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Climate variability and irrigation impacts on streamflows in a Karst watershed—A systematic evaluation

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ABSTRACT

The study area is the Lower Flint River Basin which is at the center of water conflicts in the southeastern USA.

This study focuses on a systematic evaluation and separation of El Niño Southern Oscillation (ENSO) induced droughts and irrigation water withdrawal impacts on flow levels using a novel and powerful statistical technique, called JRFit. JRFit procedure was applied to quantify significant differences in streamflows, baseflows, and low flow statistics during non-irrigation (NI) and irrigation (IR) periods associated with ENSO phases.

The results indicate that overall streamflow levels have decreased by approximately 20% after the introduction of irrigation in the study area. Lowering of flow levels mainly occur during La Niña phases which gets exacerbated (decreased by 50%) during growing season of IR compared to NI periods. Flow duration curve analysis showed that the frequency of low flows has increased during IR period impairing aquatic ecosystem. This is the first time an elimination approach is used to separate and quantify the impacts of anthropogenic and climate signals on water resources. This approach avoids the need of using complex and data intensive groundwater/surface water models in studying climate-stream-aquifer interactions which can be replicated easily in other data scarce watersheds. This study provides useful information to policymakers to devise irrigation water withdrawal policies during La Niña growing seasons for maintaining flow levels in the study area.

1. Introduction

Natural ocean-atmospheric climate variability phenomena affect temperature and precipitation around the world and are also responsible for extreme events such as hurricanes, floods, droughts, and cold waves (IPCC, 2001; Seneviratne et al., 2012). Studies have found strong influence of climate variability phenomena on components of hydrologic cycle in many parts of the world. Therefore, it is important to understand and quantify the effects of climate variability phenomena on water resources to help mitigate their adverse effects on water resources. In addition to natural, short-term climate variability induced stresses on water resources, an ever growing global population with increasing need for irrigated agriculture is putting stress on freshwater bodies such as lakes, streams, and aquifers. In the past 50 years, the demand for water consumption for human use has increased by almost three-folds, and it is projected that by 2025 five out of eight people will be living under water scarce conditions across the world including the USA (Postel et al., 1996). Around the world, water

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managers are facing challenges to meet the increasing water demands due to population growth, irrigated agriculture, and urban usage which gets exacerbated due to interannual climate variability. To be able to cope and better manage future water shortages resulting from climate variability-induced droughts and human-induced water scarcity, it is important to study the combined impact of anthropogenic factors and climatic oscillation on hydrology and their effects on water resources.

El Niño Southern Oscillation (ENSO), with a periodicity of 2–7 years, is the fluctuation in sea-surface temperature (SST) caused by the interaction between large-scale ocean and atmospheric circulations in the equatorial Pacific Ocean. ENSO has three phases such as El Niño, La Niña and Neutral. The terms "El Niño" and "La Niña" refer to the warming and cooling of SST off the shores of the West Coast of South America that leads to changes in climatic conditions around the world (Quinn, 1994; Aceituno, 1992). ENSO is one of the major modes of climate variability affecting temperature and precipitation around the world (Diaz and Markgraf, 1992; Chiew et al., 1998; Keener et al., 2007; Roy, 2006). Several studies have found that ENSO has a strong influence on droughts, streamflow, groundwater, flood frequency, monsoon, water quality, and crop yield in different parts of the world (Kahya and Dracup, 1993; Chiew et al., 1998; Rajagopalan and Lall, 1998; McCabe and Dettinger 1999; Piechota and Dracup, 1999; Kulkarni, 2000; Hansen et al., 2001; Tootle et al., 2005; Roy, 2006; Keener et al., 2007; Gurdak et al., 2007; Singh et al., 2015).

Moreover, other studies have shown that ENSO exhibits strong teleconnections with precipitation, streamflow, baseflow and groundwater in the southeastern USA (Singh et al., 2015; Mitra et al., 2014; Piechota and Dracup, 1996; Tootle et al., 2005; Mearns et al., 2003; Kiladis and Diaz, 1989; Hansen et al., 2001; Enfield et al., 2001; Johnson et al., 2013; Schmidt and Luther, 2002). This region often suffers from low surface water availability due to frequent occurrences of La Niña, which brings warm and dry conditions between the months of October and April (Kiladis and Diaz, 1989; Hansen and Maul, 1991; Schmidt and Luther, 2002; Mearns et al., 2003), making the region vulnerable to ENSO-induced droughts. Furthermore, water shortages in this region get exacerbated due to high evaporation rates during summer months and increased demand for water due to growth in population, urbanization and irrigated agriculture, especially in the past few decades. The Southeast has experienced recurring droughts that have caused losses in agricultural productivity, prompted water use restrictions on municipal and irrigated waters uses, and induced interstate water conflicts. This combined stress of climate variability-induced droughts, population growth, and irrigation withdrawal on water resources has led to the so-called "Tri-State Water Conflict" among the neighboring states of Georgia, Alabama and Florida (Jordan and Wolf, 2006). This conflict has been marked by costly, time consuming and ongoing litigations where the sparring parties have failed to reach a common ground on the allocation of water resources of the Apalachicola-Chattahoochee-Flint (ACF) River Basin (Fig. 1), thereby making the ACF one of the most contentious river basins in the United States. The freshwater resources of the ACF provide support to rapidly growing population; urban sprawl; industrial, municipal and rural water supplies; power generation; irrigated agriculture; shellfish industry; and estuarine ecosystem. One of the major issues related to the ongoing conflict is the irrigation-induced lowering of flow levels in the Flint River.

Agriculture in the Lower Flint River (LFR) Basin (in southwest Georgia) is heavily dependent on irrigation water withdrawals from surface and groundwater sources. Since the mid 1970's, groundwater withdrawals for irrigation has increased dramatically in the LFR Basin (Fig. 2) due to extensive installation of center pivot irrigation systems (Hicks et al., 1987; Pierce et al., 1984) where the ratio of groundwater sites to surface water sites is 5:1. During a drought year (typically caused by La Niña), groundwater withdrawal from the Upper Floridan Aquifer (UFA), which is the major groundwater bearing unit in the area, can run into hundreds of millions of gallons per day. The flow in the LFR is hydro-geologically connected with UFA through direct connections with many sinkhole ponds, karst sinks, conduits and trough incised streambeds, and indirect connections through vertical leakage from overburden (Mosner, 2002; Opsahl et al., 2007).

The hydrologic connectivity/interaction of groundwater with surface water has become a topic of interest among researchers worldwide since it supports baseflow and serves as a major water resource unit (Shah et al., 2000; Woessner, 2000; Stanford and Ward, 1993; Winter et al., 1998; Boulton and Hancock, 2006). Intensive groundwater withdrawal near stream channels have been linked to alterations in the quantity and quality of surface waters, which leads to changes in channel morphology, altered stream temperature, lower assimilative capacity, reduced nutrient loading to downstream communities (Pringle and Triska, 2000; Bunn and Arthington, 2002), and threats to aquatic biota including federally-protected mussel species (Golladay et al., 2004). Therefore, this study aims to understand the relationships between droughts, irrigation water withdrawals, and streamflow levels in the study area. To achieve the goal of this study, streamflows and baseflows for the non-irrigation and irrigation periods were compared with the ENSO phases. The comprehensive outcomes of this study can be used to help the state of Georgia better manage drought and irrigation induced streamflow reductions in the LFR.

2. Methodology

To attain the research goal, the nonparametric Joint Rank Fit (JRFit) procedure (Kloke et al., 2009) was used to test and estimate the ENSO-induced drought and irrigation impacts on streamflow, baseflow, one-day, and seven-day low flows levels. Additionally, flow duration curves for the lower Flint River were created and compared for non-irrigation (NI) and irrigation (IR) periods.