Synthesizing datasets to estimate terrestrial water storage trends in South Carolina from 1998-2007

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EXTENDED ABSTRACT. The goal of this work is to quantify trends in both space and time of water stored in the terrestrial environment within South Carolina during and following a period of drought. We present a water balance approach that synthesizes existing data for watersheds defined by the drainage area between streamflow gaging stations. We apply the approach to river basins in South Carolina for the period 1998-2007 using precipitation and evaporation fluxes integrated over watershed areas and observed streamflow observations at the inlet and outlet of watersheds. Results from the analysis show distinct seasonal variation in water storage for different spatial regions of the state, with the fall and the winter seasons having water surpluses, and the spring and summer seasons exhibiting water deficits. On an annual basis, the analysis quantifies the impact of the drought on water storage within the state, and shows evidence of the rate of recovery from the drought. We compared our estimates of change in terrestrial water storage with observed groundwater levels as an independent validation. The comparison shows that many of watersheds within the state exhibited a strong correlation between variation in terrestrial water storage estimates and observed groundwater levels during the period of analysis, as expected. The approach is a simple yet valuable means for estimating trends in water availability by synthesizing existing observations and model output data within a geospatially-explicit context.

INTRODUCTION

South Carolina experienced a severe drought between 1998 and 2001. During this time, precipitation decreased by 10-30% from normal levels, resulting in reduced streamflows throughout the state (Badr et al., 2004). The drought presented challenges to the state such as meeting water supply needs for human and industrial purposes, salt water intrusion, and decreased water levels in lakes and groundwater aquifers. It is important to quantify the impacts of droughts on water resources to better understand the short and long term impacts of droughts for different parts of the state. For this reason, we present a simple water balance approach that leverages historical terrestrial and atmospheric datasets to estimate the storage of water within the terrestrial environment (commonly termed Terrestrial Water Storage, TWS) on a monthly time scale. The approach is similar to that presented by Hirschi et al. (2006) except that we use regional climate models to estimate evaporation rates. Using observational data from streamflow and precipitation networks along with estimations of evaporation from climate model reanalysis products, we estimated changes in TWS for 97 sub-watersheds within the state that we defined using geospatial data describing the terrain, hydrography, and streamflow monitoring network. The results from the analysis provide evidence of the impact of the drought on TWS for different regions of the state and show how TWS recovered in different regions recovered following the period of drought.

METHODOLOGY

Model Description: The rate of change in water storage within the terrestrial portion of the hydrologic cycle can be expressed by a continuity equation

$$\frac{dS}{dt} = -Q + (P - E) \qquad (1)$$

where, *dS/dt* represents the rate of change in TWS with respect of time, *P* represents precipitation, *E* represents evaporation (or evapotranspiration), and *Q* is net streamflow exiting a watershed. Flow may enter and exit the control volume (sub-watershed) by surface and subsurface discharge, which are collectively assumed to be gaged at streamflow monitoring stations. Precipitation and Evaporation are fluxes between the terrestrial and atmospheric environments. It should be noted that subsurface interchange of water between subbasin units are not accounted for in this model.

Data Description: The NHDPlus catchment features, the NHD Flowline features, USGS streamflow monitoring station locations, and NHD network connectivity information were used to calculate the sub-watersheds used in our analysis. First, streamflow monitoring sites were referenced to the stream network using their geographic location. Then we applied an algorithm that begins at a downstream reach in the NHD Flowline feature class and "climbs" the network in the upstream direction identifying the next downstream monitoring station for each reach within the study area. With this information, we were able to calculate sub-watersheds by dissolving catchments in the NHDPlus dataset that had the same next downstream monitoring station. This data processing resulted in 97 sub-watersheds ranging in size from 1.0 to 3,645.0 km^2 where we are able to quantify inflow and outflow for the study period (Figure 1).

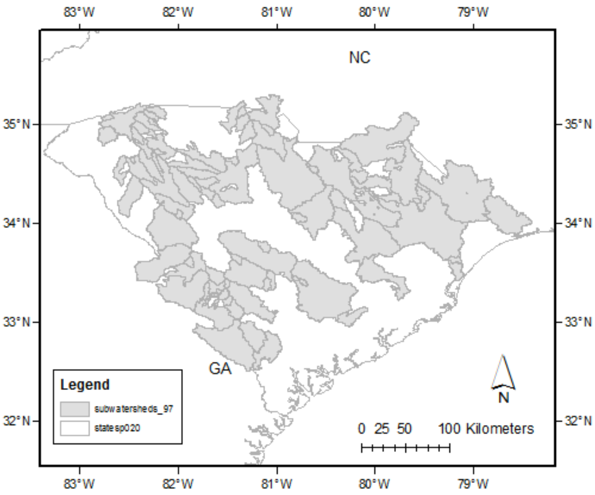

Figure 1: Study area of South Carolina watersheds

We estimated precipitation in the study region using the Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset on monthly and annual time scale and on spatially distributed form. Output from the North American Regional Reanalysis (NARR) program was used to estimate evaporation over the study region. For inclusion in the water balance calculation, precipitation or evaporation flux grids were scaled to watersheds as

$$P \text{ or } E = \frac{A_s * (p) \text{ or } (e)}{T} \qquad (2)$$

where, P is the precipitation or E is evaporation flux into a watershed [m^{3}s^{-1}], A_s is the area of a given watershed [m^2], p is incremental precipitation or e is the evaporation value [m] that was measured over the time period T [s].

Streamflow data within the state are collected by the United States Geologic Survey (USGS) at more than 170 monitoring stations and groundwater levels are observed at 85 stations. We downloaded flow and groundwater level time series data using tools from CUAHSI Hydrologic Information System (HIS) (CUAHSI-HIS, 2009) for use in the study.

RESULTS AND DISCUSSION

The results of this analysis showed clear patterns of increasing and decreasing water storage for different seasons and geographic regions of the state over the 10 year study period (Figure 2). As expected, the results suggest that fall and winter season are periods of increasing water storage whereas spring and summer months are periods of decreasing water storage within the terrestrial environment. When the data are viewed through time, the results clearly show abnormalities in TWS for the drought years (1998-2001) compared to the years following the drought (Figure 2). Spring months in particular showed much lower TWS rates in drought years compared to non drought years.

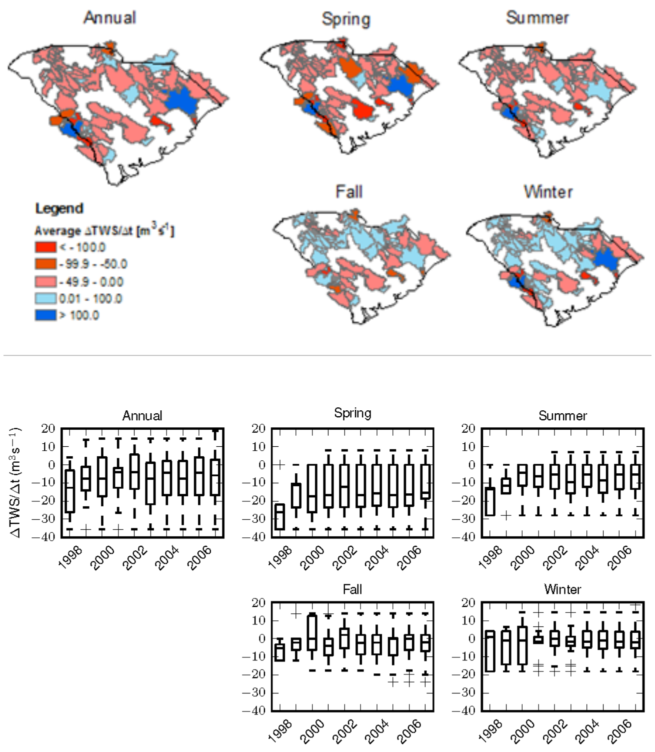

Figure 2: Spatial and temporal distribution of Terrestrial Water Storage in South Carolina (1998-2007)

We compared estimates of TWS with groundwater level (GWL) measurements to qualitatively compare the relationship between TWS and GWL for different sub-watersheds within the state. TWS is a collective term that includes both surface storage, soil moisture storage, and groundwater storage, thus we expected that TWS and GWL to be correlated. However the connection between surface hydrology and groundwater hydrology is complex and so we expected that some sub-watersheds would show clear correlations between TWS and GWL and others would not (depending on the connection between the surface and subsurface environment in different parts of the State). TWS and GWL for three sample sub-watersheds (Figure 3) show the case where TWS and GWL are correlated. An interesting feature of these plots is the time lag between changes in terrestrial water storage and groundwater storage, which is likely related to the recharge rate for different aquifers within the state.

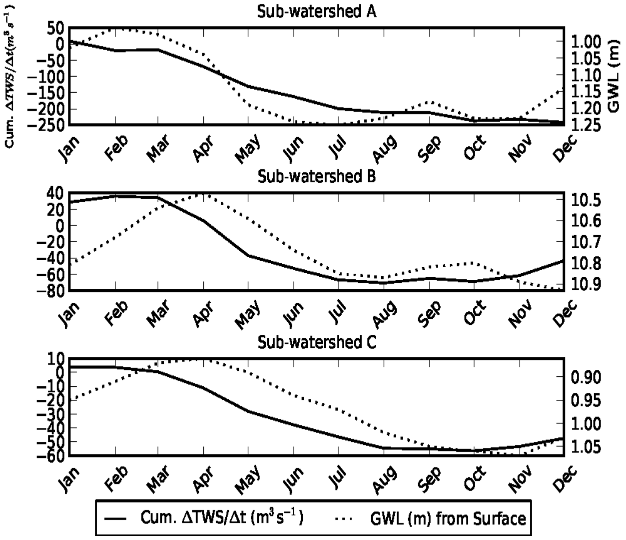

Figure 3: Groundwater relation with Terrestrial Water Storage in South Carolina (1998-2007)

CONCLUSIONS

The presented water balance approach is capable of synthesizing existing hydrologic and geographic datasets in order to provide an estimate of terrestrial water storage (TWS) over large regions. These TWS estimates can be analyzed to identify how different regions of the state responded during and following the period of drought, information that may prove useful in managing the state's water resources. Comparison of estimated rates of TWS change with observed GWL changes over the same period provides not only a validation of the TWS estimates, but also evidence of the connection (or lack of connection) between surface water and groundwater environments in different parts of the state.

Finally, it should be noted that the hydrological data inputs used in the study have different levels of uncertainty. The evaporation estimates in particular, being generated by a continental scale weather model, may not capture true evaporation rates during the study period. However, evaporation is one of the most difficult hydrologic flues to quantify as its rate depends on quantifying soil moisture through time. Future work will be directed at better quantifying evaporation during this time period by using a regional hydrologic model capable of simulating soil moisture on a daily or sub-daily time scale.

LITERATURE CITED

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