Climate Change Impacts on Florida (with a specific look at groundwater impacts)

Frederick Bloetscher

Frederick Bloetscher, Ph.D., P.E., is an associate professor at Florida Atlantic University. This article was selected as one of the top technical papers at the Florida Section AWWA Fall Conference in December 2008.

There has been significant discussion in the popular media on the topic of climate change, with much focus on the potential for greenhouse gases to be accelerating a natural warming trend on the Earth. While there are a number of possible causes that may contribute to changes in the worldwide climate, including greenhouse gases (IPCC, 2007), sun activity (Singer, 2008), land use changes (Marshall et al 2003) and even a coming change in the pole location (Hapgood, 1999), the reality is that regardless of the cause, much of the scientific community is in agreement that climate change **is** occurring (Bloetscher, 2008).

The earth's climate, however, undergoes constant changes. Ice ages first covered northern Europe, (40,000 years ago), then much of North America (13,000) years ago (Hapgood, 1999). Less than 5,000 years ago, the Sahara desert was a thriving, water-soaked area that supported a significant human population, but the climate changed and it has become a huge expanse of sand since then.

Brief interludes of warmer and cooler periods occurred during the Dark and Middle Ages. In each case, the factors creating the changes in climate are unclear. On a larger timescale, climate fluctuations vary from hundreds of millions of years to decades or less (Huggett 1991; Goudie 1994; Issar 2003; Lamy et al. 2006; Yang 2006; Dragoni and Sukhija, 2008). The only sure thing is that the climate will change in the future.

With the reporting of increased global temperatures, the 2007 IPCC report noted the following:

- Eleven of the 12 years from 1995 to 2006 rank among the 12 warmest years in the instrumental record of global temperature data (since 1850).
- The 100-year linear trend of global surface temperature (from 1906 to 2005) indicates an increase of 0.74 ± 0.18°C.
- Average Northern Hemisphere temperatures during the second half of the 20th century were very likely to be higher than during any other 50-year period in the last 500 years and likely the highest in at least the past 1,300 years.
- Rising sea level is consistent with this warming. Global average sea level has risen since 1993 at 3.1 + 0.70 mm/year, with contributions from thermal expansion, melting glaciers and ice caps, and the polar ice sheets
- Ocean CO_2 uptake has lowered the average ocean pH (increased acidity) by approximately 0.1 since 1750.

The conclusions of the 2007 IPCC report noted that water resources would be one of the areas most affected by climate change. The factors most relevant to water resources and groundwater are (IPCC 2007):

- Projected warming in the 21st century shows geographical patterns similar to those observed over the last few decades.
- Warming is expected to be greatest over land and at the highest northern latitudes, and least over the southern oceans and parts of the North Atlantic Ocean.
- Snow cover is projected to contract.
- Widespread increases in thaw depth are projected over most permafrost regions.
- The more optimistic globally averaged rises in sea level at the end of the 21st century are projected between 0.18–0.38 meters, but an extreme scenario gives a rise up to five meters.
- Temperature extremes, heat waves, and heavy precipitation events will continue to become more frequent.
- Increases in the amount of precipitation are very likely at high latitudes, but not as snow pack, so rainfall decreases are likely in most subtropical land regions.

It should be noted that there is significant uncertainty in the predictions of the models used to prepare the IPCC reports to predict the actual intensity, spatial, and time variability of rainfall and temperature for a given region, in part because the models can only be calibrated against a very short period of time, and that as time has proceeded, the predicted changes have moderated to some degree to comport with observed changes. In any case, the main concern raised by global warming is that climatic variations alter the hydrologic cycle, and that the current data indicated that hydrological cycle is already being impacted (Dragoni 1998; Buffoni et al. 2002; Labat et al. 2004; Huntington 2006; IPCC 2007; Dragoni and Sukhija, 2008).

This issue is of critical concern because the predictions that the temperature will rise by several degrees and the warming trend will last for centuries may portend consequences that can not be predicted today (Dragoni and Sukhija, 2008). For example, the uncertainty associated with temperature and precipitation yields higher uncertainty when translating rainfall and temperature to changes in evapotranspiration, runoff, and aquifer recharge (Strzepek and Yates 1997; Di Matteo & Dragoni 2006; Dragoni and Sukhija, 2008). While some agricultural scientists believe that increased precipitation will lead to more groundwater recharge, this hypothesis may vary by region and the timing of the precipitation (Bloetscher, 2008a)—and for Florida—is the major focus of this article.

Impacts to the Hydrologic Cycle on Groundwater Recharge (Bloetscher, 2008a; Florida 2030 Climate Change Report, 2008 and as noted)

The hydrologic cycle continuously replenishes water through precipitation, runoff, soil percolation, evaporation and condensation. It is well understood that precipitation patterns vary naturally from year to year and over decades. As a result, runoff varies in some relationship to rainfall quantity and intensity, depending on surface conditions.

As a further result, the change in land use from forests to agriculture or urban uses can have significant impacts on runoff characteristics. Agricultural removal of trees and other vegetation accelerates soil loss and increases runoff on the surface. Urban land use increases imperviousness when buildings, parking lots, roads and other improvements replace forest or grassland cover. In both cases, the result is an increase in the peaks for runoff, a shortening of the time of runoff, and a decrease in the amount of time available for infiltration; therefore, the amount of infiltration is less.

In many environments, the time for

Continued on page 16

Continued from page 14

recharge to occur is measured in years—in some cases, many years. Where imperviousness is high, recharge can be virtually eliminated, thereby creating a basin where recharge does not occur. Examples of this exist throughout South Florida.

Coupling land use changes with change in intensity of storms, USEPA (2008) indicates that the "primary impacts of increasing storm intensity on water resources is coastal and inland flooding, complicated in the case of coastal storms by storm surges which may be influenced by other factors such as the level of development in the watershed." In addition to flooding, increased storm frequency and/or intensity may result in adverse effects in surface and groundwater quality and contamination of water supplies; "[w]ater-borne diseases will rise with increases in extreme rainfall" (Kundzewicz et al. 2007, p. 189); and "greater rates of erosion unless protection measures are taken" (Kundzewicz et al. 2007, p. 189)."

Changes in the surface cover will change surface temperatures, which can affect evapotranspiration (ET). Open water bodies have higher ET rates than land, but land-use changes affect ET further. Scanlon et al (2005) reported that understanding impacts of land use/land cover change on the hydrologic cycle is needed for optimal management of water resources.

Salmun and Molod (2006) modeled changes in land cover in their climate models. While they note that the magnitude of the changes in climate because of deforestation differs from model to model for comparable experiments, they reported "a reduction in precipitation ranging from 15 to 640 mm [millimeters] per year, the reduction in evaporation ranged from 25 to 500 mm per year, and suggested an increase in surface temperature is from 0.1 to 2.3°C" (Salmun and Molod 2006).

Their modeling suggests that in a deforestation simulation, "lowered surface roughness (grasslands) *may* result in an *increase* in evaporation if the surface is wet enough," which makes sense, given that ET can occur as deep as four feet below the surface. Once the land is dried out completely, their modeling suggests some degree of decreased ET, but this does not necessarily mean that recharge is increased (via cracks in the surface). Forest lands are known to maintain cooler temperatures on the surface (while simultaneously incurring high ET and longer runoff times for precipitation), while open areas have generally higher temperatures (heat island effect) and faster runoff.

Rischey and Coast-Cabral (2006) reported streamflow trend changes resulting from deforestation in the Mekong basin and identified large flood and drought damages in the second half of the 20th century as exacerbated by these surface changes. Increased ET appears to result from large-scale irrigation altering regional climate through precipitation recycling (Moore & Rojstaczer, 2002; Scanlon et al 2005).

Groundwater recharge is affected by precipitation, actual ET, topography, land use, soil type, land cover, aquifer transmissivity, vegetation characteristics, and contributions to recharge along active stream channels (Herrera-Pantoja and Hiscock, 2008). McGinnis (2007) reported that "the rate at which water filters through the vadose zone [to the underlying aquifer] is controlled by interactions between soil, water, and plant systems."

Herrera-Pantoja and Hiscock (2008) note that the "contribution of wet soil to root water uptake and evapotranspiration depends on root density and soil type. For almost all crops there is a dense area of active roots near the surface that contributes 70 percent to the total water uptake. In this zone, all the water is freely available to the crop."

Beneath this zone, root density steadily decreases with depth, as well as the water uptake, with only water under relatively low suction available to plants (Ragab et al., 1997; Herrera-Pantoja and Hiscock, 2008). Green et al (2006) found that "this rate of recharge was increased by the changes in precipitation and temperature that elevated CO_2 levels are expected to bring about."

Roark & Healy (1998) and McMahon et al. (2003) report that irrigation increases the amount of water applied to the system, which generally is thought to enhance groundwater recharge, but the surface condition may play a much larger role than irrigation, since tilling and other agricultural practices alter recharge by changing soil structure (Leduc et al., 2001).

Direct recharge of an aquifer occurs by infiltration into the soil by precipitation, melting snow, and or interception of aquifer by rivers and streams (Ragab et al., 1997, Stamm et al., 1998; Sililo and Tellam, 2000; Miller et al., 1981), but even if the percolated water reaches the underlying aquifer, not all the potential recharge reaches the water table of an underlying aquifer to become actual recharge. Water that enters the subsurface commonly moves laterally and discharges to surface water bodies as springs at a lower elevation or may be taken up by plants and transpired back into the atmosphere.

Confirming that long-term recharge does not occur is Miller et al 1981, who noted that applied irrigation provided "short-lived recharge since the base streamflow in areas with extensive irrigation increased by 20 to 30 percent over the last 60 years, with greatest sea-

Continued on page 18

Continued from page 16

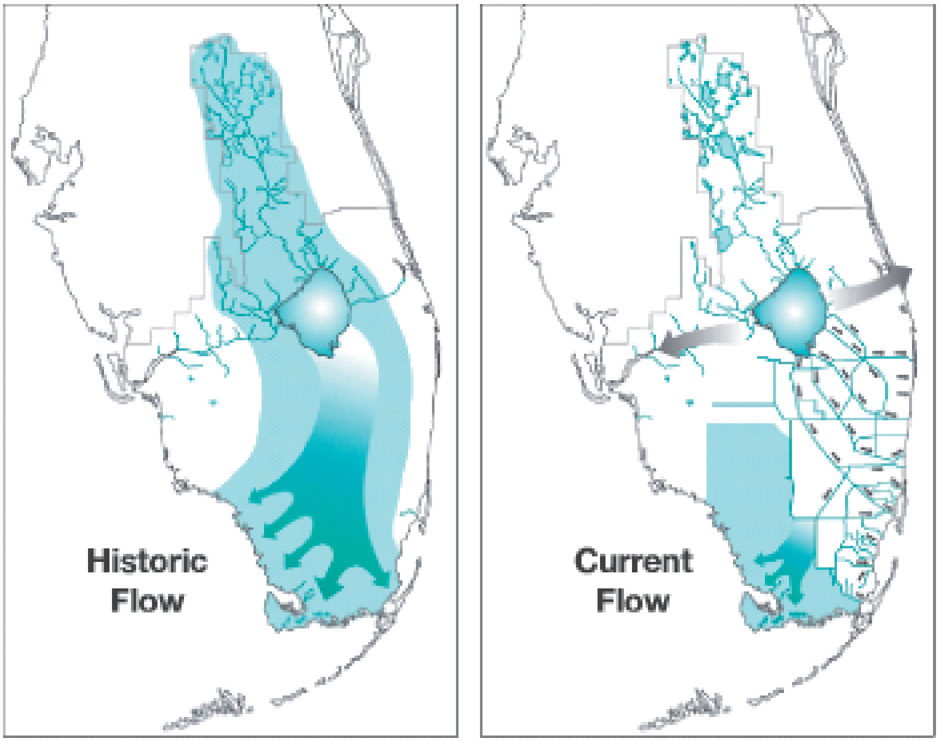
sonal increases in baseflow occurring during spring and fall when row crop fields are largely bare ground." Shilling and Zhang 2006 further verified, via lysimeter studies, that converting from perennial to seasonal cropping systems affected streamflow and water quality by "reducing evapotranspiration and increasing baseflow in many Midwestern rivers."

Similar analysis extended to other rivers in the Mississippi River basin indicates that baseflow of the river has been increasing in response to increasing row crop production, which suggested that water that has avoided ET percolates into the ground is discharged to the stream and therefore provides little long-term benefit for groundwater recharge.

The reality is that both runoff and apparent recharge in agricultural communities is a more likely contributor to streamflow, which is of little value when developing a water supply for agricultural or urban users. Confirming this suspicion is a study by Scibek and Allen (2006) who reported that "The predicted future climate for the Grand Forks area from the downscaled CGCM1 model will result in more recharge to the unconfined aquifer from spring to the summer season; however, the overall effect of recharge on the water balance is small because of dominant river-aquifer interactions and river water recharge."

Since water located as far as four feet below the surface may be evaporated naturally, recharged water needs to be more than four feet below the surface to act as potential recharge; however, it may take years for water to reach deep aquifers, if it is possible for them to do so at all. For example, portions of the Black Creek Aquifer in eastern North and South Carolina were virtually denuded in due to pumpage because there is no local recharge, rendering it useless for water supply purposes in places like Myrtle Beach, South Carolina.

Most of the aquifer use in the western states are poised similarly, since they have minimal potential for recharge and regulations permit almost unchecked withdrawals. For example, parts of the aquifers in Utah have dropped hundreds of feet, but with an average rainfall of 13-18 inches per year, there is little hope that this rainfall will recharge local aquifers. Potential exists for the same problem in southeast Florida as utilities use the Floridan Aquifer, which recharges in Georgia and north Florida, as the water supply for those two regions diminishes (for more discussion see USGS Circular 1323).



Source: South Florida Water Management District

Figure 1 – Change in natural flow paths in south Florida (source SFWMD).

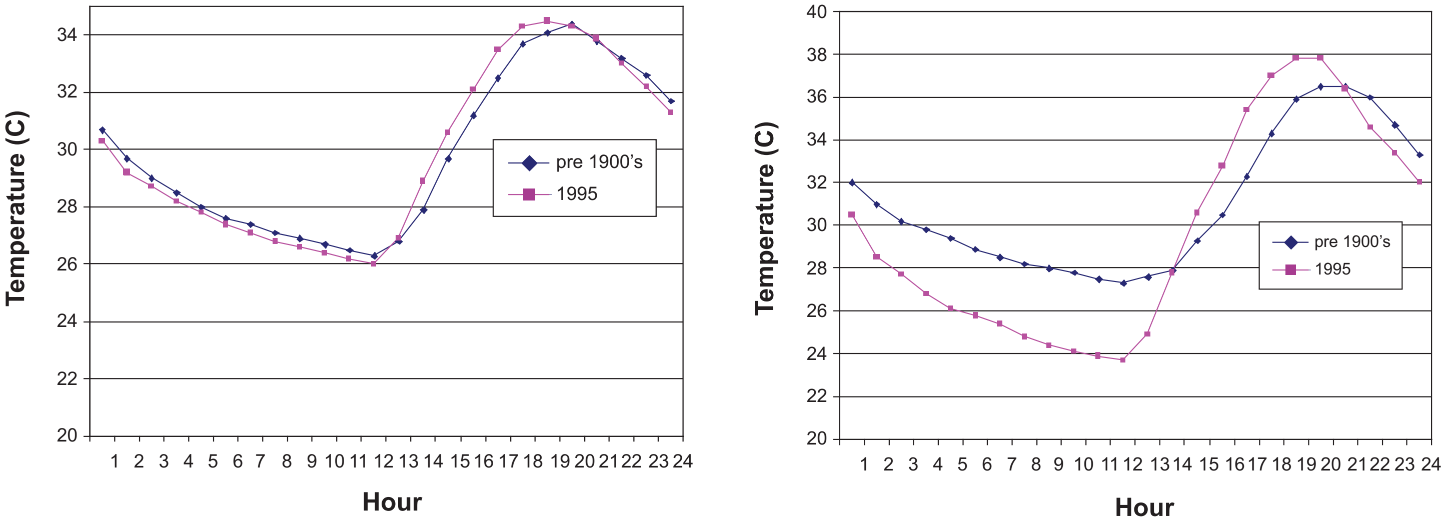


Figure 2 – Temperature changes: Hotter in summer, cooler in winter means more freezes in the winter and both higher temperatures and more ET in the summer (source: Marshall, et al 2003).

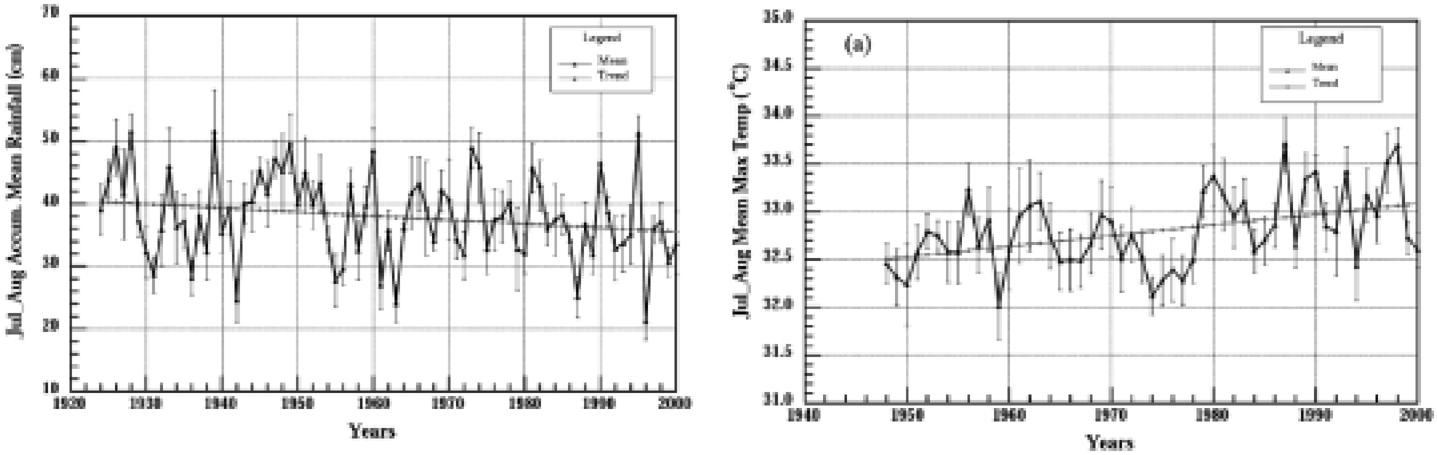


Figure 3 – Change in average rainfall and change in average temperature, 1924 to 2000. Note the reversed trend, which means groundwater inputs are lessened (source: Marshall, et al 2003).

Potential Climate Change Impacts on Florida Groundwater (Bloetscher, 2008)

In Florida, abundant water supplies are present as a result of an average rainfall of over 54 inches each year. There are several distinct areas of the state that may incur different results from climate change impacts.

The surface hydrologic budget of the southern half of the state is dominated by the Everglades. During the rainy wet season, sheets of water would move down the state from Orlando through the Kissimmee River to Lake Okeechobee, then to the Everglades. Because the land was so flat, water could flow from lake to lake, spill over natural river channels, and spread into floodplains which are the recharge areas for the Biscayne Aquifer (see Figure 1).

As a slow-moving river with few barriers and no canals to direct the flow of water, and having rainfall exceeding ET, the long surface retention time permitted significant recharge of the Biscayne Aquifer. The ponding of water in the summer was not a problem when few people lived here, but with the extensive development that started in the early 1900s, there was a demand for controlling the water and opening Florida for agriculture and development.

In the 1920s and then late 1940s, after years of severe hurricanes, then drought, then more deadly storms, Florida asked the federal government for a master plan to tame nature's excesses. The results included berming Lake Okeechobee and straightening the Kissimmee River.

Because the natural system was "controlled," freshwater marshes around and to the north of Lake Okeechobee were drained and converted to large-scale crop, cattle, and milk industries, but high-nutrient runoff discharged into the Kissimmee River and Lake Okeechobee. South of the lake, the Everglades Agricultural Area has developed to include hundred of thousands of acres of sugar cane and vegetables.

Today the "control" system consists of 1,800 miles of canals and levees, 200 water-control structures and 16 major pump stations to send water south and through waterways eastward and westward to both coasts.

The changes in land cover have wrought changes in rainfall. Marshall et al (2003) postulated that "because the sea breezes are driven primarily by contrasting thermal properties between the land and adjacent ocean, it is possible that alterations in the nature of the land cover of the peninsula have had impacts on the physical characteristics of these circulations."

This mechanism may have implications for the observed changes in the distribution of convective rainfall, which accounts for the primary wet season precipitation and over 70 percent of rainfall for a given year. Their modeling indicated that the land use changes from 1900 to date have reduced total rainfall by 12 percent, much of it in the summer, confirming the finding of Pielke (1999) who reported that "it appears that development has exacerbated their severity since landscape changes over south Florida have already appear to have reduced average summer rainfall by as much as 11 percent."

Land-use changes mean lower water levels in recharge areas and less contact time for recharge on the surface. Future changes in climate will add to the existing impacts at a time when the population of the state is expected to nearly double by 2030.

Figure 3 shows the temperature changes by season reported by Marshall et al (2003). This figure shows the temperature changes for south Florida—they are cooler in winter, which increases freeze likelihood because of loss of moisture from the swamp lands, and both higher temperatures and more ET in the summer. Both the observed and predicted patterns match. The variation is projected to worsen.

In the literature, much of the study effort has focused on the Everglades system; however, impacts exist in all other areas of the state. In northeast Florida, the area relies on the St. Johns River and the Floridan Aquifer. Rainfall variation will affect runoff in the St. Johns River.

If rainfall decreases as defined by Marshall et al (2003) exist, the summer inputs will decrease. Spring rains may be more intense, creating local flooding and faster runoff, providing less recharge. As a result, the U.S. Environmental Protection Agency cautions that water resource managers in areas like northeast Florida will face significant challenges as storm intensity increases (USEPA, 2008):

- Although there is some uncertainty about climate models addressing storm intensity and frequency, emergency plans for drinking water and wastewater infrastructure must recognize long-term increases in high-flow and high-velocity events because of intense storms, as well as potential low-flow periods.
- Damage from intense storms may increase the demand for public infrastructure funding and may require re-prioritizing of infrastructure projects.
- Floodplains may expand along major rivers, requiring relocation of some water infrastructure facilities and coordination with local planning efforts.

In Central Florida, the use of the Floridan Aquifer may be a problem. The U.S.Geological Survey identified central Florida as a region

Continued on page 20

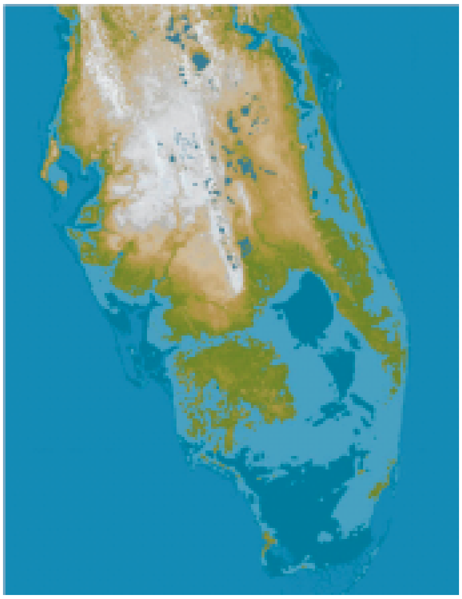


Figure 4 – Sea-level rise impacts (dark blue areas show a sea-level rise of zero to five feet, the most likely scenario, with the higher-risk alternative of five to 16 feet shown in light blue)
http://www.nasa.gov/centers/jpl/news/gracef-20060602_prt.htm.

Continued from page 19

where safe yield may be being exceeded, as indicated by significant decreases in water levels in the aquifer and land subsidence. They have identified the Floridan as one of the critical aquifers that will receive significant review in the period 2008-2013.

On the west coast of central Florida, Tampa Bay has a long history of litigation and regulatory mandates to deal with wetland losses in old wellfields in Hillsborough and Pasco County. As a result, Tampa Bay Water has migrated nearly half its groundwater supplies to surface waters.

In the case of Tampa Bay, surface waters exist. Orlando has no such luck and is looking eastward to the St. John's and desalination to resolve long-term issues. Farther south, the Floridan has no recharge source, so where is the recharge to come from, or is this another mining exercise?

In many cases, the Florida Panhandle relies on waters from other states. Fortuitously, they are higher in elevation, so sea-level rise is of limited concern in the near term. Less density and limited agriculture make their total demands less when compared to other regions but increase the percent for public supplies.

If significant sea-level rise occurs in other parts of the state, indicating a need for populations to retreat from sea level rise, the Panhandle may have limited ability to adjust to increased water demands except by pursuing desalination. Aquifer and extensive water bodies are not present in most parts of the region.

Lettenmaier et al (2008) noted that there are no current hydrologic observing systems for purposes of detecting climate change or its effects on water resources, and limited studies of hydrologic trends in the southeast or Florida. Lins and Slack (1999) showed generally increasing streamflow over most of the southeast in the second half of the 20th century, while Czikowsky and Fitzjarrald (2004) analyzed increased ET at the beginning of spring.

The U.S. Environmental Protection Agency (2008) notes that lower flows in streams during the summer and fall could reduce available dilution substantially in those streams, concentrating salts and other pollutants, meaning that minimum flows and levels would become the driving issues in limited surface-water supplies in the Panhandle.

In summary, in south Florida there is a measured decrease in rainfall, less water standing in the recharge area (the Everglades), and less contact time for recharge, meaning human activities have already altered the system. Climate changes may further disrupt rainfall patterns and rising sea levels may impact coastal communities by flooding them. In the other areas of the state, aquifers appears to be stressed or otherwise limited, creating reliance on surface water bodies that are expected to have more variable and less reliable flows.
The result is that Florida needs to plan for the future while taking into account the potential for climate induced changes. The hope is that measures can be taken to avoid the worst (and highly unlikely) case, as noted in Figure 4.

Meeting the Climate Change Challenge

The challenge for water suppliers is to determine how the hydrologic cycle provides water to service areas, in what quantities, and with what level of reliability (Bloetscher and Muniz, 2006).

Water supply reliability and sustainability are closely linked. Water supply sustainability has been defined by the AWWA's Water Resource Division as: "The planning, development, and management of water resources to provide an adequate and reliable supply of water with a quality suitable to meet their economic, environmental and social needs for current and future generations," while Murley (2006) added "in a manner that will not diminish the ability of future generations to meet their needs."

Since the production and delivery of drinking water and the treatment of wastewater are recognized as vital functions of society, long-term viability and development of water supplies are required to sustain long-term economic viability and public health, despite competing interests that may include agriculture, ecosystems, recreation, and industrial demands. Securing reliable water supplies for future generations is important in the face of changes in climatic patterns. Water supplies can become more reliable and sustainable through a comprehensive approach to water planning, which includes using alternative water sources and planning future infrastructure needs with long-term trends in mind.

The challenge for water suppliers is to determine how the hydrologic cycle provides water to service areas, in what quantities (including the potential that overall there will be less water as suggested by Freas et al (2008)), and with what level of reliability (Bloetscher and Muniz, 2006). From the water supply perspective, there are two critical issues regarding climate change: (1) how increasing hydrologic variability may affect water supply and demand and (2) in coastal areas, how sea-level rise may impact water supplies.

Changes in climatic patterns have potentially large impacts on Florida in the coming century. The 2007 IPCC report indicated that coastal management, including "spatial planning needs to take a long-term view on adaptation to sea level rise and climate changes, especially with regard to …" infrastructure.

The Pew Center Report on Climate Change indicates that the socioeconomic implications of climate change on water supplies and demands, or the lack thereof, will be related directly to the ability of water managers and planners to act on required plans, infrastructure, and development changes in the near term (Frederick and Gleick, 1999). Planning and implementation for sustainable water supplies will require an understanding of how Florida water resources are affected by climate change.

Deyle, et al (2007) outlines that the need for planning will be especially important, given the competition for scarce public dollars to develop water supplies that can adapt to climate changes over the next 20 to 100 years. Adaptation will be required in light of global changes, combined with the need to protect/armor other public infrastructure and coastal private property to prevent relocations of population centers. Three categories of adaptation should be considered carefully: protection, retreat, and accommodation (Deyle, 2007).

In keeping with these categories of protection and adaptation, considerations for groundwater recharge protection may include:

- Stormwater retention improvements.
- Conjunctive use of surface and groundwa-

ter supplies through appropriate timing.

- Relocation of wells.
- Preservation of recharge areas.
- Coastal armoring and lock structures.
- Artificial recharge scenarios.
- Aquifer storage and recovery.
- Alteration of wastewater disposal patterns to include beneficial reuse and salinity barriers.

Here is a brief outline of each of these issues:

Stormwater Retention Improvements

The Environmental Protection Agency also cautions that water resource managers will face significant challenges as storm intensity increases. Although there is some uncertainty with respect to climate models addressing storm intensity and frequency, among the concerns the agency raises are (USEPA, 2008):

- Recognition that emergency plans for water supply infrastructure include strategies for dealing with long-term increases in high-flow and high-velocity events because of intense storms, as well as potential low-flow periods.
- Private property damage to low-lying, flood plain properties, including water supply systems.
- Damage from intense storms that may increase the demand for public infrastructure funding and may require re-prioritizing infrastructure projects.
- Expansion of floodplains along major rivers requiring relocation of some water infrastructure facilities and coordination with local planning efforts.

These concerns point to the following solutions that should be reviewed:

- Acquire floodplain areas and discourage development to minimize economic losses, while maintaining rich recharge areas adjacent to streams. While the recharge areas may not complement long-term groundwater needs, they may extend supplies to surface systems that reduce the need to those groundwater supplies.
- Acquire and protect recharge areas for aquifers to protect water quality and maximize recharge potential. The redirection or retention of stormwater during wetter seasons to these areas should reap longer-term dry-season benefits.

Any time land acquisition and floodplain control measures are discussed, they become charged from the political right; however, the climate change modeling demonstrates that "business as usual" politics may not serve the greater needs of the public.

Continued on page 22

Continued from page 21

Conjunctive Use of Water Supplies

Conjunctive use of groundwater and surface water is a water supply strategy that applies in areas where multiple water sources are present and water supplies have been or could be developed. Surface water supplies will require increased storage volumes for conjunctive use with groundwater supplies, which may indicate a need to restart dam building programs. The benefits of conjunctive groundwater surface water supplies include:

- Improved resistance to droughts.
- A balance of climate impacts on source availability/timing.
- Prevention of over-use of groundwater-only sources of supply.
- Improved water supply system reliability to meet demands.

Implicit in these strategies is the concept that ***groundwater likely needs to be viewed*** not as a primary water supply, but ***as a supplementary source*** that can be used during drier months and recharged during wetter months. Where this is not possible, groundwater sources probably should not be utilized, since their use is nothing more than mining of the resource. To alter current practice would require substantial changes to the legal structure of western water law and alteration of Florida's permitting process.

Relocation of Wells

Movement of wells to areas where water supplies are more plentiful and recharge capability is stronger should be evaluated. The changes in recharge of groundwater supplies as a result of climate change are likely site specific, depending on recharge capability and interaction with streamflow.

In many areas, the safe yield of the groundwater supplies is being exceeded (safe yield meaning the volume of water that can be removed without negatively affecting the supply and without mining the resource—specific yield cannot exceed the recharge to the groundwater in the vicinity of the withdrawal). Safe yield is exceeded throughout the world, so to prevent denuding aquifers, a reappraisal of the development and economic patterns of the area should be undertaken to insure that safe yield in not exceeded in any aquifer. The stormwater and recharge area measures noted herein will support this measure.

Preservation of Recharge Areas

Preservation of recharge areas are important under the Safe Drinking Water Act to protect water quality. Unfortunately the regulations do not address the issue of water quantity for recharge. The point is that where the aquifer reaches the surface, development and paving should be avoided. To do otherwise impacts development downgradient to the coast. For example, paving over much of the eastern Everglades for development, and diverting large portions of the rainfall to tide, recharge is significantly reduced, which has created significant concerns for long term water supply availability.

Coastal Armoring—Including Lock & Salinity Structures

These concepts really apply to low-lying coastal areas where sea-level rise impacts aquifers via saltwater intrusion. The need to address these issues occurs throughout the world, since a large portion of the population in the world is located along the coast. There are many areas of the state where there are no structures to prevent the migration of seawater inland, including much of the highly populated areas of Miami-Dade and southern Broward County, where the salinity control structures may be five miles inland.

The loss of fresh stormwater and groundwater to tide is especially significant in areas where canals or channelization of natural riverine systems have occurred—good examples are the extensive canals in south Florida. When the upstream swamp (the Everglades) is dry, the aquifer levels decrease, which may lead to saltwater intrusion (i.e., migration inland and upward below wells—Bloetscher, and Muniz, 2008). For that reason, lock or salinity structures, also politically unpopular, should be evaluated to prevent contamination of aquifers from the sea. Models for this scenario and more advance solutions lie in Venice, Italy, and the Netherlands.

Another option is to use sidestream reservoirs. The Peace-River Manasota Water Supply Authority in south Florida does this. Tampa Bay Water does this to a larger extent by constructing a reservoir adjacent to the Hillsborough River, the Tampa Bypass Canal and the Alafia River. The constructed large sidestream reservoirs remove stormwater flows during wet periods to the ponds.

The Hillsborough River and Tampa Bypass Canal both have structures that prevent saltwater from mitigating upstream, thus protecting the drinking water source; however, the Alafia River does not have any salinity barrier. Rising sea levels, even minor rises, could potentially push the saltwater wedge further upstream, which could impact Tampa Bay Water's ability to withdraw freshwater from this river. Monitoring and additional modeling activities are recommended to improve the understanding of how sea-level rise may affect this water supply source (Florida 2030, 2008; Bloetscher, 2008a).

Artificial Recharge Scenarios

Artificial recharge is another option that locales can pursue in a variety of ways. Diverting stormwater to infiltration galleries is pursued on BLM property in Oklahoma. Pumping treated stormwater or applying large amounts of stored water on permeable land can recharge surficial groundwater supplies locally.

Wastewater can also be used for recharge, as has been done at Water Factory 21 in Orange County, California. Water Factory 21 has been used to recharge groundwater in western Orange County for 30 years. This facility was recently reconstructed with reverse osmosis and ultraviolet disinfection. Based on the costs for the construction of the new Water Factory 21, construction costs for similar facilities in southeast Florida would approach $12 per gallon treated (CDM report), yielding a total cost above current treatment, plus piping, plus over $10 per 1,000 gallons for water treated. There are many scenarios that can be explored for artificial recharge.

Aquifer Storage & Recovery

Aquifer Storage and Recovery (ASR) is a practice used for the management of water supplies in both potable and non-potable systems. ASR sites have been active in the United States for over 30 years at over 50 locations in at least 26 states (AWWA, 2002).

The principal objective of these ASR projects is to store water supplies underground, long- and short-term, for later recovery and use where conditions permit, to improve the efficiency of water treatment plants. Beneath the surface, the injected freshwater displaces native water in the aquifer. This scenario creates an underground storage reservoir or "bubble." The stored water then can be withdrawn to meet peak demands for short periods of time.

Where the water quality difference between the native and injected water is significant, however, buoyancy forces will cause the bubble to rise toward the top of the formation over time. The result is that after some period, withdrawals may contain high quantities of native water (Bloetscher and Muniz, 2003).

ASR wells require the right geology (confinement and thin, transmissive zones), and the proper operation and management of the system to be successful. The use of a denuded aquifer is a solution that has been pursued in eastern South Carolina and could apply elsewhere, but geochemical changes create other

Continued on page 24

Continued from page 22

problems to resolve. Pyrite leaches arsenic, which has raised significant questions in Florida ASR wells.

If the goal of an aquifer storage and recovery system is to store water for future use, the ability to store water for a given length of time, must be measured. Time becomes ***the*** critical variable. Generally, time has been ignored in past testing programs.

Once the issue of time is dealt with, there remain concerns about the proposed ASR systems: risk of migration into other waters, risk of contamination from other injection sources, emerging water quality impacts and the impact of aquifer parameters (Bloetscher and Muniz, 2003; Bloetscher, 2008a).

Alteration of Wastewater Disposal Patterns to Include MFLs, Beneficial Reuse & Salinity Barriers

The most common method used to dispose of wastewater is via outfall to a stream. Much of central Florida's wastewater has been diverted from streams, creating a conflict with minimum flows and levels (MFL) regulations. In the future, the changes in the hydrology associated with streams may create significant negative water quality impacts during dry periods.

Lettenmaier et al (2008) noted that water quality in streams is also sensitive to increased water temperatures, changes in patterns of precipitation, and changes in pollutant loadings. If stream temperatures increase because of climate change, there will be both direct and indirect effects on aquatic ecosystems, especially during low-flow periods.

The Environmental Protection Agency (2008) notes that "lower flows in streams during the summer and fall could substantially reduce available dilution in those streams, thereby concentrating salts and other pollutants." Temperature will reduce dissolved oxygen (by increasing temperature and increasing metabolism). As a result, it may become more difficult to meet current water quality or drinking water standards.

Wastewater dischargers may need to change treatment to reflect the increased degree of difficulty in meeting current standards. Some standards (i.e., pollutant-specific goals) may need to change to reflect more sensitive environmental conditions (USEPA, 2008). The effects of climate change may lead to relocating sewage treatment plants and discharge outfalls.

Another alternative, and a useful substitute to discharge outfalls, is the use of treated wastewater (i.e., reclaimed water). Over 1,000 treatment facilities in the United States currently use reclaimed water in a variety of ways, including irrigation of agricultural land, golf courses, roadway medians, landscaping, and residential homes, as well as industrial uses such as cooling towers.

Reclaimed wastewater is a useful replacement for industries needing lower-quality water, such as agriculture, which may compete with other water needs in a given basin. Concurrently, municipal (potable water use supplies associated with development) and agricultural usage have increased demands on groundwater sources in many places.

Water supplies for human and ecosystem use are typically of higher quality than those demanded for agricultural use, so the wastewater reuse rules are designed to provide water to match evapotranspiration rates for a given area, so that the needs of agriculture, golf course, lawns, etc., will be fully met with regulatory application rates.

Reclaimed wastewater use, however, requires proactive regulatory encouragement of reuse to supplement or replace groundwater use for non-potable purposes in developed areas. A positive outcome has been reducing inland groundwater withdrawal, especially in sensitive ecological areas.

The cost of implementing reclaimed water use systems is $3 to $5 per gallon in capital costs, but locally the costs, particularly in developed urban environments, are much higher than the cost of traditional groundwater supplies. To help offset these higher costs, regulatory and water management entities must provide incentives to develop reclaimed water systems that offset the need for potable water supplies.

Reclaimed wastewater can also be used, with appropriate treatment for artificial recharge and salinity barriers. Water Factory 21 supplies artificial recharge in this manner. Other communities have explored the salinity barrier concept to increase groundwater levels and slow movement of saltwater intrusion. However, concerns about water quality of reclaimed water and the potential risk for lower quality water to enter drinking water sources should be a major consideration of any reuse program. Risk assessments can be conducted to answer many of these questions.

Conclusions

There is strong evidence that global climate change is having an impact upon the world's water resources. These impacts include changing precipitation patterns that may result in more severe drought or floods, varying stream flow patterns, rising sea levels along the coasts, and contamination of freshwater aquifers and coastal water bodies as a result. Since climate change appears to be a reality that water supplies must plan for in the coming decades, future changes in climate may affect the water resources upon which the state of Florida depends as a result of precipitation variability and sea-level rise.

Water utilities must continue to provide uninterrupted, high-quality service to their present customers, and many must also plan for rapidly growing populations. Water management agencies and utilities rely upon historical hydrological precipitation patterns to regulate or manage source water supplies, stormwater runoff, and wastewater conveyance and treatment. The scenarios that appear to have the most traction indicate that wet seasons will be wetter, dry seasons drier, temperatures generally warmer but with more variation, and less snow-pack storage of water supplies. While extremes in weather phenomena are not new to Florida, where hurricane occurrence cycles vary every 20 years or so, and periodic droughts are noted to occur in roughly seven year cycles, the historical records may provide less certainty than planning has traditionally taken.

The uncertainty caused by climate change relative to its impacts on water resources poses a daunting challenge for water management districts and drinking water, wastewater, and stormwater utilities responsible for managing water resources throughout the state and within local communities. From the water, wastewater, and stormwater utilities' perspective, there are two critical issues regarding climate change: (1) how increasing hydrologic variability may affect water supply and demand and wastewater collection and treatment, and 2) in coastal areas, how sea-level rise may impact water supplies, utility infrastructure, and relocation of coastal population centers. The impact on groundwater has received limited attention, but what attention has been paid indicates that groundwater recharge will decrease in many areas, but will be localized and depend on:

- Land use and historical land use changes
- Imperviousness of the surface
- Potential for stream interception of groundwater supplies
- Runoff patterns that may decrease retention, and thus percolation time

Solutions to protect groundwater supplies mostly involve reductions in reliance on groundwater supplies without demonstrated localized recharge, and also structural improvements to improve recharge. The conjunctive use of water supplies, including wastewater to replace lesser-quality needs, must be evaluated.

As politically charged as the issue of climate change is, the solutions for dealing with it are much more significant, and will likely require the expenditure of large amounts of tax dollars and significant changes in both how water supplies are regulated and the groundwater rights of usage doctrines throughout the world.

References

- American Water Works Association (2002), *Survey and Analysis of Aquifer Storage and Recovery (ASR) Systems and Associated Regulatory Programs in the United States*, AWWA, Denver, CO.
- Bloetscher, F. (2008a), The Potential Impact of Climate Change on Groundwater Recharge, Groundwater Protection Council Annual Forum Proceedings - Cincinnati, GWPC, Oklahoma City, OK
- Bloetscher, Frederick and Muniz, Albert (2003), "Water Quality Of Aquifer Storage And Recovery Systems May Define Limitations In Use," *GWPC Annual Meeting Proceedings*, GWPC, Oklahoma, OK
- Bloetscher, Frederick and Muniz, A. (2008), "Water Supply in South Florida - The New Limitations," *Sustainable Water Sources (Reno) Conference Proceedings*, AWWA, Denver, CO
- Bloetscher, F. and Muniz, A. (2006), "Defining Sustainability for Water Supply Purposes," *Florida Section AWWA Conference Proceedings*, Hollywood, FL.
- Buffoni, L., Brunetti, M., Mangianti, F., Maugeri, M. & Nanni, T. (2002), Variazioni Climate Change And Groundwater: A Short Review 7, *Climatiche in Italia Negli Ultimi 130 Anni. Bollettino Geofisico Anno XXIII.*
- Czikowsky, M. J., and Fitzjarrald, D. R. (2004), Evidence of seasonal changes in evapotranspiration in eastern U. S. hydrological records. *Accepted to J. Hydrometeor*
- Deyle, R.E.; Bailey, K.C.; and Matheny, A. (2007), *Adaptive Response Planning to Sea Level Rise in Florida and Implications for Comprehensive and Public Facilities Planning*, Florida State University, Tallahassee, FL.
- Di Matteo, L. & Dragoni, W. (2006), "Climate change and water resources in limestone and mountain areas: the case of Firenzuola Lake (Umbria, Italy)," *Proceedings of the 8th Conference on Limestone Hydrogeology, Neuchaˆtel, Switzerland,*

Continued on page 26

Continued from page 25

21–23 September 2006, Presses universitaires de Franche- Comte´ (FRANCE), 83–88.

- Dragoni, W. (1998), "Some considerations on climatic changes, water resources and water needs in the Italian region south of the 438N." In: ISSAR, A. S. & BROWN, N. (eds) *Water, Environment and Society in Times of Climatic Change.* Kluwer, 241–271.
- Dragoni, W. and B. S. Sukhija (2008), Climate change and groundwater: a short review, *Geological Society, London, Special Publications*; v. 288; p. 1-12
- FDEP (2008), Chapter, 62-610, F.A.C. Reclaimed Wastewater Rule, accessed 7/1/2008, http://www.dep.state.fl.us/legal/Rules/wastewater/62-610.pdf
- Fernald, E. A. and Purdum, E. D., eds. (1998), Water Resources Atlas of Florida. Tallahassee: Institute. of Science and Public Affairs, Florida State University, Tallahassee, FL.
- Florida 2030 Climate Change Subcommittee (2008), Climate Change And Florida Water Supplies FSAWWA, Orlando, FL, (unpublished formally).
- Freas, K.; Bailey, R.; Muneavar, A.; and Butler, S. (2008), Incorporating Climate Change in Water Planning, *JAWWA*, v 100 no 6, p 93-99.
- Frederick, K. and Gleick, P (1999), "Water and Global Climate Change" *Potential Impacts on US Water Resources*, Pew Center on Global Climate Changes, Arlington, VA.
- Galloway, Devin; Jones, David R. and Ingebritsen, S.E., *Land Subsidence in the United States*, U.S. Geological Survey Circular 1182, USGS, Washington, DC.
- Goudie, A. (1994), *The Human Impact on the Environment.* The MIT Press Cambridge, Massachusetts.
- Green, Timothy R., Makoto Taniguchi and Henk Kooi, (2006), "Potential Impacts of Climate Change and Human Activity on Subsurface Water Resources," *Water Resources Research, Vol. 42, W11405, doi:10.1029/2005WR004742, 2006*
- Hapgood, Charles H. (1999), *Path of the Pole* (2nd Ed), Adventures Unlimited Press, Kempton, IL.
- Herrera-Pantoja, M. and K. M. Hiscock (2008), "The effects of climate change on potential groundwater recharge in Great Britain," *Hydrol. Process.* 22, 73–86
- Huggett, R. J. (1991), *Climate, Earth Processes and Earth History*, Springer-Verlag.
- Huntington, T. G. (2006), "Evidence for intensification of the global water cycle: Review and synthesis," *Journal of Hydrology*, 319, 83–95.
- Intergovernmental Panel on *Climate Change - IPCC (2007) – Climate Change 2007: The Physical Science Basis*
- Issar, A. S. (2005), "Mitigating the greenhouse effect by sequestering carbon by woods planted in dry-zones, utilizing wasted water resources," *Presented at World Water Week in Stockholm*, 21–27 August, 2005. Workshop 2 – Coping with Climate Variability, Climate Change and Water-Related Hazards.
- Kundzewicz, Z. W.; Mata, L. J.; Arnell, N. W.; Döll, P ; Jimenez, .;Miller, K.; Oki, T.; Şen, Z. and Shiklomanov, I (2007), "The implications of projected climate change for freshwater resources and their management," *Hydrological Sciences Journal*, Volume: 53, Issue: 1, Page(s): 3-10.
- Labat, D., Godde´ Ris, Y., Probst, J. L. & Guyot, J. L. (2004), "Evidence for global runoff increase related to climate warming," *Advances in Water Resources*, 27, 631–642.
- Lamy, F., Arz, H. W., Bond, G. C., Bahr, A. & Patzold, J. (2006), "Multicentennial-scale hydrological changes in the Black Sea and northern Red Sea during the Holocene and the Arctic/North Atlantic Oscillation," *Paleoceanography*, 21, PA1008, 11.
- Leduc C, Favreau G, Schroeter P (2001), "Long-term rise in a Sahelian water-table: the continental terminal in south-west Niger," J*ournal of Hydrology*, 243, 43–54.
- Lettenmaier D.P. (2008) Chapter 4 Water Resources, in Walsh, M (ed), *The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States, U.S. Climate Change Science Program and the Subcommittee on Global Change Research*, USDA, Washington, DC.
- Lins, H. F. and Slack, J. R. (1999) Streamflow trends in the United States. *Geophysical Research Letters*, Vol. 26, 227–230.
- Marshall, Curtis H.; Pielke, Roger A. Sr.; Steyaert, Louis T. And Debra A. Willard (2003), "The Impact of Anthropogenic Land-Cover Change on the Florida Peninsula Sea Breezes and Warm Season Sensible Weather,"28 *Monthly Weather Review*, vol. 132.
- McGinnis, L (2007), *Climate Change and Groundwater Recharge*, http://www.ars.usda.gov/IS/pr/2007/070831.htm accessed 8/8/08.
- McMahon PB, Dennehy KF, Ellett KM et al. (2003), "Water movement through thick unsaturated zones overlying the central High Plains aquifer, southwestern Kansas, 2000–2001," *USGS Water Resources Investigation Report*, 03-4171, 32pp.
- Miller MR, Brown PL, Donovan JJ et al. (1981), "Saline-seep development and control in the North American Great Plains: hydrogeological aspects," *Agricultural Water Management*, 4, 115–141.
- Moore N, Rojstaczer S (2002), "Irrigation's influence on precipitation: Texas High Plains, U.S.A," *Geophysical Research Letters*, 29, 2-1–2-4.
- Murley, J. (2006), Charting the Course, Where is South Florida Heading, Florida Atlantic University, Boca Raton, FL.
- NOAA (2007), Observing Climate Variability and Change http://www.research.noaa.gov/climate/t_observing.html, accessed 3/24/2007
- U.S. Climate Change Science Program (2008), "Synthesis and Assessment Product 4.3: The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States" http://www.climatescience.gov/Library/sap/sap4-3/final-report/default.htm, accessed 8/8/08
- Pielke, R. A., L. T. Steyaert, P. L. Vidale, G. E. Liston, W. A. Lyons, and T. N. Chase (1999), "The Influence of Anthropogenic Landscape Changes on Weather in South Florida," *Monthly Weather Review*, July 1999, p. 1669.
- Ragab R, Finch JW, Harding RJ. (1997), Estimation of groundwater recharge to chalk and sandstone aquifers using simple soil models. *Journal of Hydrology* 190: 19–41.
- Reilly, Thomas E.; Dennehy, Kevin F.; Alley, William M. and Cunningham, William L. (2008), *Ground-Water Availability in the United States*, U.S. Geological Survey Circular 1323, USGS Washington, DC.
- Richey, J E.; Costa-Cabral, M. (2006), "Floods, Droughts, and the Human Transformation of the Mekong River Basin," *Eos Trans.* AGU, 87(52), Fall Meet. Suppl., Abstract.
- Roark, D.M., Healy, D.F. (1998), "Quantification of deep percolation from two flood-irrigated alfalfa fields, Roswell Basin, New Mexico," *USGS Water Resources Investigation Report*, 98-4096, 32pp.
- Salmun, Haydee and Andrea Molod (2006), "Progress in modeling the impact of land cover change on the global climate," *Progress in Physical Geography* 30, 6 (2006) pp. 737–749
- Scanlon, Bridget R., Robert C. Reedy, David A. Stonestrom, David E. Prudic and Kevin F. Dennehy (2005), "Impact of land use and land cover change on groundwater recharge and quality in the southwestern US," *Global Change Biology* 11, 1577–1593.
- Schilling, K.; and Zhang, Y (2006) "Effects of LULCC on Streamflow and Nitrate-N Concentrations in Iowa and the Mississippi River Basin," *Eos Trans.* AGU, 87(52), Fall Meet. Suppl., Abstract.
- Scibek J, Allen DM. (2006), "Comparing modelled responses of two high permeability, unconfined aquifers to predicted climate change," *Global and Planetary Change* 50: 50–62.
- Sherif MM, and Singh, VP. (1999), "Effect of climate change on sea water intrusion in coastal aquifers," *Hydrological Processes* 13: 1277–1287.
- Sililo OTN, and Tellam J. (2000), "Fingering in unsaturated zone flow: a qualitative review with laboratory experiments on heterogeneous Systems," *Ground Water* 38: 864–871.
- Singer, F.E. (Ed) (2008), *Nature, Not Human Activity, Rules Climate Change, Summary for Policy Makers*, the Nongovernmental International Panel on Climate Changes, The Heartland Institute, Chicago, IL.
- Stamm CH, Fluhler HJ, Leuenberger J, and Wenderli H. (1998), „Preferential transport of phosphorus in drained grassland soils," *Journal of Environmental Quality* 27: 515–522.
- Strzepek, K. M. and Yates, D. N. (1997), "Climate change impacts on the hydrologic resources of europe: a simplified continental scale analysis," *Climatic Change*, 36, 79–92.
- USEPA (2008), *National Water Program Strategy: Response to Climate Change*, USEPA, Washington, DC.
- U.S. Geological Survey, 1984, *National water summary 1983—Hydrologic events and issues*: U.S. Geological Survey Water-Supply Paper 2250, 243 p.
- van Roosmalen, Lieke,*, Britt S. B. Christensen and Torben O. Sonnenborg (2006) "Regional Differences in Climate Change Impacts on Groundwater and Stream Discharge in Denmark," *Water Resources Research, Vol. 42, W11405, doi:10.1029/2005WR004742, 2006*
- Yang, M., Yao, T., Wang, H. & Gou, X. (2006), „Climatic oscillations over the past 120 kyr recorded in the Guliya ice core, China," *Quaternary International*, 154–155, 11–18.