An Assessment of Water Availability in Texas Using The Noah Land Surface Model

USGS Grant 2011TX395B

Final Report

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PROJECT NUMBER: 2011TX395B

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ABSTRACT

The state of Texas suffers from both short term and long term droughts, which have resulted in losses equivalent to several billions of dollars. The recent exceptional drought that hit the southern United States is the worst drought on record for the state of Texas; associated loss to the state's agricultural sector is estimated at $5.2 billion, making it the costliest drought on record. Several studies have shown that precipitation and indeed drought are strongly related to climate teleconnection patterns. Spatial correlation between climate and drought indices shows that watersheds across the state are not uniformly affected by droughts – instead some are more vulnerable than others. While this qualitative information is useful to the water manager, it does not help the latter to plan adequately. In this study we used the Noah land surface model to model water availability in the Rio Grande basin – a transboundary basin shared between three states in the US and straddles the state of Texas and Mexico. It was found that El Niños (La Niñas) generally cause an increase (decrease) in runoff, but the pattern is not consistent; percentage change in water availability varies across events. Further, positive Pacific Decadal Oscillation (PDO) enhances the effect of El Niño and dampens that of La Niña, but during neutral/transitioning PDO, La Niña dominates meteorological conditions. Long El Niños have more influence on water availability than short duration high intensity events. We also note that the percentage increase in water availability during El Niños significantly offsets the drought-causing effect of La Niñas. The results from this study will help give an early warning on expected changes in water availability to water managers and thus help in the medium and long term water planning.

PROBLEM AND RESEARCH OBJECTIVES

Large scale circulation indices such as the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) have a significant influence on local atmospheric and hydrologic variables and hence water availability. Several studies have investigated the influence of climate teleconnections on precipitation [e.g. *McCabe and Dettinger*, 1999; *Piechota and Dracup*, 1996; *Ropelewski and Halpert*, 1986; *Woolhiser et al.*, 1993], streamflow [e.g. *Barlow et al.*, 1998; *Kahya and Dracup*, 1993; *Redmond and Koch*, 1991], and drought [e.g. *Özger et al.*, 2009; *Schoennagel et al.*, 2005]. The information provided by studies conducted thus far is not completely useful for water planners and managers as they provide qualitative information on the degree of association of these hydrologic variables and climate patterns.

In this study we investigate the influence of two large-scale climate indices, namely ENSO and PDO, on the water availability in one of the most important basins in the United States and the state of Texas – the Rio Grande/Río Bravo del Norte basin (RG). RG is a transboundary basin shared between three states in the US and straddles US and Mexico, two countries very dissimilar economically. It is a vital source of water for the region, but is already in a state of absolute water scarcity, with less than 500 m^3/person/day; the only transboundary basin in this category [*Wolf*, 2002]. This region is also extremely vulnerable to droughts; records show that it suffers from both short-term and long-term droughts [*Quiring and Goodrich*, 2008]. Subjected to a burgeoning population, which will further increase the stress on water allocation, and climate change, which will likely result in a decrease in precipitation [*IPCC*, 2007], the potential for conflicts cannot be overlooked. It is therefore imperative to understand the mechanisms driving water availability and quantify any change for long-term sustainable water planning and management.

MATERIALS/METHODOLOGY

The Noah land surface model (LSM) was used to develop a hydrologic model of the basin. The model was developed within NASA GSFC's Land Information System [LIS; *Kumar et al.*, 2008; *Peters-Lidard et al.*, 2007] and driven with the North American Land Data Assimilation System Phase 2 dataset [NLDAS-2; *Mitchell*, 2005].

Noah Land Surface Model

Noah LSM is a stand-alone 1-D column model that can simulate soil moisture (both liquid and frozen), soil temperature, skin temperature, snowpack depth, snowpack water equivalent, canopy water content, and water and energy flux terms of the surface water and energy balance [*Mitchell*, 2005]. It has a 2 m deep soil layer divided into the following four sub-layers: a 100 mm thick top layer, a second 300 mm thick root zone layer, a 600 mm deep root zone layer, and a 1000 mm thick sub-root zone layer. The latter layer acts as a reservoir with gravity drainage at the bottom. The volumetric soil moisture content obeys the law of conservation of mass and is determined using the diffusive form of Richard's equation which is derived from Darcy's law under the assumption of rigid, isotropic, homogeneous, and one-dimensional vertical flow. The total evaporation, in the absence of snow, is the sum of direct evaporation from the topmost soil layer, evaporation of precipitation intercepted by plant canopy, and transpiration from canopy of vegetation. The model adopts a gravity free-drainage subsurface scheme, and surface runoff is the excess after infiltration [*Schaake et al.*, 1996]. *Chen and Dudhia* [2001] give a complete description of the model physics and order in which computations are carried. Noah has been a candidate in major off-line land surface experiments, such as the Project for Intercomparison of Land-surface Parameterization Schemes [PIPLS; *Henderson-Sellers et al.*, 1996] and the Global Soil Wetness Project [GSWP; *Dirmeyer et al.*, 1999], among others. It has been validated in both coupled and uncoupled modes [*Mitchell*, 2005] and is implemented in the MM5 modeling system (http://www.mmm.ucar.edu/mm5/mm5-home.html), the Weather Research and Forecast (WRF; http://www.wrf-model.org) model and also NCEP's operational Global Forecast System (GFS; http://www.emc.ncep.noaa.gov/GFS/).

Noah has been extensively tested against other LSMs and has been found to have a small bias in both evaporation and runoff when compared with observed annual water budget and is able to reproduce streamflow with high accuracy [*Mitchell et al.*, 2004], thus making it a suitable candidate for modeling runoff in RG.

North American Land Data Assimilation System – Phase 2

NLDAS-2 was used as forcing data for the model. It has a 1/8° latitude/longitude resolution over a domain covering the conterminous United States, part of Canada, and Mexico (125°W–67°W, 25°N–53°N), thus allowing the modeling of both the US and Mexican portions of the basin. The dataset has been extensively compared, tested, and validated for snow cover and snow water equivalent [*Pan and Mahrt*, 1987; *Sheffield et al.*, 2003], soil moisture [*Schaake et al.*, 1996], and streamflow and water balance [*Lohmann et al.*, 2004]. Additional parameters required as inputs to Noah include land cover [*Hansen et al.*, 2000], seasonal maximum snow free albedo maps, monthly greenness fraction, bottom temperature, and soil texture (sand, clay, and silt) and color [*Zobler*, 1986].

Model Output

The LSM is run retrospectively for a period of 30 years (1 January 1979 to 31 December 2008) at a time step of 30 minutes and output files are written for every 3 hours, thereby creating 8 files for each day from which runoff was extracted at the pixel scale and spatially averaged and temporally aggregated over the region of interest. Both the precipitation and the modeled runoff were validated. The precipitation field was compared to gauged measurements and the monthly runoff was validated against flow in the Río Conchos sub-basin and it was found that Noah faithfully captured the monthly variation in runoff in the basin. A comprehensive description of the modeling and validation exercise is available in *Khedun et al.* [2012b].

Using the modeled runoff and standardized runoff index as a proxy for water availability, water deficit durations and associated severity of drought events were extracted and copula was employed to analyze the bivariate characteristics of water deficit duration and severity in different parts of the basin [*Khedun et al.*, 2011; 2012a].

PRINCIPAL FINDINGS

The principal findings of the study are given below. The first section highlights the main conclusions from the study on the influence of ENSO and PDO on water availability and the second section summarizes the results from a bivariate water deficit duration and analysis based on the Noah model runoff.

Influence of ENSO and PDO

It was found that ENSO and PDO do indeed influence local meteorological and hydrological variables, and hence water availability in RG. The correlation between PDO and three ENSO indices, namely Niño 3.4, MEI, and EMI, with gauged precipitation respectively showed that both ENSO and PDO have a strong influence on the winter and spring precipitation in the basin. The overall correlation is positive, except for the Upper RG region which includes the headwaters in the San Juan range in the Rocky Mountains in southern Colorado. Therefore, higher snowfall during La Niña conditions may help in maintaining flow in the river and offset precipitation reduction in arid/semi-arid New Mexico.

A general increase (decrease) in water availability during El Niños (La Niñas) was noted but some individual events actually caused a decrease (increase) in water availability. By classifying El Niño and La Niña events using criteria such as duration or maximum (or minimum sea surface temperature anomaly), it was found that not all ENSO events are created equal. Some have short duration but high intensities while others may linger for several years. By further investigating the effect of the different ENSO events thus classified on water availability, it was found that El Niños lingering for long periods have more influence on water availability than short duration high intensity events. The upper-middle section of the basin records a higher increase in winter water availability during El Niño events (200-300%) while the lower half, including the Río Conchos, experiences a more modest change. A positive PDO enhances the effect of El Niño and dampens the negative effect of La Niña. When it is in its neutral/transition phase, La Niña dominates climatic conditions and reduces water availability. Finally, the percentage increase during El Niños significantly offset the decrease registered during La Niñas. This finding is important for water resources planning.

Bivariate Water Deficit and Severity Analysis

In order to assess the bivariate water deficit and severity, the basin was divided into 6 sub-regions, since the basin is subject to different climatological conditions, and nine copulas are tested on each region using graphical assessment and analytical goodness-of-fit tests. It is found that given that water deficit duration and severity characteristics varied across regions, different copulas are deemed suitable.

The conditional probability models for severity given a threshold duration and duration given a threshold severity were found to be different. Comparing two climatologically distinct regions (Upper RG and Lower-Middle RG) it was found that the conditional probability of minor events are almost similar but that for long duration high severity events are very different, reflecting the nature of deficit events in these regions.

Finally it was found that model derived water deficit conditional probabilities can be used in tandem with observation driven conditional probabilities for long term water planning and management and model derived information may be used in regions having limited ground observation data.

SIGNIFICANCE

This study extends the discussion between the influence of large-scale circulation indices and local meteorological and hydrological conditions by quantifying the seasonal percentage changes in water availability, which is more tangible information for water planning. Climate change may alter the frequency and intensity of ENSO events and may cause droughts that are more extreme and/or of longer duration than on record. The current results, while are not intended for prediction purposes, may help in the long-term sustainable water planning and management within the basin for Texas, the United States, and Mexico. Finally, the methodology developed in this study is not limited to RG, but can be adapted to other watersheds in Texas and can even be applied to larger continental scale to assess the need and effectiveness of interstate water transfers for example.

PUBLICATIONS

The funds from the USGS Grant 2011TX395B along with other funds were used to support the following two peer-reviewed publications (one is currently under review), a poster and a paper at the 2011 Symposium on Data-Driven Approaches to Droughts, and a poster at the 2011 American Geophysical Union Fall Meeting.

Peer-reviewed Publications

Khedun, C. P., A. K. Mishra, J. D. Bolten, H. K. Beaudoing, R. A. Kaiser, **J. R. Giardino**, and **V. P. Singh** (2012), Understanding changes in water availability in the Rio Grande/Río Bravo del Norte basin under the influence of large-scale circulation indices using the Noah land surface model, *J. Geophys. Res.*, *117*(D5), D05104.

Khedun, C. P., H. Chowdhary, A. K. Mishra, **J. R. Giardino**, and **V. P. Singh** (2012), Water Deficit Duration and Severity Analysis Based on Runoff Derived from the Noah Land Surface Model, *Journal of Hydrologic Engineering (under review)*.

Conference Paper

Khedun, C. P., H. Chowdhary, A. K. Mishra, **J. R. Giardino**, and **V. P. Singh** (2011), Analysis of Drought Severity and Duration Based on Runoff Derived from the Noah Land Surface Model, in *2011 Symposium on Data-Driven Approaches to Droughts*, Purdue e-Pubs, Purdue University, West Lafayette, IN

Conference Poster

Khedun, C. P., H. Chowdhary, A. K. Mishra, **J. R. Giardino**, and **V. P. Singh** (2011), Analysis of Drought Severity and Duration Based on Runoff Derived from the Noah Land Surface Model, in *2011 Symposium on Data-Driven Approaches to Droughts*, Purdue e-Pubs, Purdue University, West Lafayette, IN

Khedun, C. P., A. K. Mishra, **J. R. Giardino**, and **V. P. Singh** (2011), Probabilistic Water Availability Prediction in the Rio Grande Basin using Large-scale Circulation Indices as Precursor, *American Geophysical Union*, Fall Meeting 2011, Abstract #H43H-1333

REFERENCES

Barlow, M., S. Nigam, and E. H. Berbery (1998), Evolution of the North American Monsoon System, *Journal of Climate*, *11*(9), 2238-2257.

Chen, F., and J. Dudhia (2001), Coupling an Advanced Land Surface–Hydrology Model with the Penn State–NCAR MM5 Modeling System. Part I: Model Implementation and Sensitivity, *Monthly Weather Review*, *129*(4), 569-585.

Dirmeyer, P. A., A. J. Dolman, and N. Sato (1999), The Pilot Phase of the Global Soil Wetness Project, *Bulletin of the American Meteorological Society*, *80*(5), 851-878.

Hansen, M. C., R. S. Defries, J. R. G. Townshend, and R. Sohlberg (2000), Global land cover classification at 1 km spatial resolution using a classification tree approach, *International Journal of Remote Sensing*, *21*(6), 1331-1364.

Henderson-Sellers, A., K. McGuffie, and A. J. Pitman (1996), The Project for Intercomparison of Land-surface Parametrization Schemes (PILPS): 1992 to 1995, *Climate Dynamics*, *12*(12), 849-859.

IPCC (2007), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*Rep.*, Cambridge, United Kingdom and New York, NY, USA.

Kahya, E., and J. A. Dracup (1993), U.S. streamflow patterns in relation to the El Niño/Southern Oscillation, *Water Resour. Res.*, *29*(8), 2491-2503.

Khedun, C. P., H. Chowdhary, A. K. Mishra, J. R. Giardino, and V. P. Singh (2011), Analysis of Drought Severity and Duration Based on Runoff Derived from the Noah Land Surface Model, in *2011 Symposium on Data-Driven Approaches to Droughts*, edited, Purdue e-Pubs, Purdue University, West Lafayette, IN

Khedun, C. P., H. Chowdhary, A. K. Mishra, J. R. Giardino, and V. P. Singh (2012a), Water Deficit Duration and Severity Analysis Based on Runoff Derived from the Noah Land Surface Model, *Journal of Hydrologic Engineering (under review)*.

Khedun, C. P., A. K. Mishra, J. D. Bolten, H. K. Beaudoing, R. A. Kaiser, J. R. Giardino, and V. P. Singh (2012b), Understanding changes in water availability in the Rio Grande/Río Bravo del Norte basin under the influence of large-scale circulation indices using the Noah land surface model, *J. Geophys. Res.*, *117*(D5), D05104.

Kumar, S., C. Peters-Lidard, T. Yudong, R. Reichle, J. Geiger, C. Alonge, J. Eylander, and P. Houser (2008), An Integrated Hydrologic Modeling and Data Assimilation Framework, *Computer*, *41*(12), 52-59.

Lohmann, D., et al. (2004), Streamflow and water balance intercomparisons of four land surface models in the North American Land Data Assimilation System project, *J. Geophys. Res.*, *109*(D7), D07S91.

McCabe, G. J., and M. D. Dettinger (1999), Decadal variations in the strength of ENSO teleconnections with precipitation in the western United States, *International Journal of Climatology*, *19*(13), 1399-1410.

Mitchell, K. E. (2005), The Community Noah Land-surface model. User's Guide, Public Release Version 2.7.1, edited.

Mitchell, K. E., et al. (2004), The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system, *J. Geophys. Res.*, *109*(D7), D07S90.

Özger, M., A. K. Mishra, and V. P. Singh (2009), Low frequency drought variability associated with climate indices, *Journal of Hydrology*, *364*(1-2), 152-162.

Pan, H. L., and L. Mahrt (1987), Interaction between soil hydrology and boundary-layer development, *Boundary-Layer Meteorology*, *38*(1), 185-202.

Peters-Lidard, C., et al. (2007), High-performance Earth system modeling with NASA/GSFC's Land Information System, *Innovations in Systems and Software Engineering*, *3*(3), 157-165.

Piechota, T. C., and J. A. Dracup (1996), Drought and Regional Hydrologic Variation in the United States: Associations with the El Niño-Southern Oscillation, *Water Resour. Res.*, *32*(5), 1359-1373.

Quiring, S., and G. Goodrich (2008), Nature and causes of the 2002 to 2004 drought in the southwestern United States compared with the historic 1953 to 1957 drought, *Climate Research*, *36*(1), 41-52.

Redmond, K. T., and R. W. Koch (1991), Surface Climate and Streamflow Variability in the Western United States and Their Relationship to Large-Scale Circulation Indices, *Water Resour. Res.*, *27*(9), 2381-2399.

Ropelewski, C. F., and M. S. Halpert (1986), North American Precipitation and Temperature Patterns Associated with the El Niño/Southern Oscillation (ENSO), *Monthly Weather Review*, *114*(12), 2352-2362.

Schaake, J. C., V. I. Koren, Q.-Y. Duan, K. Mitchell, and F. Chen (1996), Simple water balance model for estimating runoff at different spatial and temporal scales, *J. Geophys. Res.*, *101*(D3), 7461-7475.

Schoennagel, T., T. T. Veblen, W. H. Romme, J. S. Sibold, and E. R. Cook (2005), ENSO and PDO Variability Affect Drought-Induced Fire Occurrence In Rocky Mountain Subalpine Forests, *Ecological Applications*, *15*(6), 2000-2014.

Sheffield, J., et al. (2003), Snow process modeling in the North American Land Data Assimilation System (NLDAS): 1. Evaluation of model-simulated snow cover extent, *J. Geophys. Res.*, *108*(D22), 8849.

Wolf, A. T. (2002), *Atlas of International Freshwater Agreements* United Nations Environment Programme, Nairobi, Kenya.

Woolhiser, D. A., T. O. Keefer, and K. T. Redmond (1993), Southern oscillation effects on daily precipitation in the southwestern United States, *Water Resour. Res.*, *29*(4), 1287-1295.

Zobler, L. (1986), A World Soil File for Global Climate Modelling*Rep.*, NASA Goddard Institute for Space Studies, New York, New York, USA.