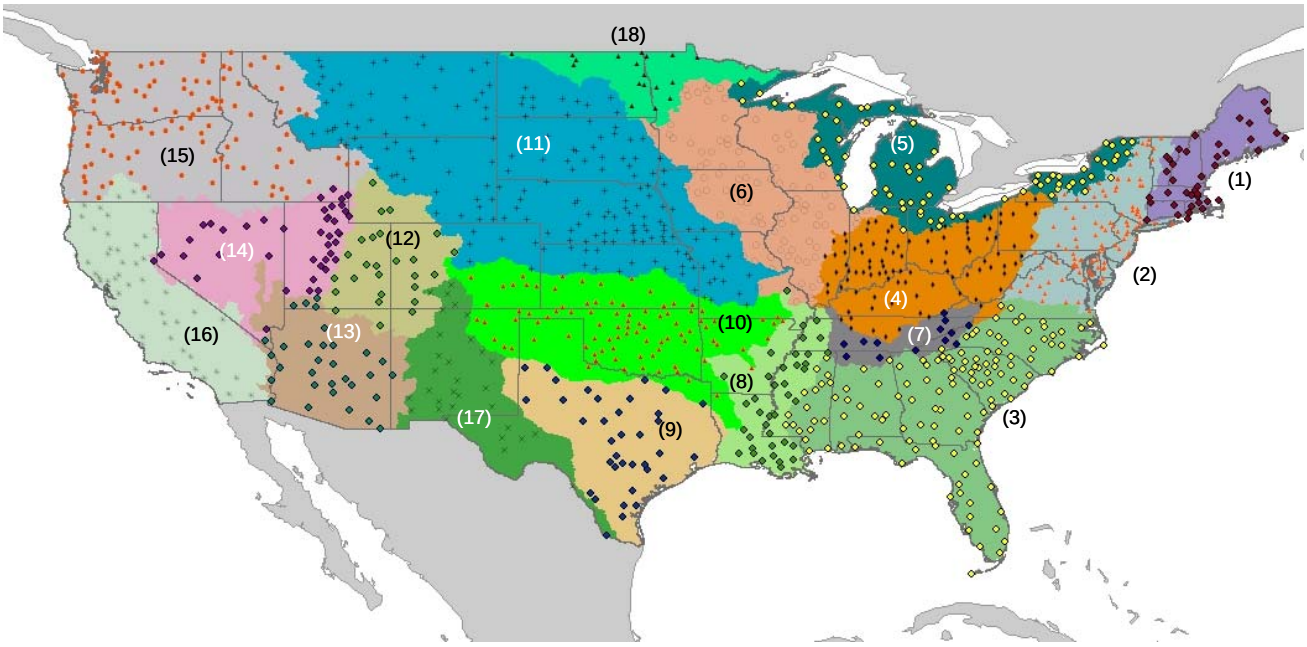

Figure 1 Major watershed basins and distribution of the 1062 USHCN climate stations in the contiguous U.S. Colored areas are watershed basins: 1) New England; 2) Mid-Atlantic; 3) South Atlantic – Gulf of Mexico; 4) Ohio region; 5) Great Lakes; 6) Upper Mississippi; 7) Tennessee region; 8) Lower Mississippi; 9) Texas – Gulf of Mexico; 10) Arkansas – White Red; 11) Missouri; 12) Upper Colorado; 13) Lower Colorado; 14) Great Basins; 15) Pacific Northwest; 16) California; 17) Rio Grande; and 18) Souris – Red Rainy.

measures. These include the drought occurrence and water reuse in the southwest, salt water intrusion and prevention measures in Florida. Due to the space limitation, we will provide an overview of these three hydrological changes (e.g., precipitation, water reuse, and salt water intrusion) and associated adaptation approaches. Detailed results and quantitative engineering discussions will be published elsewhere.

METHODOLOGY

The continental United States comprises of 18 large watershed basins (Fig.1) that are grouped into the Mississippi watershed system, the Great Lakes system, the East Coast and New England watershed systems, and the western coast watershed system, which are geographically separated by the Appalachia Mountains in the east and by the Rockies and coastal mountains in the west. Bounded by Atlantic and Pacific Oceans on the east and west and by the Gulf of Mexico in the south, the temperate contiguous United States is characteristic of a climatic condition influenced by three climatic systems registered in the Southern Oscillation Index (SOI), Pacific Decadal Oscillation (PDO), and Northern Atlantic Oscillation (NAO). Corresponding water resources distribution is highly uneven and its response to future climate change is expected to differ among the regions (USGCRP, 2001; McKenney et al., 2006).

Data sources

Two sets of precipitation records were used to characterize hydrological changes in the contiguous U.S. In time-series analysis, historical precipitation records were obtained for a total of 1062 climatic observation stations from the U.S. Historical Climatology Network (USHCN) administrated by NOAA and DOE (Fig.1). Monthly precipitation averages are available for all stations in computation of long-term change trends. Daily averages are available for selected stations for which the 24-hr precipitation return intervals (PRI) are examined. In stations of high latitudes, snow precipitation is converted to equivalent water depth by an assumed conversion factor of 0.21 as an imprecise approximation. It is known that snow precipitation is not immediately transferred into liquid water and released into overland runoff; the time delay depends on latent heat and weather conditions following precipitation which are highly variable in space. Because of their time delay, the snow –water equivalent is not accounted for in computation of the 24-hr PRI.

As noted in Williams et al. (2006) and Easterling et al. (1996), The USHCN precipitation database is compiled from a network of collaborative climatic stations where there exists a systematic difference, for example, to define the starting time of a 24-hr measurement period. Resulted impacts are noticeable in temperature measurements (Williams et al., 2006), while the effect on average daily precipitation is not assessed. However, it is expected that any resulting variations between stations become negligible in computation of monthly average precipitation and yearly precipitation total. Yearly total precipitation is calculated in a backward moving time window of 12 months.

The second set of precipitation data comes from calculated precipitation values at each node of 0.5^o x 0.5^o grid cells over the contiguous U.S. that the University of Delaware

generated using an interpolation algorithm of a spherical distance-weighting method and the station data of Legates and Willmott (1990). In this study, the grid precipitation values are computed in generation of NetCDF files for analysis of spatial variations in ArcGIS. Exhibited precipitation variations are then further correlated to distribution of water utilities and water demand changes. In total, 50 years (1950-2000) of spatial precipitations are analyzed and parameterized.

Wavelet Analysis for Time Series precipitation data

Khaliq et al. (2006) showed the successful application of wavelet analysis of hydrological systems in time series. In this study, temporal variations in precipitation data are processed and identified using a 2-D continuous Morlet wavelet transformation:

$$W_n(s) = \sum_{n'=0}^{N-1} x_{n'} \sqrt{\frac{\Delta t}{s}} \Psi_0 \left[\frac{(n'-n)\Delta t}{s} \right] \tag{1}$$

$$\Psi_0(\eta) = \pi^{-0.25} e^{im\eta} e^{-0.5\eta^2} \tag{2}$$

$\Psi_0(\eta)$ is the mother Morlet wavelet, a Gaussian-windowed complex sinusoid as a function of dimensionless time parameter η and wave number m. Parameter N is the data length, Δt is the sample interval, s is the wavelet scale, and n is the localized time index. Using the equations, a data sequence is convoluted in form of a scaled and translated mother wavelet

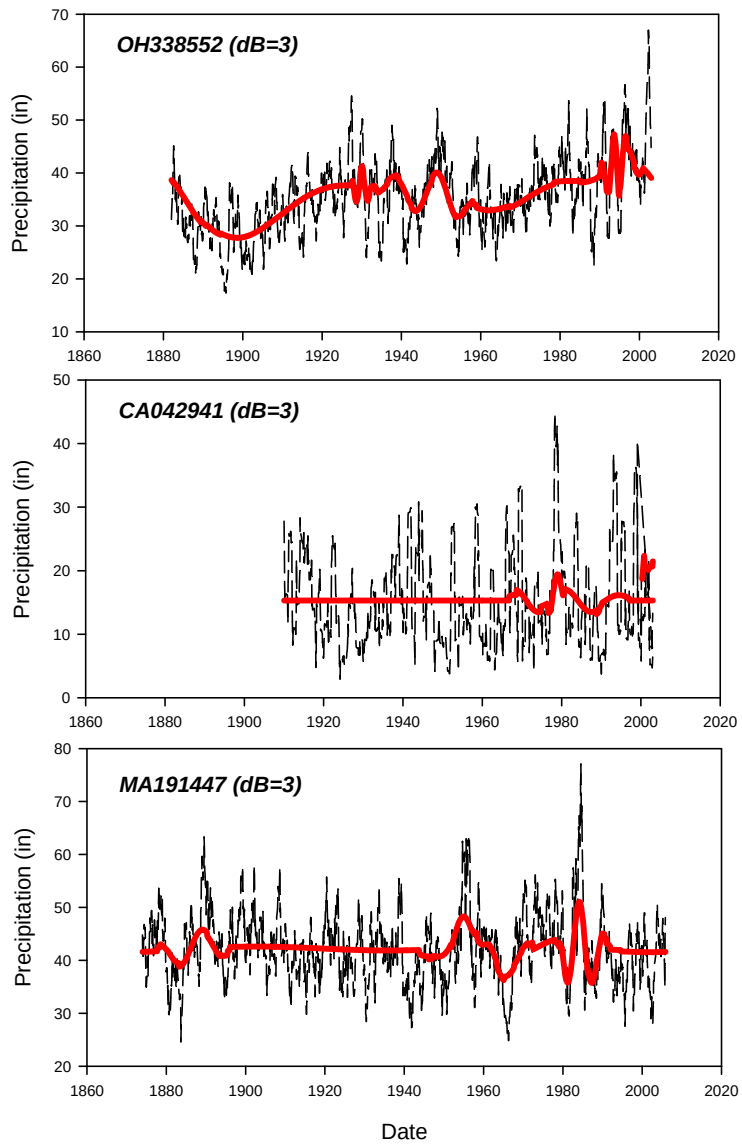

Figure 2 Precipitation variations with time (dashed line) and the Morlet wavelet reconstructions (red solid line) for selected climate stations in the contiguous U.S. The decadal variations in wet-dry switching are apparent in the monthly total precipitation. Denoised wavelet results show long-term multi-decadal periods and the significant discontinuities in variations.

by which successive segment of a data stream is computed and compared. Compared to continuous fast-Fourier transformation (FFT), wavelet transformation is uniquely effective for detection of discontinuities in variation such as precipitation changes in transition from one dominant climate system to another. In this investigation, the Morlet wave number *m*=6 at which time-frequency spectrums were reconstructed for time-series precipitation data and the data noise was filtered at various frequencies at which disruptive events imprinted in the data series are detected. At dB=3, selected examples of wavelet filtering and reconstructed data series are shown in Figure 2 for selected climate stations in Ohio, California and Massachusetts. Data for other 1059 climate stations have been analyzed in various wavelet forms.

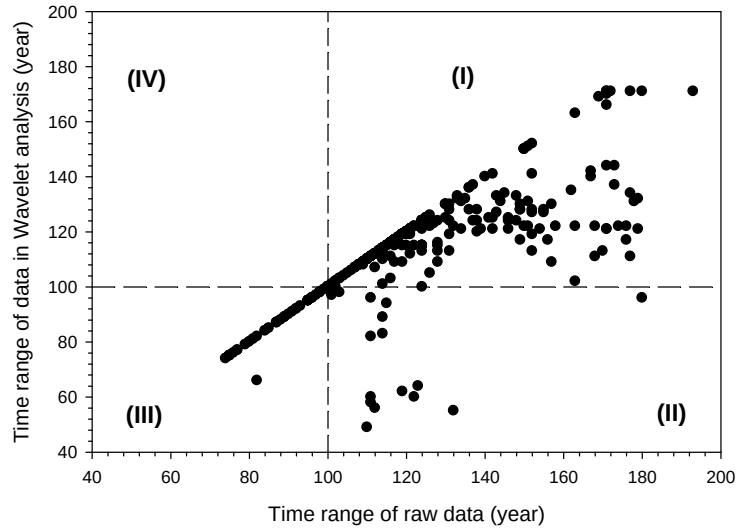

Figure 3 Data time range of monthly average precipitation measurements used in the continuous Morlet wavelet transformation, which is equal to or smaller than the raw dataset due to exclusion of discontinuous data segments. To decode long-term variations, datasets of >100 years in Region I are emphasized. Short time range datasets in Region III are not used for long-term variation determination, but for decadal change assessment.

The wavelet denoise and reconstruction operations were performed to daily precipitation data, monthly total precipitation, and the running yearly total precipitation. In the monthly precipitation dataset, about 20% stations have some measurements missing from the records. The missing data can arbitrarily lead to lower values of the running yearly total precipitation, and result in varying Δt in Eq.1 when wavelet is computed. For these reasons, the missing data segments are excluded from data analysis and as a result the data range in wavelet analysis is less than the climatic records (Fig.3). Fortunately around 80% of the stations have uninterrupted precipitation records in a time length >100 years, for which the multi-decadal variations and periodicities are evident. Most notable discontinuities shown by higher wavelet frequencies occurred 1890-1910, 1945-1970, and 1990-2005, particularly for those dataset of long durations. Between the discontinuities are periods of small variations in yearly precipitation (Fig.2).

MAJOR IMPACTS AND ADAPTATION APPROACHES

The wavelet analysis of climatic and hydrological data at the monitoring stations has led to preliminary findings that are noteworthy in considering climate adaptation strategies and managing risks imposed by the climate change. General patterns of hydrological responses such as precipitation begin to emerge, pointing to the differences between geographic regions for which customized adaptation responses are necessary for better resilience and adaptability of the water infrastructure. In addition to continental precipitation changes, sea level rise is another form of impact significant to the water infrastructure in Florida and other coastal regions in general.

Table 1 lists major categories of climate change impacts to infrastructure services and their likely regions of manifestation. Direct climatic impacts includes: 1) drought in Florida, southern California, and the southwestern U.S.; 2) flash floods due to increase in precipitation intensity and duration (e.g., Ohio River basins); 3) early snow melts in Oregon and Washington; 4) salt water intrusion in response to sea level rise in the coastal states. Under future conditions of warmer atmospheric and water temperatures, high degrees of sediments and nutrients (e.g., N, P) are expected to occur in surface water as the source water for many drinking water treatment plants. The impact on drinking water treatment and distribution systems (Table 1) is expected.

Table 1. Selected major categories of climate change impacts onto drinking water infrastructures in the U.S.

Global change	Characteristics	Likelihood of impacts			Likely region of manifestation (examples)
		DW supply	Storm water	Wastewater	
Direct climatic impacts					
Drought	Cyclic drought, increased frequency and duration	Very likely			Southwestern states, south California and Florida
Flash floods	High precipitation intensity	Likely	Very likely	Likely	New England and north Atlantic states, Ohio River basins
Early snow melt	Change of hydrologic region in receiving rivers and groundwater replenishment	Likely	Very likely		Northwestern states (e.g., Washington, Oregon)
Sediment and nutrient loading in surface water	Increased sediments (turbidity) and nutrients (e.g., N,P) in source water of drinking water plants	Very likely			Atlantic East coast, Ohio River basins, and Midwest
Salt water intrusions	Increased salt water intrusion due to anticipated sea level rises	Very likely	Possible	Likely	East Coast and Gulf Mexico costal areas particularly the permeable Floridian aquifer systems, California Central Basin and aquifers along the coast
Indirect climatic impacts					
Alternative water resources development	Water quality in increased alternative water resources (e.g., wastewater reuse) development	Likely	Possible	Possible	California, Florida, southwestern United States, High Plain states
Ethanol and alternative energy production	High water usage demand in raw material production and increased use of pesticides and agriculture chemicals	Likely	Likely	Likely	Midwest and High Plains states in the Mississippi River basin
Groundwater overproduction	High demand excessively lowers groundwater table and accelerates dissolution of inorganic contaminants	Very likely			High arsenic levels in Silurian-Devonian sandstone aquifers

Indirect impacts of climate changes on water resources are the consequence of adaptation and mitigation to global climate changes. The types and degrees of indirect impacts

could be in various forms as a function of specific adaptation and mitigation actions. Three types of indirect impacts are apparent (Table 1): alternative water resources development (e.g., water reuse), ethanol and alternative energy development, and groundwater overproduction. For example, expanded corn-based ethanol production in the High Plains states and other Midwest region could stress the water supply condition and increase the groundwater production in the High Plans aquifer system and other smaller aquifer systems to the northeast (Fig.4) where groundwater levels have been in constant decline as the result of overproduction mostly for agriculture productions (McGuire, 2007). Such actions can introduce significant changes in water quality. In the Silurian-Devonian aquifer in Illinois, Michigan, Wisconsin where corn production is concentrated, lowering of groundwater table has been directly linked

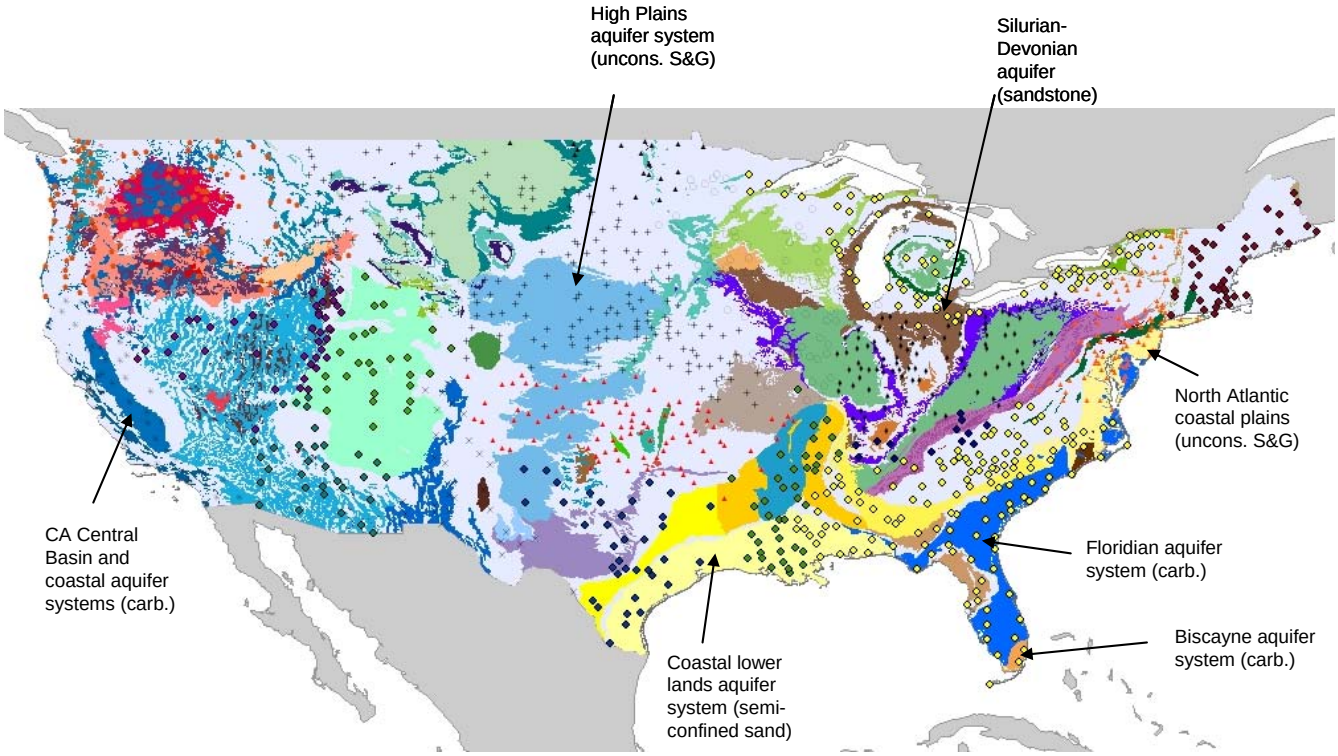

Figure 4 Major groundwater aquifer systems in the contiguous U.S. (data from USGS), and distribution of 1062 USHCN climate stations. Each type of symbols represents a major watershed basin in Figure 1. Potentially vulnerable aquifer systems are marked under future global change conditions.

to the increase of naturally occurring arsenic concentration in groundwater of drinking water sources (Thomas, 2003) due to oxidation and subsequent dissolution of arsenic-bearing pyrites abundant in the sandstone geological formation.

A number of publications (e.g., Fowler et al., 2007; McKenney et al., 2006, and references therein) have generally discussed the global climate change impacts on water resources. More detailed assessment and adaptation analysis are unfolding in watershed basin scales. In this paper, we have limited our general discussion to the three major areas described below.

Hydrological Periodicity and Water Infrastructure Engineering

The service resilience of a water infrastructure depends on its capability providing uninterrupted drinking water, storm water and wastewater services in its design life in which climate changes would occur. Precipitation recurrence interval (PRI) and design precipitation are often the basis for hydraulic engineering and operation of nearly all water infrastructures such as retention ponds, combined sewer system, wastewater conveyance and treatment systems, and reservoirs of source water for drinking water productions. In many U.S. state engineering standards, for example, 10-year PRI of 24-hour duration storm as the design basis is used to size storm water retention ponds and storm water pipes. Such a determination often relies on historical precipitation data of a minimum of 20 years.

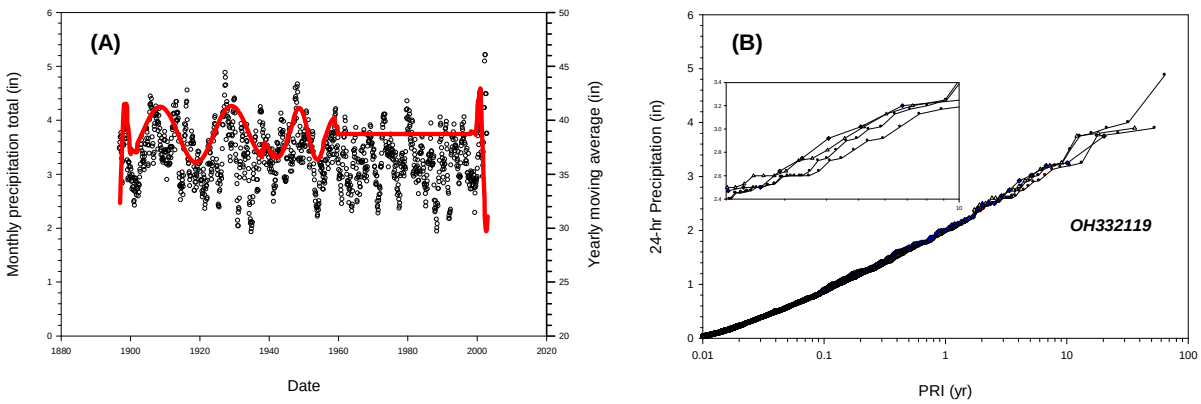

Figure 5 The effect of precipitation periodicity on calculation of the 24-hr precipitation return interval (PRI) at the OH332119 station. The PRI and its variations are commonly used in hydraulic design and engineering of a water system. A) Monthly precipitation data (1897-2003) and yearly total precipitation of wavelet reconstruction results (solid line) showing periodicity in the precipitation total and two major discontinuities at 1910s and 2000s; B) The PRI curves for different data segments of 24-hr precipitation leading to nearly 10% differences in 10-yr design storm for the relatively small variance of precipitations.

The precipitation periodicity revealed in the Wavelet analysis can affect the PRI determination as a function of the data length in calculation. Figure 5 shows an example at climate station OH332119 in central Ohio near the Big Walnut Creek watershed. The monthly precipitation total (1897-2003) showed no significant changes in overall trend as indicated by the variation in Morlet wavelet reconstructed yearly precipitation total (Fig.5a). The periodicity in the hydrologic system is obvious in the Morlet wavelet variations (solid line) with two major discontinuities in 1910s and 2000s. In 24-hr precipitation data, smaller discontinuities are detected in 1984, 1964, and 1947 yielding 4 data segments potentially for PRI calculations: all data (1936-2001), 1947-2001, 1964-2001, and 1984-2001. The precipitation recurrence curves for these 4 data segments (Fig 5b) show systematic differences; calculated 24-hr PRI is 7.74 (1936-2001), 8.08 (1947-2001), 8.31 (1964-2001), and 8.26 (1980-2001) cm. The difference is 7.3%, largely due to more frequent heavier precipitation events in recent years of records. The

difference could be much larger for locations with greater precipitation variability, for which the water infrastructure needs to be sized and managed accordingly.

This simple example illustrates the need to incorporate global climate change into the design and operation of water infrastructure. The ongoing investigations have found substantial regional differences in hydrological periodicity and long-term climate changes in the U.S. Understanding and quantification of both spatial variations and temporal changes in the future climate is necessary in proper water infrastructure engineering for better service resilience and adaptation to climate changes.

Water re-distribution and water reuse

The GCM simulations have indicated that precipitation regimes in U.S. will continue to evolve in the coming decades (IPCC, 2001; USGCRP, 2001). Moderate precipitation increase is expected in the north Atlantic coast, the New England area, Ohio River region, and the Northwest. Under model-simulated scenarios, increased duration and frequency of drought is a very likely possibility in the southwestern U.S., southern California, Florida and southeastern costal states. These model-based future predictions are consistent with observed precipitation and its variations in the historical records. Our GIS spatial analysis of precipitation distribution between 1950 and 2000, for example, shows that much of the Great Plains states and California received a monthly average precipitation <1.5 inches. While the precipitation increase is in the Ohio River region and the eastern coastal states, the 2.5 in/month precipitation contour line shifted northward toward Wisconsin leaving much of the south except for the lower Mississippi River basin with less precipitation and increased droughts (Yang et al., 2007). These spatial changes in precipitation accelerated in the 1980s and 1990s that are the periods of hydrological discontinuity observed in the wavelet analysis of the precipitation data for a large number of climate stations in the Southwestern U.S. The trending directions after the disturbance periods (1980s-1990s) are less defined, and how they are consistent with GCM predictions is little understood.

Populations and economic activities as the other important factors have increased in the past decades in some drought-prone regions as observed in the U.S. population census data. The U.S. population size has increased since 1900 and the rate of increase has accelerated since the 1970s. Worthy to note, the five water-poor states (Nebraska, Arizona, Florida, Utah, and Nevada) have experienced the largest growth rate above the national average in the last 3 decades; the growth rate in Nebraska will level off in the next 25 years (2006-2030). It is also noted that Nebraska, for example, has high fresh water usage per capita largely because of agriculture irrigation and >50% fresh water is derived from the High Plains aquifer system (McGuire, 2007).

In this study, detailed Wavelet analysis defines the long-term precipitation trends that agrees in the further precipitation declines in Arizona, parts of the Texas, Nebraska, Florida and Georgia. Future water supply in these areas may necessitate water and wastewater reuse as a viable adaptation measure to the future water resource imbalances and scarcity (Asano and Levine, 1996; Yang, et al., 2007) and to supplement ecological needs in low flow and

intermittent surface streams. In expanded use of water and wastewater reuse, technical questions remain pertinent to the environmental and human health safety, surface water and groundwater quality protection, new drinking water treatment requirement and distribution of reclaimed water. Despite a substantial amount of previous research (e.g., Lo et al., 2002; Scheytt et al., 2006; Bouwer et al., 1981; Sen et al., 2005) and existing official guidelines (U.S. EPA, 2004; WHO, 2006), knowledge gaps still exist particularly in the fate and transport of emerging contaminants (e.g., endocrine disruption compounds, pharmaceuticals), bacteria and pathogens in water and wastewater reuse applications. Sustainable reuse practices, water treatment and conveyance under future climate conditions are the areas for further investigations.

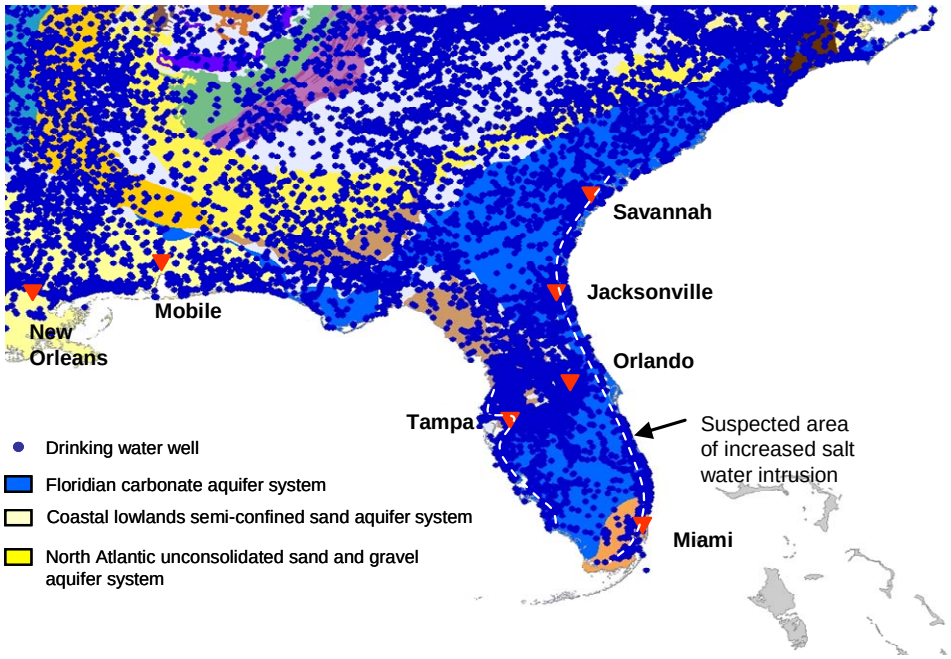

Figure 6 High densities of drinking water production wells are clustered along the coast area around population centers in Florida and southeast of Georgia. The highly permeable and productive Floridian and Biscayne aquifer systems (see Figure 4) make these wells vulnerable to salt water intrusion under the rising sea levels. Increased water infrastructure resilience through measures discussed in text is necessary in successful adaptation and effective risk management.

Salt water intrusion and system operations

Large scales of salt water intrusion, which disrupts conventional drinking water treatment process, materialize in areas of permeable aquifer formation and groundwater overproduction that depresses the groundwater table and introduces hydraulic gradient toward inland. Under current climate and water demand-supply conditions, salt water intrusion into potable groundwater sources has been observed in many coastal regions such as Los Angeles of California, Tampa-Clearwater region and other coastal cities in Florida. As sea level arises in future climate conditions, the salt water intrusion and its disruptions to sustainable water infrastructure will accelerate.

Figure 6 shows drinking water production wells and the aerial distribution of the highly productive Floridian aquifer. The aquifer serves as primary potable source water in the

drought-prone Florida and southeast Georgia, comprising of permeable limestone formation and outcrops in the sea bed prone to salt water intrusion in response to groundwater over-pumping. Groundwater withdrawal, on the other hand, is expected to increase under future climate conditions of warmer temperature and reduced precipitation in these regions. With expected sea level rise of up to 0.5-1.4 meters in the next contrary (Rahmstorf, 2007; IPCC, 2001), the combined effect is greater degree of salt water intrusions making the well-head protection programs vulnerable for drinking water well clusters in the Florida coast perimeters and the Georgia Atlantic coast. Potentially sensitive areas include Tampa-Clearwater, Miami-West Palm coast, Jacksonville region of Florida, and Savannah in Georgia (Fig.6), for which a vulnerability assessment study is being conducted.

Groundwater barrier and management is an effective technique to mitigate salt water intrusion in coastal areas (Narayan et al., 2007) and has been used in Los Angles, California and Tampa, Florida (Elrawady and Tsai, 2006). For future climate conditions, other adaptation measures are required in total water management in order to assure adequate supply of quality water and increase the infrastructure resilience. A sustainable adaptation framework would require water conservation in reducing water demand, water and wastewater reuse in groundwater barrier maintenance and ecological needs, adaptive re-engineering of water treatment and distribution for increased salt content in source water, and even consideration of alternative water-wastewater supply and treatment management schemes such as decentralized wastewater treatment, reuse, drinking water treatment and distribution. In all cases, climate change and its negative impacts should be evaluated and considered in long-term water resource management and water supply planning.

SUMMARY AND CONCLUSIONS

Global climate change has manifested in many forms such as higher ambient temperature, changes and redistribution of precipitation, flash floods due to greater storm intensity, increased salt water intrusion, directly affecting the sustainability and services of water infrastructure. This study presents some preliminary results for the research that characterizes the effects of climate change in precipitation, water availability and water quality and identifies adaptation measures for effective risk management. Major results are:

- Wavelet analysis of long-term historical precipitation data at 1062 climatic stations across the contiguous U.S. demonstrated precipitation periodicity reflecting decadal and multi-decal climate changes and variations. Yearly running average precipitation shows switching of dry and wet periods at varying intervals. The monthly total precipitation and the 24-hr rainfall intensity exhibited changes in storm intensity with time, which should be considered in hydraulic design of water infrastructure.

- Spatially, the long-term change is shown by the increased precipitation in the eastern U.S., Ohio River region, and other parts of the Midwest. Flash floods and heavy precipitation would likely occur in the lower Mississippi / Gulf Mexico basin, and intensified droughts

could occur in the Great Plain and Southwestern states, Florida and southern California. The results are in general agreement with the published general circulation model (GCM) predictions.

- In Florida and other coastal areas, greater degrees of salt water intrusion to productive permeable aquifers could materialize due to predicted sea level rise and the continued groundwater overproduction. Analysis indicates that drinking water well clusters along the coastal population centers in Florida, which withdraw water from the productive Floridian aquifer, could be increasingly vulnerable under future global change scenarios. A sustainable water supply and greater resilience of water infrastructure requires a total water management framework, based on which wastewater treatment and reuse, drinking water treatment and supply are holistically considered under future climate and socioeconomic conditions.

- Adaptation to future climate change is necessary in water infrastructure planning and engineering. For example, we consider precipitation periodicity should be considered in calculation of design storms for infrastructure design, particularly in areas of large variations and increased storm intensities. In adaptation to more frequent droughts, safe wastewater reuse and other alternative water resources development are options to increase the infrastructure capability to adapt.

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