Southwest Climate Science Center

Annual __ Final _X_ Project Report

(please mark)

1. **USGS GRANT/COOP AGREEMENT _____**

2. **PROJECT TITLE:** Multicriteria Sensitivity Analysis of the Vulnerability of Hydrologic Systems to Climate Variability and Change

3. **PRINCIPAL INVESTIGATOR EMAIL:** tyferre@gmail.com
4. **CO-PRINIPAL INVESTIGATOR EMAIL:** jdickins@usgs.gov

5. **PERSONNEL**
    a. Principal Investigator (Name and institution) Ty Ferré, University of Arizona (UA)
    b. Co-Investigators (Name(s) and institution(s)) Jesse Dickinson, U.S. Geological Survey (USGS); Christopher Castro, UA; Peter Troch, UA
    c. Undergraduate Students (Names and institutions)
    d. Graduate Students – MS or MA (Names and institutions)
    e. Graduate Students – Ph.D. (Names and institutions) Jesse Dickinson, USGS; Matthew Switanek, UA
    f. Postdoctoral Researchers (Name(s) and institution(s))
    g. Other (please specify)

6. **PROJECT START DATE** (10/2012):

7. **EXPECTED COMPLETION DATE** (09/2014):

8. **PURPOSE AND OBJECTIVES:** The objective of our work is to develop a general and transferrable approach to defining how any given hydrologic system will filter climatic forcings. We will develop a framework that can allow for rapid assessment of the vulnerability of hydrologic systems to predicted climate changes of varying complexity, often without the need for site-specific hydrologic models. Our approach will guide site-specific modeling, where appropriate, to focus on those components of predicted climate change that are most likely to persist through the groundwater system. We are focusing on the role of the unsaturated zone in the filtering of climatic forcings. More specifically, we are examining how variations in infiltration are smoothed out with depth in the unsaturated zone and in basin-scale aquifers.

9. **ORGANIZATION AND APPROACH:** Our approach for investigating how hydrologic systems filter climatic forcings uses a combination of statistical analysis of hydrologic time series and numerical and analytical modeling. We have developed a framework for investigating a range of hydrologic systems that are typical in the southwestern U.S. Our approach, however, can be applied to any hydrologic system. Our framework is developed in three parts. The first part uses General Circulation Models (GCMs) to generate historic and future predictions of precipitation in the southwestern U.S. In the second part, we generate hydrologic responses to the atmospheric data using a surface water model and statistically-derived temporal modes of variability from time series data. In the third part of the project we identify which characteristics of the unsaturated zone and basin-scale aquifers control the filtering of the climatic forcings in hydrologic systems.

    In the first part of the project, we used outputs from the GCMs to develop climatic forcings to our hydrologic models. We obtained climate projections from two dynamically-downscaled GCMs

(HadCM3 and MPI-ECHAM5) for the A2 emission scenario for the mid-20th century to the end of the 21st century. We chose these models based on their ability to represent climatic conditions in the southwestern U.S. The meteorological outputs from the climate models were used to develop infiltration patterns and inputs for our hydrologic models.

In the second part of the project, we obtained estimates of recharge variability from the surface-water model VIC (Variable Infiltration Capacity). The VIC model was run for the Verde and San Pedro Watersheds, but the results indicate patterns of recharge variability that likely to be similar to hydrologic systems throughout the Southwest. The recharge outputs from VIC are used to develop hydrologic models that predict potential hydrologic responses in similar systems. We used spectral analysis methods to identify patterns in precipitation that serve as the drivers to our hydrologic models. These spectral methods include Fourier, Maximum Entropy Method, and Singular Spectrum analysis. These methods identify periodic components that explain most of the variability in the original climatic datasets. Our spectral estimates have identified periodic oscillations with periods that range from 1 to 20 years.

In the third part of the project, we used the numerical model HYDRUS and an analytical solution to identify which characteristics of unsaturated zones control the filtering of climatic signals in groundwater recharge. These models are used to examine how the factors of periodicity of climate forcings, the soil properties, and the infiltration flux control the filtering. The ranges of these factors are based on the climatic forcings identified in parts one and two and for typical soil conditions in the southwestern U.S.

10. **RESULTS:** We have developed a comprehensive system for predicting how any periodic climate forcing of infiltration is filtered in the unsaturated zone. Using this system, we developed a screening tool that predicts whether any infiltration forcing can be approximated as either transient or steady recharge to any aquifer system. More specifically, the tool predicts the amount that infiltration variations are damped with depth in the vadose zone—if a variation is sufficiently damped, it can be approximated to result in steady recharge to aquifers. The tool can be used by scientists or water resource managers for creating maps of watersheds that indicate the degree that climate variability affects recharge to aquifers. More specifically, the maps indicate whether recharge is more complex and variable through time, or where recharge it more simple and constant through time. Scientists and water managers have already used the tool to predict if climate variability can affect groundwater resources in aquifers.

    For scientists, the screening tool can simplify the construction of groundwater models. The advantage of having steady state conditions is that the recharge in the model can be a simple function of the average climatic conditions. If the recharge in part of a watershed is identified to be transient, then complex hydroclimatic processes may be required in order to obtain time-varying recharge rates to groundwater models.

    For water managers, climate-controlled recharge can affect the amount of stored water in aquifers. As water resources become more limited, an understanding of how climate variability affects recharge may produce more accurate forecasts of water resources. Resource managers can use our tool to predict if climate variations, such as ENSO, affect the variability of aquifer storage.

11. **NEXT STEPS:** We are completing an analysis of how nonlinear processes in the vadose zone result in unexpected hydrologic responses to cyclical climate variability. We have found that because of the nonlinearity, groundwater flow cycles can differ from those cycles observed in atmospheric climate. We anticipate that another paper with these results will be published in early 2015.

12. **OUTPUTS**

a. Please list any **peer-reviewed publications** that have resulted from this project (full citations). Please include articles in preparation, in review, accepted, or published.

Dickinson, J.E., Ferré, T.P.A., Crompton, B., Bakker, M., (2014), A screening tool for delineating subregions of steady recharge within groundwater models, Vadose Zone Journal, v.13, no. 6, doi:10.2136/vzj2013.10.0184

Dickinson, J.E., Ferré, T.P.A., untitled paper on nonlinearity in groundwater systems, in preparation.

Switanek, M.B., Troch, P.A., Castro, C.L., Chang, H., Matej, Luong, T., Durcik, M., Demaria, E., Hydrologic implications of dynamically downscalled climate projections in the southwestern United States, in preparation.

b. **Non-peer-reviewed publications** (full citations).

none

c. Please list any **conference talks** you have given based on this project (conference title, date, and location).

Dickinson, J.E., T.P.A. Ferré, 2013, Screening tool for delineating subregions of steady recharge within groundwater models, Arizona Hydrological Society Conference, Tucson, AZ, September 20th, 2013.

Dickinson, J.E., T.P.A. Ferré, 2014, Damping of multi-frequency infiltration with depth in the vadose zone, American Geophysical Union Fall Meeting, San Francisco, CA, December 16, 2014.

d. Please list any **data outputs, maps, decision-support or other informational tools** developed as part of this project and provide: 1) a very brief description of the product 2) Internet links if applicable.

We have released a matlab program for predicting the amount of damping of any infiltration cycle in the vadose zone. The program creates nomograms that indicate the amount of damping at different depths in the vadose zone. The nomograms can be created for any combination of soil and infiltration characteristics that are found in real watersheds. Thus, the nomograms can be used to predict if recharge is steady if the soil and infiltration is known. The software is documented in the appendix of our paper:

Dickinson, J.E., Ferré, T.P.A., Crompton, B., Bakker, M., (2014), A screening tool for delineating subregions of steady recharge within groundwater models, Vadose Zone Journal, v.13, no. 6, doi:10.2136/vzj2013.10.0184.

The software can be downloaded from a USGS Arizona Water Science Center webpage: http://az.water.usgs.gov/software/damp.html

In our paper, we also present maps that show the amount of infiltration variability that makes it to the water table. That is, the maps show where recharge can be approximated as steady state, or where it must be treated as transient. Our maps are for the Central Valley aquifer in California, which is under severe drought conditions and water restrictions.

13. **OUTREACH AND ENGAGEMENT:** Describe all project-related outreach opportunities to date.

a. Please list any **presentations, seminars, webinars, or workshops** made to stakeholders, the public at large, or any other group outside the research community.

We presented our tools to water managers and water professionals at the Arizona Hydrological Society meeting:

Dickinson, J.E., T.P.A. Ferré, 2013, Screening tool for delineating subregions of steady recharge within groundwater models, Arizona Hydrological Society Conference, Tucson, AZ, September 20th, 2013.

Dickinson, J.E., R.T Hanson, 2013, Software for assessing the relations between variable climatic and hydrologic time series, Arizona Hydrological Society Conference, Tucson, AZ, September 20th, 2013

b. **Communications with decision-makers**, including their name and agency and the date(s) and frequency of your communications. Information on whether the decision-makers were involved in the design of the project plan or if the research has been tailored to address a specifically stated management need is also helpful.

- We met with wildlife managers at the San Bernardino National Wildlife Refuge September 1st 2014 and the Buenos Aires National Wildlife Refuge on September 2nd, 2014 to describe our results and brainstorm ideas for applications and future collaboration. We presented our results to the Bureau of Land Management in Tucson, AZ on September 29th, 2014. The BLM manages the San Pedro Riparian Conservation Area in the San Pedro watershed and has special interest in the effects of climate on the conservation of the San Pedro River. To ensure that our results were useful for decision makers, the test cases in our project were designed to match the groundwater systems common in the Southwest. That is, results have immediate applicability to the groundwater systems in San Bernardino, Buenos Aires, and the San Pedro basin.

- We presented our results with the Arizona Land and Water Trust (ALWT) on May 29th, 2014. The ALWT identifies and priorities sensitive ecological areas for conservation. They are interested in using our tools to identify where climate could be strongly affecting water resources in these areas.

- Shortly after publishing our paper on the screening tool (Dickinson et al, 2014), we received a letter from water managers in New Jersey that requested a copy of the paper.

- Jesse Dickinson was interviewed by a science journalist Madeline Fisher about the screening tool and propagation of climate forcings in groundwater. Her article was published July 17th, 2014:

  https://www.soils.org/discover-soils/story/new-tool-eases-task-simulating-aquifer-refill

c. Are you aware of any **resource management decisions** that have come out of this project? If so, please provide a brief description.

We are not aware of any projects that have directly used our screening tool, but the concept of climate variability in groundwater systems has resulted in new collaboration with the San Bernardino and Buenos Aires National Wildlife Refuges and the Arizona Land and Water Trust.

14. **OTHER** project impacts, outcomes, or communications not discussed above.

Jesse Dickinson developed a software package, HydroClimATe, which performs the time series and spectral analysis methods used in this project. HydroClimATe was funded by the USGS Office of Groundwater but was developed in parallel with our SWCSC project. The software is freely available from the USGS and runs through a graphical user interface on a windows machine.

http://water.usgs.gov/ogw/hydroclimate/

Dickinson, J.E., Hanson, R.T., and Predmore, S.K., 2014, HydroClimATe -- Hydrologic and climatic analysis toolkit: U.S. Geological Survey Techniques and Methods 4-A9, 49 p.

HydroClimATe is currently being used by groundwater climate researchers and has been used to perform analysis of nationwide effects of climate on groundwater systems.

In 2014, Jesse Dickinson started a new project with the USGS Office of Groundwater to develop a tool for forecasting nationwide groundwater responses to climate indicators. The findings from our SWCSC project have led to the development of this new USGS project.

15. **BUDGET:** Briefly describe the budget, with particular emphasis on changes to the budget that was submitted in the original proposal. Please discuss reasons for substantial budget modifications or why funds have not been spent as expected.

Our budget had very little change from our original proposal. A modification was that Jesse Dickinson carried over $20,000 from FY13 to FY14.

The budget for FY12 was as follows:
A PhD student was funded approximately $22,000 to complete the GCM and runoff modeling for the San Pedro and Verde watersheds.
Ty Ferre was funded approximately $8,000
A PhD student and USGS employee Jesse Dickinson was funded approximately $15,000 to develop the initial groundwater models

The budget for FY13 was as follows:
Ty Ferre was funded ~$12,000
Jesse Dickinson was funded ~$52,000 to perform the hydrologic model runs, sensitivity analyses, and develop the screening tool for identifying areas of steady recharge.

The budget for FY14 was as follows:
Jesse Dickinson was funded $20,000 to perform hydrologic model runs and sensitivity analyses.

Submitted by:

(Project PI name) _____ Ty Ferré _____ **1 /20 /2015**

(Project Co-Principal name(s)) _____Jesse Dickinson_____ **1 /20 /2015**

Reviewed by:

Jonathan T. Overpeck, Award PI (if applicable)
University of Arizona _____ **/ / /14**

Stephen T. Jackson, SWCSC Director, USGS _____ **/ / /14**

Forwarded to USGS: (USGS POC)_____ / / /14