HYDROLOGIC MODELING OF THE RIO GRANDE BASIN

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ABSTRACT In this study we investigate the use of the NOAH model along with NLDAS2 forcing in building a hydrological model of the Rio Grande basin to study the effect of climate variability and change on water availability in the basin. The model was run retrospectively for the period 2002 to June 2009. This paper describes the steps taken in building the model and a preliminary analysis of the outputs. We note that the model has to be run for a longer time period to remove biases due to model spin up. We also note that further investigation is required to assess the accuracy of the outputs by comparing the results to gauged data and the model's sensitivity to the major forcing parameters needs to be quantified.

1 INTRODUCTION

The Rio Grande/Río Bravo is a transboundary river shared between Colorado, New Mexico and Texas and between the United States and Mexico. The basin is an important source of water for both the US and Mexico, helping them in meeting municipal, industrial, and agricultural needs. According to the United Nations definition, the basin, with a current water availability of less than 500 m^3/person/year is already in a state of absolute water scarcity. Several cities, including El Paso in Texas and Cuidad Juarez in Mexico, are relying heavily on groundwater from the Hueco Bolson as their sole drinking water supply. Pumping already exceeds recharge and the declining level of water in the aquifer has led to the intrusion of brackish water, hence further reducing fresh water storage capacity. Furthermore there is already an over allocation of the available water and the potential for finding new affordable sources are dim as competition increases between urban, agricultural, hydroelectric and recreational water needs.

Climate variability and change along with persistent long-term drought exacerbates the problem. Uncertainty in the ways these phenomenons will affect the water availability in the coming decades could possibly impede the effective long-term policies and management of water resources.

In this study we present preliminary results of an optimized hydrological model of the Rio Grande / Rio Bravo watershed that can be used to investigate the impact of climate variability and change and projected demographic changes and demands on the water resources. The model is based on the community NOAH model and uses high spatial and temporal resolution forcing

data. A trial run of the model for the period 2002 to 2009 was conducted within the Land Information System (LIS) developed at NASA Goddard Space Flight Center. The preliminary results of the run and possible refinement that can be brought to the model is discussed in this report.

2 PHYSICAL DESCRIPTION OF THE BASIN

The Rio Grande/Río Bravo basin extends over an area of 656,100 km^2 of which 341,800km^2 is in the US and 314,300 km^2 is in Mexico. The headwaters of the basin are located in the San Juan Mountains (at an altitude of 3 660 m (12,000 ft) amsl) in southwestern Colorado.

Across New Mexico, the river flows through plains bordered by the Sangre de Cristo Mountains on the east and by the San Juan and Jiménez Mountains on the west. The river enters Texas near El Paso/Juárez and runs through a dry arid region in its upper reach. In the middle reach, the river is fed by several tributaries. The water is stored in two national reservoirs located in this relatively water abundant stretch. In its last reach, before it discharges into the Gulf of Mexico near Brownsville/Matamoros, the water is used by the bordering communities for irrigation purposes.

The flow in the river is relatively smaller from the mouth to the middle reach. In the latter section the river flow is more substantial from water in Río Conchos which originates from increased precipitation and snowmelt in the Tarahumara Mountains of Chihuahua and Durango in Mexico. Río Conchos has five main tributaries and there are five water storage reservoirs in its basin. Further down, the river flows across the Big Bend, until it reaches Langtry, Texas. The Alamito and Terlinga creeks discharge into the river. The Amistad Reservoir is the first major reservoir on the Rio Grande. The Pecos and Devils rivers also feed into the reservoir. The Pecos river originates in the Sangre de Cristo Mountains in New Mexico. Moving further down the Amistad Reservoir, the river is fed by four Mexican rivers: Río San Diego, Río San Rodrigo, Río Escondido, and Río Las Vacas. The first three rivers originate in the del Burro Mountains in Coahuilla.

Further south, water in the Rio Grande is stored in the Falcon Reservoir, which is the second major reservoir in the basin. The Río Salados, which carries water from the Sabinas, Salados de la Nadadores, Sabinas Hidalgo River, and Cameron Creek discharges into the Rio Grande. A number of rivers also feed the Rio Grande downstream of the Falcon Reservoir.

There are approximately 30 monitored streams flowing into the Rio Grande between the El Paso and Gulf of Mexico reach [*Eaton and Andersen*, 1987]. In addition, there exist several USGS and USDA Soil Climate Analysis Network (SCAN) sites that can be used for model calibration and validation within the basin.

Figure 1. The Rio Grande/Río Bravo Basin
(Source: http://www.tceq.state.tx.us/.../sharedwater.html)

2.1 CLIMATE

The climate of the basin varies along the length of the river. The northern section is characterized by desert with high temperature and low water resources while the south benefits from a tropical climate. The precipitation varies considerably from west to east – around 250 mm (10 in) at El Paso and 580 mm (23 in) near Rio Grande City and Matamoros.

Temperature as well varies across the basin. The temperature increases from the northern portions towards the south. July and August are the warmest months (82 to 92 ^{o}F) while December and January are the coldest months (49 to 60 ^{o}F). The evaporation rate varies considerably, decreasing from west to east of the basin.

2.2 WATER USE IN THE BASIN

The water in the Rio Grande is used by both Mexico and the United States to meet municipal, industrial, mining, livestock, manufacturing, irrigation and electricity production needs. Turner [2000] argues that more water is being diverted from agricultural use to urban use and this trend will continue since population in the region is growing.

Given the shortage in surface water availability El Paso in Texas and Cuidad Juarez in Mexico, are relying heavily on groundwater from the Hueco Bolson as their sole drinking water supply. The population in El Paso-Cuidad Juarez region, for example, has grown from less than 60,000

to over 2 million over the last 100 years and the population is expected to increase to around 6 million in the next 50 years [*Turner*, 2000] thereby putting more pressure on the surface and ground water resources of the region.

2.3 TREATIES AND AGREEMENTS

The water in the basin is shared between the US and Mexico through a set of treaties and agreements. It allows the two governments to construct, operate, and maintain dams in the mail channel of the river. The treaties have been visited on several occasions to address infrastructural needs and water quality concerns. While the treaties and agreements do make provision for the allocation of water in the event of a drought, there is no definition of an "extraordinary drought" or of "climatic changes" and how to identify the onset of such events. Recent droughts coupled with the construction of dams in the subbasin have increased tension between the US and Mexico.

3 THE LAND INFORMATION SYSTEM

The Land Information System (LIS) is an integrated hydrologic modeling and data assimilation framework [*Kumar et al.*, 2008; *Peters-Lidard et al.*, 2007]. It uses various data assimilation tools to constrain and improve the model performance. The platform is currently being used for weather and climate model modeling, flood and water resources forecasting and military mobility assessment among others [*Kumar et al.*, 2008].

LIS evolved from the North American Land Data Assimilation System (NLDAS) and the Global Land Data Assimilation System (GLDAS) [*Mitchell et al.*, 2004; *Rodell et al.*, 2004]. The latter two systems operate at a resolution of $^{1}/_{8}$ and $^{1}/_{4}$ degree respectively, while LIS allows modeling at higher spatial and temporal resolution through a modular framework and high-performance computing design. The main components of LIS include a core that integrates the use of different Land Surface Models (LSM), high computing capabilities, data management, and domain execution [*Kumar et al.*, 2006]. Figure 2 below gives a schematic representation of LIS.

LSMs represent the different components of the hydrologic cycle: precipitation, atmospheric variations, soil-water dynamics, plant physiology and characterizes the mass, energy, and momentum fluxes across the land-atmosphere interface [*Kumar et al.*, 2008]. LIS is capable of operating a number of different LSMs including NOAH, the Community Land Model (CLM), the Variable Infiltration Capacity (VIC) model, the Simplified Simple Biosphere Model, the Catchment model etc. In this work the NOAH model is used to study the Rio Grande watershed.

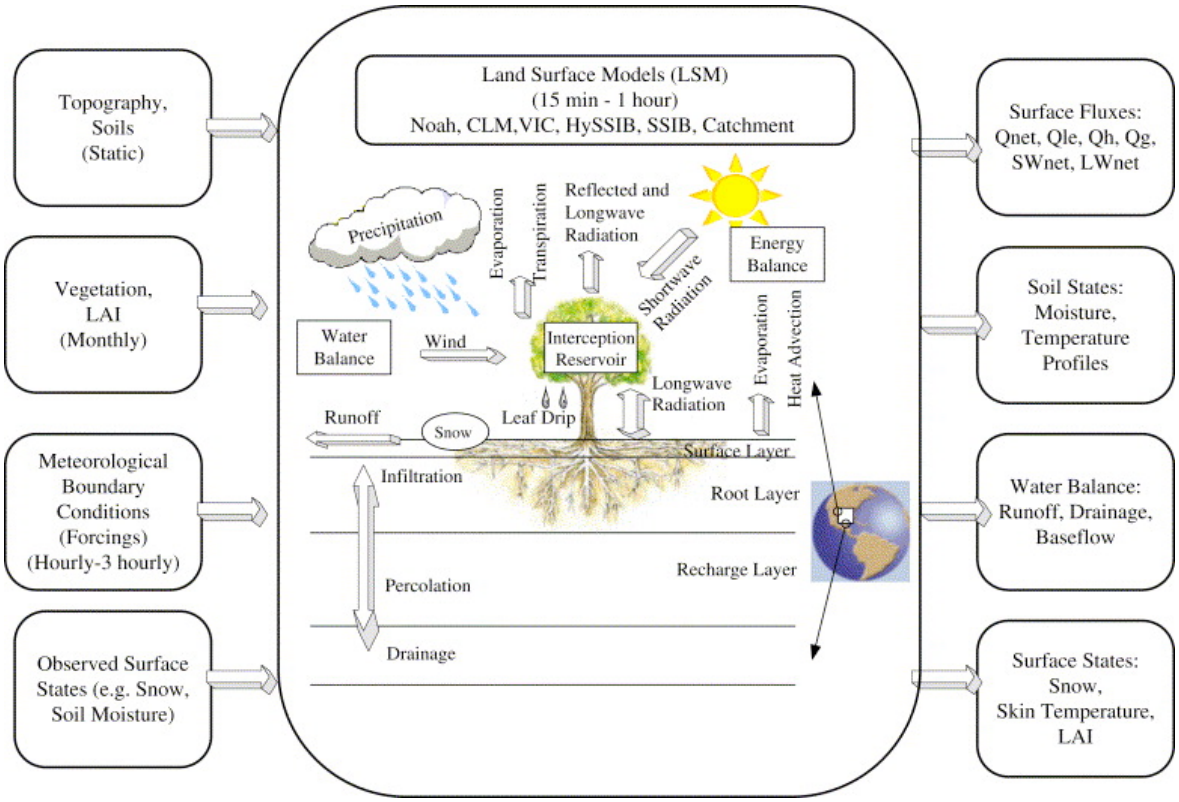

Figure 2. A schematic representation of LIS
(Source: [Kumar et al., 2006])

3.1 THE NOAH MODEL

The community NOAH land surface model [*Chen et al.*, 1996; *Ek et al.*, 2003; *Koren et al.*, 1999] is the product of the joint collaboration between the National Centers for Environmental Protection (NCEP), Oregon State University (Department of Atmospheric Sciences), Air Force (both AFWA and AFRL - formerly AFGL, PL), and the Hydrologic Research Lab (now Office of Hydrologic Development – OHD). We have chosen to apply the NOAH LSM in this work based on results from previous studies demonstrating its ability to accurately model the water and energy budgets in similar climatic zones and land cover [*Lohmann et al.*, 2004; *Luo et al.*, 2003; *Robock et al.*, 2003]. The LSM simulates soil moisture, soil temperature, skin temperature, snowpack depth, snow water equivalent, canopy water content, and energy flux and water flux of the surface energy and water balance [*Mitchell*, 2001]. This LSM builds upon the Oregon State University Planetary Boundary Layer model, developed between 1980 and 1990. The model was compared to a set of LSMs (the simple bucket model, the Simplified Simple Biosphere Model, and the simple water balance model) and was deemed to perform better and was therefore chosen for further refinement and implementation into NCEP's regional and global coupled weather and climate models.

The driver routine of the LSM include reading of the atmospheric forcing data, interpolation of the monthly-mean surface greenness and albedo to Julian day of the time step, assigning downward solar and longwave radiation from the input forcing, calculation of actual and

specific humidity from atmospheric forcing, and assigning wind speed. Further description of the model physics is available in Grunmann [2005].

3.2 NLDAS2

The hydrological cycle is governed by processes occurring in the atmosphere, the land surface and subsurface and their interaction. Thus to hone their predictions, numerical weather prediction (NWP) centers have incorporated land surface schemes into their model. However, it has been found that errors in forcing accumulate in the surface and energy stores leading to incorrect surface water and energy partitioning [*Gottschalck et al.*, 2005; *Oki et al.*, 1999]. The Land Data Assimilation Scheme (LDAS) developed by NASA in collaboration with Princeton University and the University of Washington is not affected by forcing biases as it consists of uncoupled models forced with observations. It synergistically applies Surface Vegetation Atmosphere Transfer Schemes (SVATS) in near real time at $^1/_8$ degree resolution for North America and $^1/_4$ degree globally with LDAS model prediction, satellite data, gauge data, and radar precipitation measurements. The model parameters are derived from existing soil and vegetation maps and assess water and energy balances which are validated with in-situ observations.

The North American Regional Reanalysis (NARR) based NLDAS forcing dataset [*NASA/GSFC*, 2007] has an hourly temporal frequency and is based on the World Meteorological Organization GRIB-1 data format grouped in two files (A and B). The variables from File A as used in this exercise are listed below:

- U wind component (m/s) at 10 meters above the surface
- V wind component (m/s) at 10 meters above the surface
- Air temperature (K) at 2 meters above the surface
- Specific humidity (kg/kg) at 2 meters above the surface
- Surface pressure (Pa)
- Surface downward longwave radiation (W/m^2)
- Surface downward shortwave radiation (W/m^2) – bias corrected
- Precipitation hourly total (kg/m^2)
- Fraction of total precipitation that is convective (no units): from NARR
- CAPE: Convective Available Potential Energy (J/kg): from NARR
- Potential evaporation (kg/m2): from NARR

The land forcing fields, excluding precipitation is from the NCEP North American Regional Reanalysis (NARR). It utilizes a 25 year retrospective analysis (1979-2004) and is updated daily. NARR has a spatial field of 32 km and a temporal resolution of 3 hours. The NARR field is spatially interpolated to produce the $^1/_8$ degree resolution in NLDAS2. The surface pressure, surface downward longwave radiation, near-surface air temperature and nearsurface specific

humidity are adjusted vertically to account for the vertical difference between the NARR and NLDAS fields of terrain height. The precipitation component in File A is from the temporal disaggregation of gauge records. In this study only File A is used in the model. The reader is referred to [*NASA/GSFC*, 2007] for further description of the characteristics of File A and B.

4 METHODOLOGY

The initial calibration of the NOAH hydrologic model for the Rio Grande basin is made using a retrospective run with 30 minute NLDAS2 forcing data for the period January 2002 to June 2009. The latitude and longitude of the center of the lower left and upper right pixel are [25.0625, -108.9375] and [38.9375, -93.0625] respectively. At $^{1}/_{8}$ degree resolution, the domain spans 128 by 112 tiles covering the basin under study and extends across New Mexico and Texas and half of Colorado.

Additional model parameters include seasonal maximum snow free albedo maps, monthly greenness fraction, bottom temperature, and soil texture (sand, clay, and silt). The soil maps are based on Zobler's assessment of FAO Soil Units [*Zobler*, 1986].

The model runs at a time step of 30 minutes and the output files are written for every 3 hours, thereby creating 8 files for each day. The output files were written in GRIB format and GrADS [*Doty*, 1995] was used to visualize, analyze and extract the data for further analysis.

The time period from model start-up to stabilization of the model variables (reflecting expected energy and water dynamics) is referred to as model spin-up. During the spin-up period significant biases are often observed in model outputs while the model variables stabilize from initial conditions. Cosgrove et al. [2003] studied the effect of different model start-up and spin-up states on complex spatial and temporal LSM and concluded that models using NLDAS forcings reach a state of rough equilibrium within 1 to 2 years, thereby concluding that a one year spin up time is retrospective NLDAS simulations eliminate spin-up problems. Therefore, in this study, the output generated for the first year of simulations, i.e., 2002, were not used.

5 PRELIMINARY RESULTS

The NOAH model within LIS generates a series of model outputs. The variables of interest for assessing the water budget include precipitation (which is equivalent to the precipitation from the forcing dataset), runoff, evapotranspiration, and soil moisture. The NOAH model has four soil layers extending from 0 to 10 cm, 10 cm to 40 cm, 40 cm to 100 cm, and 100 cm to 200 cm. The data from all four layers were aggregated to represent the soil moisture component in the model. Since the model was run over a rectangular domain, a mask was created representing the extent of the catchment and values outside the mask were ignored. The data contained in each 3 hourly files were extracted and daily averages of each variable under consideration were computed.

A qualitative analysis of the model runoff estimates was performed by comparing the spatial structure of this output with the observed daily precipitation. A snapshot of precipitation, and runoff on July 14, 2004 is shown in Figure 3 below. It is evident from this figure that the NOAH model gives reasonable estimates of daily runoff based on the daily precipitation map. The spatial structure of the modeled runoff closely resembles the accumulated precipitation for this day, particularly in Southwest Texas. The spatial pattern of the daily runoff seen in Central New Mexico is not as easily explainable. It is possible that the evapotranspiration and/or soil type/land cover type is more complex in this region and leads to dampened runoff signal. This will be investigated further by applying SCAN data from this region.

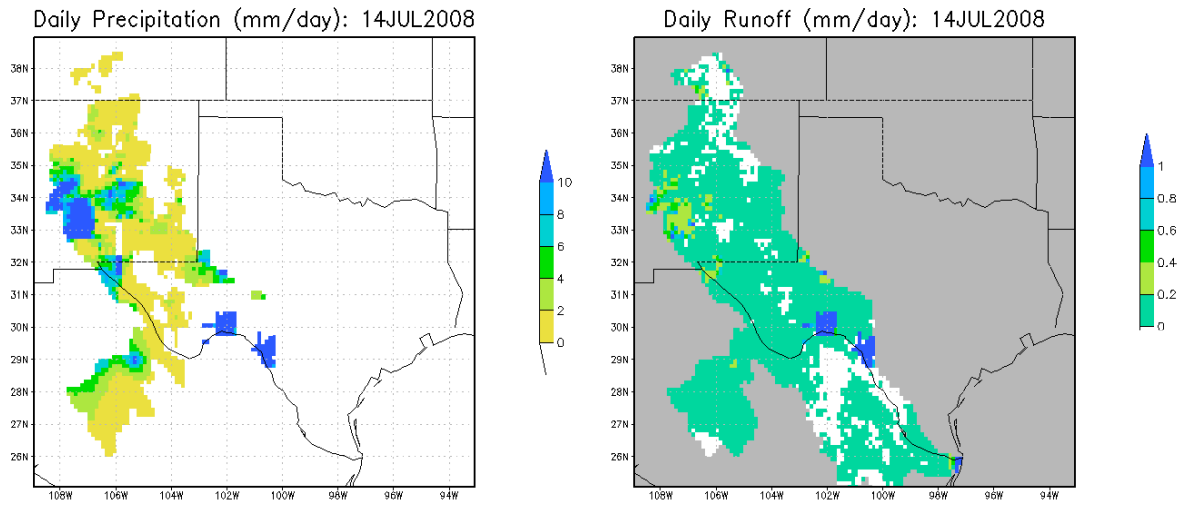

Figure 3. A snapshot of the model run showing daily precipitation and runoff within the catchment

To evaluate the overall performance of the model for the study area, we calculated daily and monthly averages of the precipitations, soil moisture, and runoff from the entire basin from 2003-2009. From these calculations, the water and energy budget components can be partitioned and analyzed by examining their temporal trend and correlation.

Figure 4 below gives a plot of the time series of the average daily precipitation across the whole basin for the entire simulation. The spin-up period of one year is grayed in the chart. The seasonal cycle is clearly visible in the monthly variation. The region experiences a large percentage of its annual rainfall in the summer and autumn. Examination of historical gauge record of rainfall indicates that the wettest months in this region are July, August, and September – the same variation can be seen in the model output.

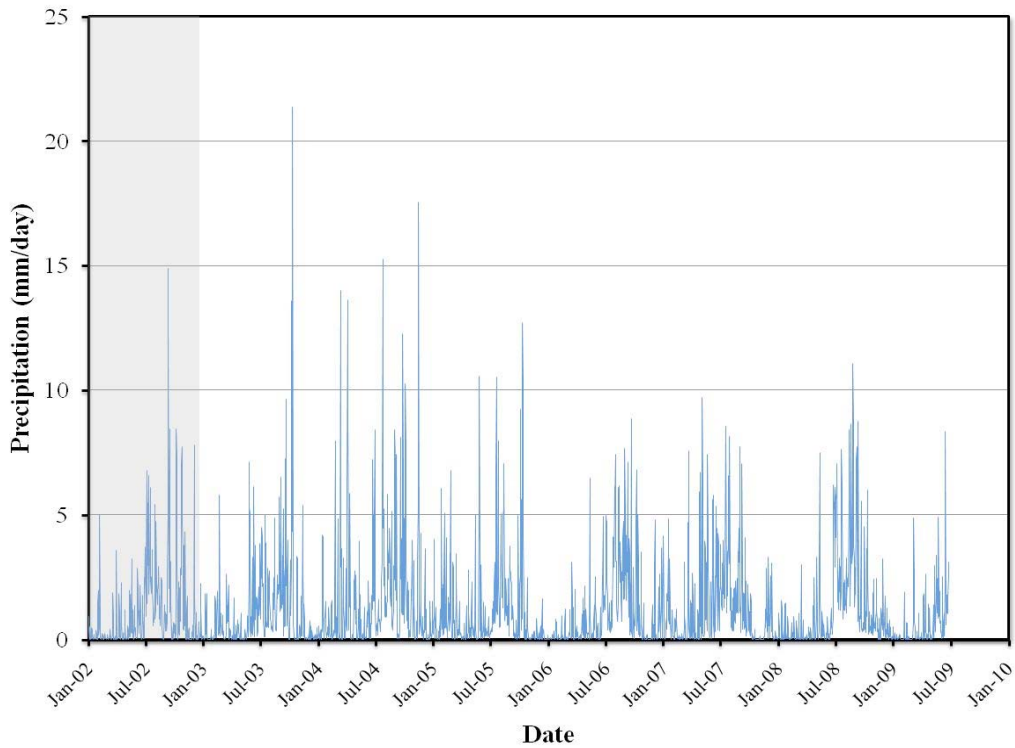

Figure 4. Variation of average daily precipitation for the period 2002 to June 2009
(Spin-up period is grayed)

Figure 5 below give the variation in average daily runoff and evapotranspiration for the duration of the simulation. It can be seen that that the seasonal variation is reflected in time series of both variables. It is important to assess the sensitivity of the model to variation in the forcings and how it is translated into the main hydrological outputs.

Norwine [1995] notes that the variability of rainfall in the South Texas is unusually large for semi arid regions, arguing that this extreme is due to heavy autumnal rainfall associated with tropical storms and hurricanes which may bring between 200-500 mm in 24 hours and can lead to devastating floods in certain areas. These isolated events are not clearly visible in the figures because both precipitation and runoff have been averaged over the whole of the basin. An examination of precipitation over each subcatchment against the time of occurrence of major storm events may help in verifying if the model is able to capture the response to these events. This may also help in the identification of flood prone areas.

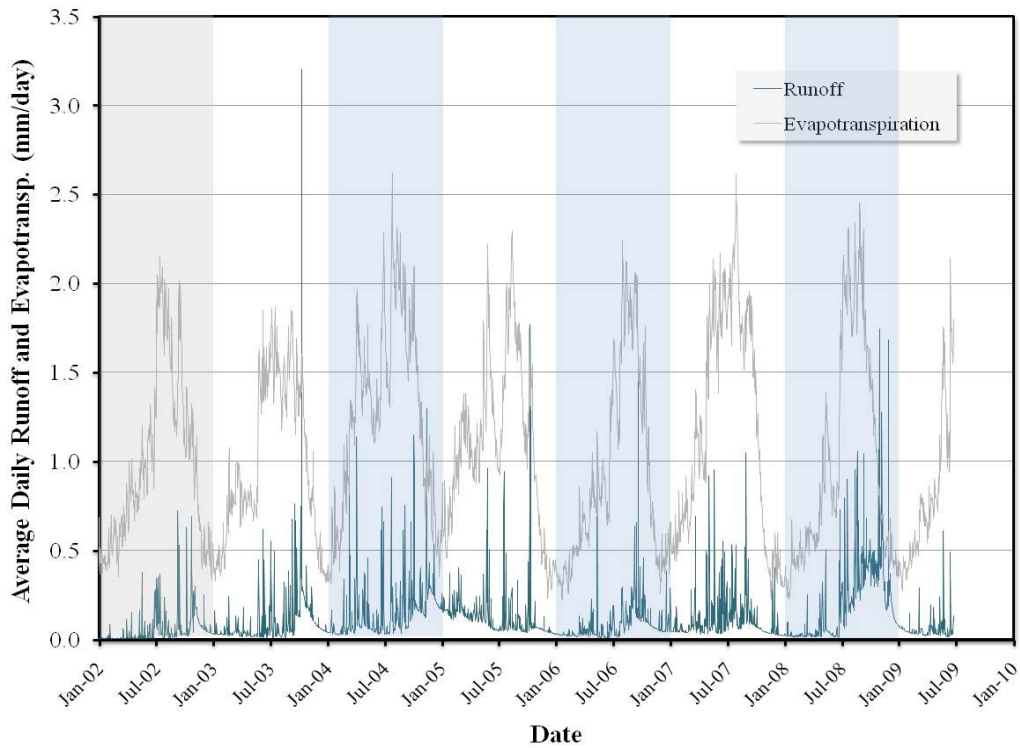

Figure 5. Average daily runoff and evapotranspiration for the period 2002 to June 2009
(Spin-up period is grayed)

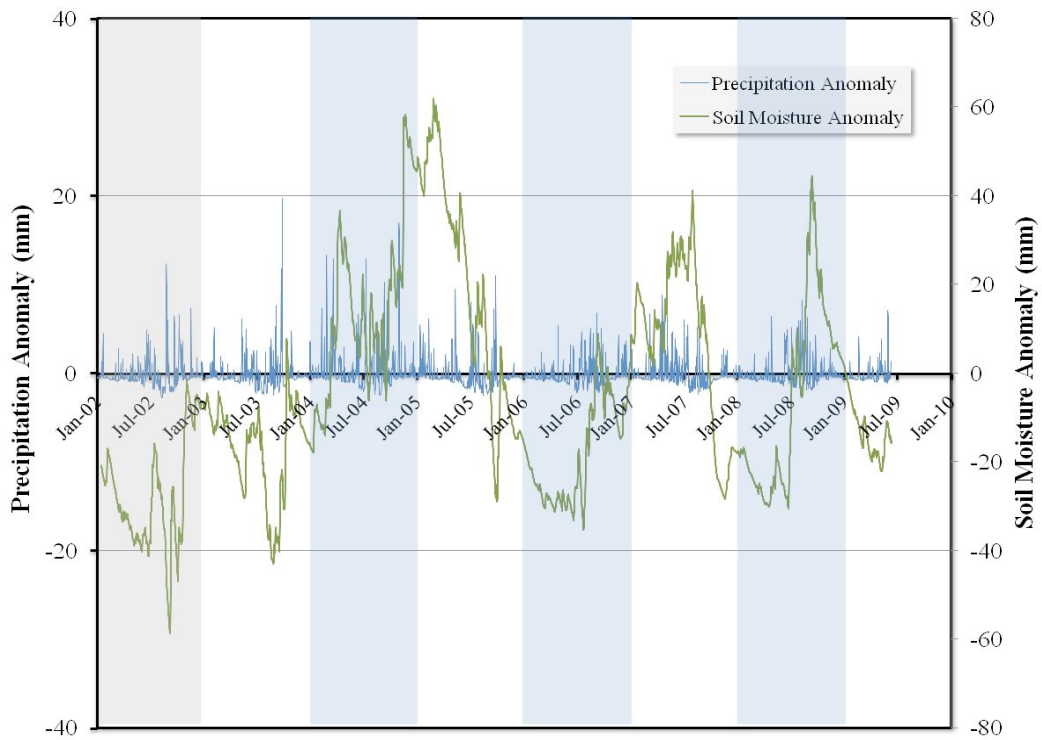

Figure 6. Precipitation and soil moisture anomaly for the period 2002 to June 2009
(Spin-up period is grayed)

Figure 6 above shows the precipitation and soil moisture anomaly for the period of study. The soil moisture represents the total soil moisture in a column extending down to 200 cm (represented by four distinct layers in the model). The anomaly was calculated over the mean for the years 2003 to 2008. Year 2002 was not considered and is grayed in the figure above, to avoid errors due to spin up from trickling through the calculations. The soil moisture for period 2002-03 while generally on a rising trend does not respond instantly to precipitation events. Further investigation of the sensitivity of each soil layer to precipitation may help in explaining this trend.

It can be seen that there is a relatively strong relationship between precipitation events and soil moisture for the period 2004 to 2009. For the period November to March 2005 the soil moisture content is positive but slowly decreases during summer 2006 to become negative. The same pattern can be observed in 2007 whereby the soil moisture anomaly is positive in winter and spring and decreases in the summer of 2007.

5.1 WATER BUDGET

The amplitude of soil moisture, which is measure of the variability of soil moisture, was calculated using the following equation:

$$Amplitude = \frac{\sum_i^n \left((\max SM_i - \min SM_i)/2 \right)}{n}$$

where *SM* is the soil moisture, *i* is the year, and *n* is the number of years over which the amplitude is being calculated. The amplitude for 2003 to 2008 is 42.2 mm/yr. The total average precipitation for the same time period is 450.5 mm/yr. The corresponding evapotranspiration and runoff is 395.9 and 50.0 mm/yr respectively. The delta storage which is average precipitation minus the sum of evapotranspiration and runoff is 4.6 mm/yr. The soil moisture amplitude results indicate a dynamic hydrological system within the basin, which will be ideal for studying the regional impact of climate change on the water and energy cycle. The result from our water budget calculations (a surplus of 4.6 mm/yr) is very promising and indicates that we were able to model the system with a reasonable amount of accuracy.

6 CONCLUSION AND FUTURE WORKS

Through this preliminary study we have shown that the NOAH model can be effectively used for the hydrological modeling of the Rio Grande basin. However, a longer simulation period is required to allow for spin-up and to be able to validate the model outputs with observed data. The NLDAS2 dataset goes back to 1979, thus a 30 years retrospective model can be constructed.

The different input and output variables can be compared to gauged data from different stations within the basin and the model can be calibrated accordingly. A routing scheme can be incorporated either within LIS, or the output can be post-processed in a hydrologic routing

model (e.g. within ArcGIS) and the flow can be compared to stream gauge discharge values. The later will have to be normalized to remove land use land cover changes in the flow. The methodology developed by Wurbs [2006] for naturalizing flows in rivers in Texas can be used. The method is currently implemented in the Water Availability Modeling system used for water management activities in 23 rivers in Texas, including the Rio Grande. The method removes the effect of historical reservoir storage and evaporation, water supply diversion, and return flows from surface and groundwater sources.

The model can be further used for an assessment on the water availability based on the IPCC climate change scenarios and projected trend in demographic change and water demands. The outcome of this modeling exercise can help water managers in both the United States and Mexico in developing a water plan. It can also help policy makers in assessing the viability of the current treaty and in incorporating any change that may be deemed necessary to cater future climatic impacts and adaptation strategies for long term droughts.

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