USING RAINFALL-RUNOFF MODELS TO CHARACTERIZE THE FLOW REGIME OF DESERT STREAMS IN THE U.S. SOUTHWEST

By

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TABLE OF CONTENTS

TABLE OF CONTENTS – *Continued*

TABLE OF CONTENTS – *Continued*

LIST OF FIGURES

LIST OF FIGURES – *Continued*

LIST OF TABLES

ABSTRACT

In the southwestern United States, the ephemeral nature of most streams often obscures the importance of the underlying ecohydrological processes that occur within them. The integrity of the riparian vegetation is primarily determined by the hydrologic regime of the adjacent stream channel. Determining the frequency and magnitude of streamflow events is an essential component of any assessment of riparian productivity. Flow permanence and peak flow are two key metrics that have been used to describe the flow regime in dryland environments; however, the lack of observational data collected from ephemeral or intermittent streams makes characterization difficult. The objectives of this study are to 1) develop a methodology for determining flow permanence values based on metrics derived from a continuous rainfall-runoff model, 2) determine peak flows from 2, 10, and 100-year, 1-hour design storms from an event orientated rainfall-runoff model, and 3) use climate projection data to explore flow regime changes in response to increasing temperatures to identify which areas would be most susceptible to climate change. Utilizing the Automated Geospatial Watershed Assessment (AGWA) toolkit to set up and run the Soil and Water Assessment Tool (SWAT) and the Kinematic Runoff and Erosion (KINEROS2) models, I was able to replicate hydrologic conditions and provide estimates for flow permanence and peak flow metrics. SWAT model calibration and validation were possible at two stream gauge locations where acceptable streamflow estimates were obtained at monthly intervals. A comparison between different SWAT precipitation inputs revealed that NEXRAD-MPE yielded as reasonable estimates as rain gauge data, justifying its use in areas where observational data are

limited. Characterizing the hydrology of ephemeral and intermittent stream channels can allow land managers to better assess riparian conditions and may be used to predict response to changes in the hydrologic regime associated with human disturbances. It can also be used to direct land use activities away from ecologically sensitive areas to help preserve ecosystem health and take into consideration some of the environmental concerns associated with future land use and climate change.

1. INTRODUCTION

1.1 Purpose

Conventional stream classifications based on flow attributes and/or channel morphology have primarily been focused on perennial stream networks common to mesic environments (Rosgen, 1994; Montgomery & Buffington, 1997; Puckridge *et al.,* 1998). In arid to semiarid systems, where ephemeral and intermittent streams are the dominant fluvial features, scarce observational data has hindered most attempts to perform similar stream classifications. While ephemeral and intermittent streams perform similar hydrologic and ecologic functions as their perennial counterparts (Levick *et al.,* 2008) they generally are not incorporated in most watershed-based assessments. This research aims to fill that void by developing a stream classification for ephemeral and intermittent streams based on hydrologic characteristics, mainly flow regime attributes, that can easily be related to vegetation attributes and can be used in defining ecohydrological relationships.

1.2 Study objectives

The work described in this paper is just one component of a larger research project working towards an ecohydrological classification of ephemeral and intermittent streams in the southwestern United States. This component of the project focuses primarily on the hydrologic component by characterizing the flow regime of streams based on the timing, duration, frequency, and volume of flows. The primary objectives are to: 1) develop a methodology for determining flow permanence values based on metrics derived from a continuous rainfall-runoff model, 2) determine peak flows from 2, 10, and 100-year, 1-hour design storms from an event orientated rainfall-runoff model, and 3) use climate projection data to explore flow regime changes in response to increasing temperatures to identify which areas would be most susceptible to climate change. The results from these characterizations will be used to create a classification of ephemeral and intermittent streams based on the timing and duration of flows and discharge patterns. Such a classification can be used to make correlations with vegetation characteristics such as canopy height and percent cover that can then be used to model riparian conditions and predict changes under different flow regimes associated with various land cover and climate change scenarios.

2. LITERATURE REVIEW

2.1 Ecohydrology of semiarid riparian areas

Scientists have recently begun to embrace a more interdisciplinary approach to improve our understanding of the links between hydrological, biogeochemical, and ecological processes (Rodriguez-Iturbe, 2000; Newman *et al.,* 2006). As a result, ecohydrology has emerged as a branch of science that explores the interactions between hydrological and ecological processes and their associated feedbacks across both spatial and temporal scales. The study of ecohydrology in arid and semiarid ecosystems is of particular importance due to the lack of water and the tight coupling of hydrological partitioning and ecological dynamics being more evident yet not as clearly understood (Jackson *et al.,* 2009). Ecohydrological research offers a holistic approach to ecosystem studies, but a solid understanding of underlying hydrologic processes must be in place prior to making any attempts to establish relationships.

Soil moisture has been identified as one of the key variables linking climate fluctuations and vegetation dynamics (Rodriguez-Iturbe, 2000). Distinct vegetation patterns have been observed along ephemeral and intermittent streams where greater soil moisture concentrations allow for increased plant biomass or the establishment of more mesic species. These riparian areas are a unique part of the landscape where hydrologic connectivity is maintained throughout the watershed to supply the water and nutrients needed to fuel downstream biogeochemical reactions. Riparian areas are especially important in desert landscapes because of their essential ecological role in providing nutrients, critical habitat, and migration routes for many species of wildlife.

Riparian ecology is controlled largely by local and regional flow patterns determined by the variability in the intensity, timing, and duration of precipitation interacting with terrain, soil texture, and evapotranspiration (Poff *et al.,* 1997). The interaction between a stream's flow regime and riparian communities are largely determined by how precipitation translates into moisture stored in the soil and other components of the water budget expressed in the equation:

$$P = R + ET + S + D$$

Where P = precipitation, R = runoff, ET = evapotranspiration, S = storage in soil, and D = deep aquifer recharge. Below I summarize how each component of the water budget is tied to a stream's flow regime and how they influence riparian vegetation communities.

Arid and semiarid systems are characterized by having a mean annual precipitation that is less than potential evapotranspiration rates (Allison & Hughes, 1983) creating conditions that limit surface water availability. For most streams, flow typically occurs in response to precipitation events resulting in ephemeral streams being the dominant fluvial features of the landscape. An ephemeral stream's flow regime is not influenced by groundwater inflow but is solely tied to the timing and magnitude of precipitation pulses that are in turn driven by seasonal to decadal climatic patterns (Loik *et al.,* 2004). In semiarid regions of the United States the majority of precipitation events are small (0 to <5mm) events with most of the rainfall returning to the atmosphere via evaporation resulting in less water available for plant uptake (Lauenroth & Bradford, 2009). More important are the less frequent, higher intensity summer convection storms that contribute to the local recharge and determine the amount of water available for desert riparian vegetation (Baillie *et al.,* 2007).

Riparian vegetation is influenced by flow regime characteristics such as presence of surface or groundwater flows and high and low flow conditions (Stromberg *et al.,* 2005). The increased biodiversity and ecological function of riparian areas are attributed in part to the dynamic nature of the flow regime's regulation of soil moisture. The width of the riparian zones is largely determined by the size of the stream, the position of the stream within the watershed, the flow regime, and local geomorphology (Naiman *et al.,* 1993). Species richness in riparian zones varies greatly both spatially and temporally along the stream channel (Naiman *et al.,* 1993). The degree to which these vegetation changes occur is primarily regulated by the flow regime (Naiman *et al.,* 1993), which determines how much subsurface moisture travels from the hyporheic and parafluvial zones beneath the active channel to the riparian zone. It is within these areas where the majority of ecohydrological processes occur and where the other components of the water budget determine riparian characteristics (Naiman & Decamps, 1997).

Runoff is typically the smallest component of the water budget in arid and semiarid ecosystems, often accounting for less than 5% of the total annual budget (Wilcox, 2003). In regions of the southwestern United States subject to the North American monsoon, runoff is most often associated with high intensity, summer thunderstorms (Stone *et al.,* 2008). Runoff can also be generated from late summer and fall tropical depressions. In higher elevations where shallow soils and bedrock are common, runoff also occurs with rapid snowmelt and low intensity winter rainfall, enhanced by El Niño conditions (Woolhiser *et al.,* 1993). While topography and soil texture can influence runoff behavior, how it responds once it encounters vegetation is an important determinant of ecohydrological processes. Upland vegetation patches help obstruct runoff leading to sediment deposition and infiltration facilitating their own growth and promoting greater biological activity (Ludwig *et al.,* 2005). Riparian areas perform in a similar manner as upland vegetation patches, but are tied directly to the stream channel where the additional soil moisture supports more vegetation growth and/or can influence the flow regime.

Rates of evapotranspiration vary greatly depending on vegetation type, soil texture, and meteorological conditions. Plants are often organized into different functional groups (i.e. grasses, shrubs, trees) based on similar rooting densities and depths to better understand vegetation response to water fluxes (Jackson *et al.,* 1996). Semiarid riparian areas typically contain assemblages of these functional groups with a wide variety of canopy and rooting structures that can lead to complex interactions between evapotranspiration and soil moisture.

Evaporation in riparian areas occurs both at the vegetation canopy and at soil surfaces. Small precipitation events (<5mm) provide little moisture for vegetation uptake due to most of it being intercepted by the vegetation canopy and returning to the atmosphere via evaporation (Owens *et al.,* 2006). The amount that is lost from the canopy is controlled mainly by leaf area of the vegetation and referred to as interception loss. Evaporation from the soil surface is typically limited to the top 15cm (Wilcox, 2003).

With larger intensity or longer duration storms, precipitation will exceed the storage potential of the canopy and reach the surface as throughfall or stemflow. Beneath the canopy of trees and large shrubs where shading from solar radiation regulates temperature and the accumulation of organic debris promotes infiltration, exists a microclimate that facilitates the establishment of understory shrubs and grasses. This is often reflected in riparian areas with a shrub or tree overstory contributing to the establishment of a grass understory (Scholes & Archer, 1997).

Water that is not lost to evaporation can infiltrate to deeper soil horizons where it becomes available for plant uptake and is used to cycle nutrients throughout the plant until it is eventually transpired through their stomata as water vapor. The amount of transpiration that takes place in riparian areas is related to the vegetation type and size with larger species having higher levels of transpiration compared to smaller sizes of the same species (Tong *et al.,* 2008). The ratios of transpiration/evapotranspiration and evaporation/evapotranspiration have been shown to be highly regulated by precipitation seasonality with evaporation being the main component of evapotranspiration when small infrequent rain events occur, but later shifts to transpiration becoming the main component when precipitation events are more frequent and/or of greater intensity (Cavanaugh *et al.,* 2011).

When a tree is not transpiring it has the unique ability to transfer moisture from wet to dry areas of the soil via its root system. This important mechanism, known as hydraulic redistribution, influences both carbon and nutrient fluxes and can impact vegetation composition and structure. Sap flow measurements in *Prosopis velutina*

Woot. (velvet mesquite) showed that significant amounts of soil water were redistributed both via hydraulic lift during the growing season and via hydraulic descent during winter dormancy (Hultine *et al.,* 2004; Scott *et al.,* 2008). Certain understory species (shrubs and grasses) may also benefit from overstory tree species delivering moisture from deep to shallow soil layers via hydraulic lift (Zou *et al.,* 2005). In riparian areas the results of such water movement can have considerable influence on the soil water budget through increases in transpiration or decreases in groundwater recharge and is an important consideration for any ecohydrological assessments.

The volume of flow in alluvium-dominant ephemeral channels tend to decrease as it travels downstream due to in channel infiltration of water, referred to as transmission loss, which can serve as the principal contribution to deep aquifer recharge (Lane, 1983; Goodrich *et al.,* 2004). Channel soil properties (e.g. soil texture, structure, antecedent soil moisture) determine infiltration rate and control if water will make it beyond the rooting depth of riparian vegetation to eventually recharge the deepwater aquifer. Recent hydrologic models suggest that for most arid to semiarid interdrainage areas, no deep drainage has occurred since the onset of the Holocene some 10,000 - 15,000 years ago (Seyfried *et al.,* 2005). Therefore, it can be inferred that most deep drainage occurs at or near ephemeral channels, which would be partially regulated by transpiration of riparian vegetation (Goodrich *et al.,* 2004).

Some riparian species are able to facilitate their own establishment and growth by modifying the rate of hydrological processes through changes in roughness, albedo, and soil moisture beneath their canopy thereby promoting seedling establishment and plant growth (D'odorico *et al.,* 2010). These interactions between biotic and hydrologic processes result in a positive feedback that can influence riparian vegetation composition and structure. Biological feedbacks are complex processes that have tremendous impacts on hydrologic and vegetation interactions from individual stream reach to watershed scales and being able to explain how they relate to ecohydrological processes poses one of the greatest challenges to ecohydrologists today.

2.2 Flow permanence

Quantifying the relationship between flow regime and stream ecology in dryland ecosystems requires a measurement that captures the stochastic nature of flow pulses and accurately describes hydrologic connectivity throughout the stream. Flow permanence offers this by determining the degree of stream intermittency by quantifying the amount of time in a given period that flow is present in the channel (Leenhouts *et al.,* 2006). Aside from providing soil moisture for transpiration, flow pulses are responsible for initiating biogeochemical processes by stimulating microbial activity, cycling nutrients and organic matter, and transporting these resources to downstream areas where they are available to the adjacent riparian zone (Larned *et al.,* 2010). In effect, riparian areas exposed to longer periods of flow duration, or higher values of flow permanence, will be expected to have noticeable patterns, such as greater vegetation biomass and height compared to interdrainage vegetation. A stream classification based on flow permanence can be used as a key indicator of the frequency in which soil moisture becomes available for riparian vegetation uptake and can be used to assign different levels of ecological importance among various stream reaches.

Several studies exist that have looked at the importance of the relationship between flow permanence and vegetation or aquatic species attributes. Hupp (2000) showed that for low-gradient coastal rivers a similar metric known as the hydroperiod, or the annual period of inundation, controls riparian vegetation distribution and is useful for assessing plant ecological patterns. Stromberg *et al.* (2005) showed that in a semiarid environment stream flow and soil moisture are positively associated with plant species richness suggesting that flow permanence could be used in ephemeral and intermittent streams as a possible indicator of riparian species composition. Arscott *et al.* (2010) analyzed benthic invertebrates species richness across a longitudinal intermittence gradient of an alluvium stream in New Zealand and found that 1.9 taxa/m^2 were added per 10% increase in flow permanence.

2.3 Peak flows

Large flood events that are common to ephemeral and intermittent streams are responsible for much of the changes in channel morphology and can have considerable influence on riparian plant species (Friedman & Lee, 2002). Peak flow represents the highest point of discharge on a hydrograph and is a useful metric for describing the magnitude of large flood events (Pitlick, 1994; Osterkamp & Friedman, 2000). It is also often used to assess the hydrologic response of a watershed to a particular storm event and can be used as a measurement of watershed condition (Hernandez *et al.,* 2000). Peak flow estimates are possible using a rainfall-runoff model driven by design storms generated from precipitation frequency maps. These estimates can provide evidence of areas within a watershed that may experience large alterations in channel morphology and/or high loads of sediment transport (Friedman & Lee, 2002). These areas can then be considered in directing site or road development to more stable locations or used to justify culvert construction for existing roadways.

2.4 Rainfall-runoff models

Hydrologic models that measure rainfall-runoff relationships are often utilized to determine streamflow characteristics to address water resource problems in ungauged watersheds (Gassman *et al.,* 2007). Rainfall-runoff models calculate stream discharge by employing mathematical equations that partition rainfall into each of the hydrologic components based on the interactions with various watershed characteristics including topography, soil type, and vegetation cover (Arnold *et al.,* 1998). The output from these models can be used to assess the impact of management and climate on water supplies (Arnold & Fohrer, 2005). Rainfall-runoff models are useful for determining flow permanence because they operate at a daily time-step (Arnold *et al.,* 1998); the smallest practical unit of time used to determine the percent of time when flow is present in a stream reach.

One major challenge in determining flow permanence is the lack of observed data in ephemeral and intermittent channels; however, new methods that use hydrologic models to simulate flow regimes have begun to emerge. Kirkby *et al.* (2011) used a hydrological model to dynamically partition precipitation to estimate how much water was available for evapotranspiration and how much was left for runoff to determine when critical low-flow stages were present in semiarid rivers across Europe. Gallart *et al.* (2012) used rainfall-runoff simulations to develop flow-permanence and seasonal predictability of zero flow period metrics that were used to classify ephemeral streams into distinct aquatic regimes.

Hydrologic models have also shown to be useful in determining additional streamflow metrics such as runoff depth and peak discharge. Hernandez *et al.* (2000) used two rainfall-runoff models to assess watershed condition by measuring runoff response to land cover change. Wollmuth & Eheart (2000) used a rainfall-runoff model to calculate discharge volumes so that they could distribute water allocations to meet both irrigation demand and environmental flows necessary to sustain riparian vegetation. Both of these studies indicate that with the absence of measured data, model simulated results can be used as a substitute, though some discretion must be used in the quantitative results of such efforts depending on whether model calibration and validation are possible.

2.5 NEXRAD data

The reliability of rainfall-runoff modeling results can vary depending on the level of detail of the precipitation data used as input into the model. The relatively few and remote location of rain gauges located in the southwestern United States and the highly variable nature of rainfall has led many modelers to look for alternative sources of precipitation data that better captures the spatial variability of non-uniform events. Consequently, Next Generation Weather Radar (NEXRAD) data has emerged as a viable option to improving modeled flow results. For instance, Moon *et al.* (2004) reported that NEXRAD was useful for capturing localized rainfall events in a large watershed in the Trinity River Basin in Texas and performed well in modeling streamflow. Wang *et al.* (2008) compared the performance of rain gage corrected NEXRAD Stage III dataset to the rain gage and satellite corrected NEXRAD Multisensor Precipitation Estimation (NEXRAD-MPE) dataset using a high-density rain gauge network in the Upper Guadalupe River Basin of the Texas Hill Country and found that both datasets were better at detecting non-uniform precipitation events than rain gages alone, but that Stage III data tended to overestimate (20%) and MPE tended to underestimate (7%) precipitation values. Tobin and Bennett (2009) report that runoff model results using NEXRAD Stage III data outperformed rain gauge data (standard error +/- 13%) in two watersheds in the Middle Rio Grande at a monthly time scale.

2.6 Climate projections for the Southwest

The Intergovernmental Panel on Climate Change Working Group II's Contribution to the Fourth Assessment Report (Parry, 2007) describes how global climate change is influencing regional weather patterns that may be resulting in changes to local precipitation patterns. Such changes have the potential to negatively impact many terrestrial systems leading to declines in biodiversity and ecosystem goods and services (Parry, 2007). Understanding how climate change will affect the Southwest is key to any adaptation plans and is slowly becoming possible using spatially and temporally downscaled global climate data projections (Meehl *et al.,* 2007; Seager *et al.,* 2007). Meehl *et al.* (2007) used the combined results from 25 climate models that successfully explained past global climate changes to predict that a warming of 1.8-3.4°C is expected by the year 2100. Seager *et al.* (2007) reported that the multi-model mean from 19 climate models showed a transition to more arid conditions in the Southwest is expected in the late 21st century and should already be under way. A study by Cayan *et al.* (2010) used downscaled global climate data to predict a 2-4°C increase in temperature and a decrease in precipitation by the end of the 21st century would lead to more extreme drought conditions in the Southwest.

3. METHODOLOGY

3.1 SERDP

The core of this research is funded by the Department of Defense's Strategic Environmental Research and Development Program (SERDP), which provided access to study areas at four military installations in the Southwest. These sites were chosen because they represent the main desert ecoregions (Chihuahuan, Sonoran and Mojave Deserts; Figure 1) and the natural variations in climatic conditions and precipitation (Figure 2) that naturally occur across the Southwest.

3.2 Study sites

Fort Irwin is a National Training Center located in the High Mojave Desert of Southern California. It covers approximately 1,180 mi^2 (3,056 km^2) and averages 4.33 inches (110 mm) of precipitation per year (NOAA's National Climatic Data Center [NCDC], http://www.ncdc.noaa.gov/). It is the only installation included in this study that is not influenced by the North America monsoon and receives most of its rainfall during the winter season (NOAA NCDC, http://www.ncdc.noaa.gov/). Yuma Proving Ground (YPG) is used mainly as a military equipment-testing center located in the Sonoran Desert of southwestern Arizona. It has an area of approximately 1,300 mi^2 (3,367 km^2) and is located in one of the driest parts of the United States receiving an average annual precipitation of only 3.65 inches (92.7 mm; NOAA NCDC, http://www.ncdc.noaa.gov/). Fort Huachuca serves mainly as a communication center with minimal outdoor training activity and is located in the Sonoran-Chihuahuan transition zone in southeastern Arizona. Its eastern boundary runs adjacent to the town of Sierra Vista and includes parts of the Huachuca Mountains to its west, where the only perennial streams included in this study are found. It is the smallest of the four study areas covering approximately 127 mi^2 (329 km^2), but receives the most precipitation with an annual average of 15.6 inches (381 mm; NOAA NCDC, http://www.ncdc.noaa.gov/). Fort Bliss is an army post located in the Chihuahuan desert in southwestern New Mexico. It is the largest of the study areas at approximately 1,740 mi^2 (4,506 km^2) and receives an average of 8.66 inches (220 mm) of precipitation per year (NOAA NCDC, http://www.ncdc.noaa.gov/).

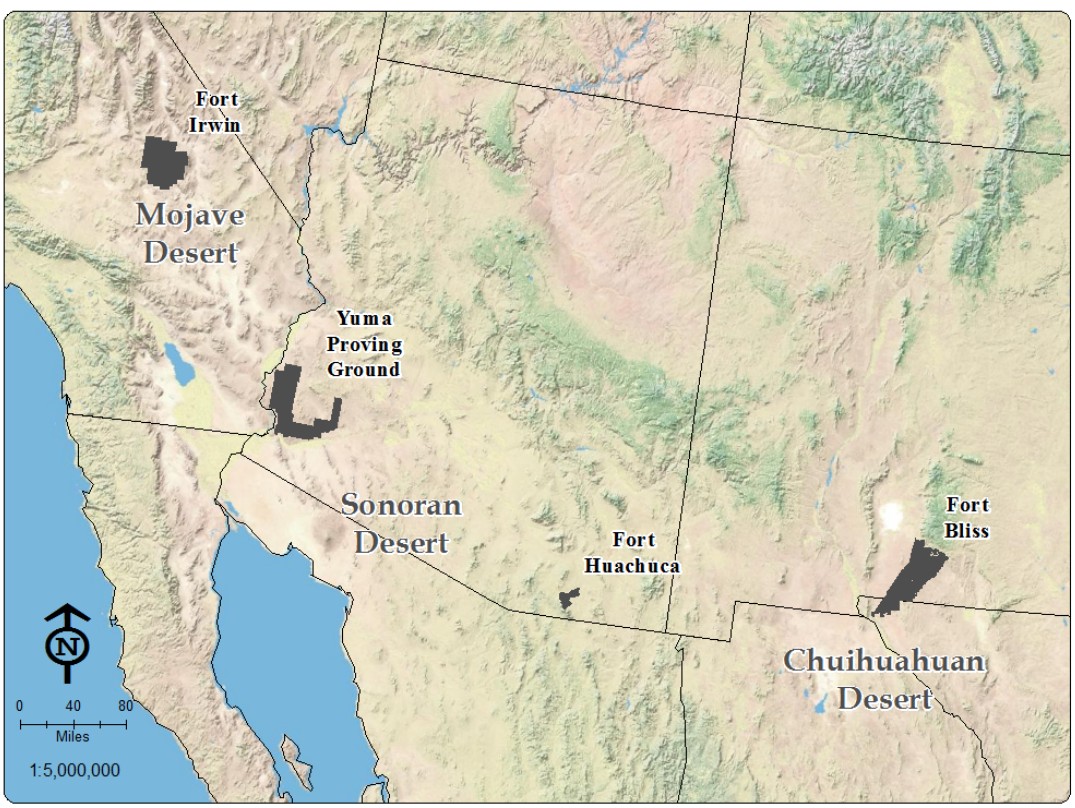


Figure 1. Location of the four military installations used as research sites for the SERDP project.

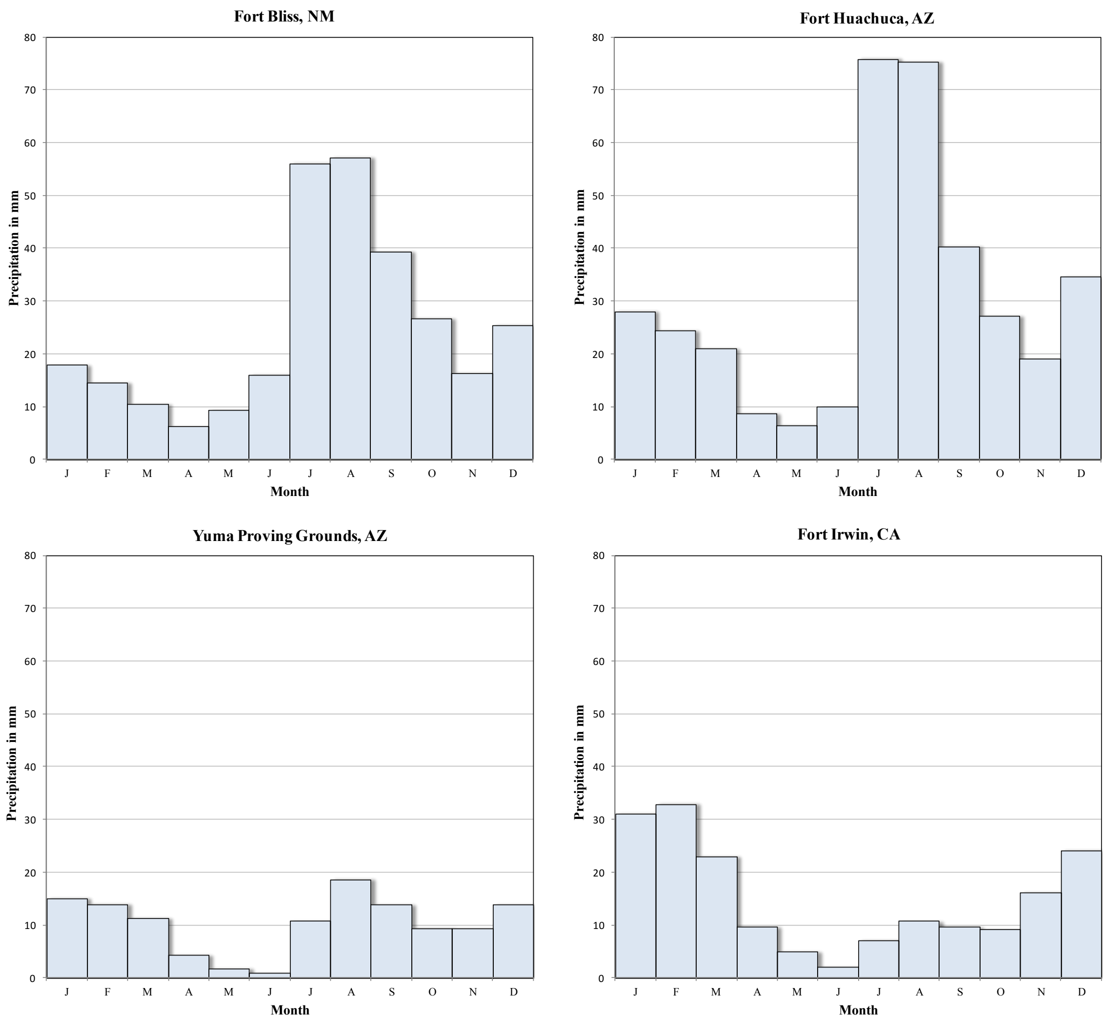


Figure 2. National Climatic Data Center (NOAA NCDC, www.ncdc.noaa.gov) average monthly precipitation records from 1960-2012 at Fort Bliss, NM; Fort Huachuca, AZ; Yuma Proving Grounds, AZ; and Fort Irwin, CA.

3.3 AGWA description

The Automated Geospatial Watershed Assessment (AGWA) toolkit was chosen for this study because of its consideration of each of the hydrologic components of the water budget within each of the two separate runoff models. An added benefit of using two separate models is that it allows the evaluation of the flow regime at different temporal scales permitting a wider analysis from varying perspectives. The first model uses long-term data to provide daily measurements that are used to calculate flow permanence, or the average annual time period when flow is present in the channel, while the second model uses event-specific rainfall depth to determine peak discharge values. Combined these metrics can be used to develop different classes of stream types that can be used to establish relationships with different riparian attributes.

AGWA Version 2.0 is an open source toolkit that automates the tasks of assigning topographical, soil, and landcover parameters to watershed units in preparation for running a pair of hydrologic models (Miller *et al.,* 2007). AGWA is embedded in common geographic information system (ESRI ArcGIS) software where watershed boundaries are delineated and subdivided then overlain with spatial data to obtain the necessary information needed to run the models. At the core of AGWA are two distributed hydrologic models that allow for watershed assessment across spatial and temporal scales. The Soil and Water Assessment Tool (SWAT) is a continuous simulation model that was designed for predicting watershed response to land management practices for large basins over large periods of time (Arnold *et al.,* 1998). It uses a modified Curve Number methodology to partition rainfall into infiltration and overland flow and reports water and sediment yields on a daily time-step, monthly, or annual time-step (Miller *et al.,* 2007). The Kinematic Runoff and Erosion model (KINEROS2) is an event specific model that details the processes of interception, infiltration, surface runoff, and erosion from small watersheds (Woolhiser *et al.,* 1990; Goodrich *et al.,* 2012). AGWA is designed to lead the user through the process to parameterize and execute the chosen model and display the results for visual analysis and change detection in response to landscape alterations (Miller *et al.,* 2002a; Figure 3).

AGWA was developed jointly by the USDA Agricultural Research Service (ARS) Southwest Watershed Research Center branch, the United States EPA Office of Research and Development, and the University of Arizona (Miller *et al.,* 2007). The tool has been used to demonstrate hydrological impacts from decadal-scale landcover change, estimate post-fire impacts on runoff and sediment transport, and assess the potential impacts of rangeland management actions on soil erosion and sediment yields (Miller *et al.,* 2002b; Canfield *et al.,* 2005; Goodrich *et al.,* 2011). Recent improvements include a landcover modification tool that allows users to modify the landcover input layer to determine the hydrologic effects associated with changes from fire, urbanization, climate change or other natural or anthropogenic disturbances (Burns *et al.,* 2007). AGWA is under constant development to improve performance and incorporate additional features and planned additions include the representation and modeling of fire and drought; parameterization procedures based on Ecological Site Descriptions and State-and-Transition Models; tools to modify water locations, fences, and buffers; an economic analysis toolkit; and a web-based version of AGWA (Goodrich *et al.,* 2011).

AGWA is primarily designed to provide qualitative estimates of runoff and erosion useful for assessing relative change between simulation results or between the different subunits within the larger watershed; however with proper calibration, it can provide quantitative estimates as well (Miller *et al.,* 2002a). In this study, AGWA was used to characterize the flow regime of ephemeral, intermittent, and perennial stream channels in unmonitored basins within semiarid to arid parts of the southwestern United States. SWAT was used to determine historical and projected average annual flow permanence based on over a decade of observed rainfall data as well as downscaled climate projection data from a representative global circulation model. KINEROS2 was used to estimate peak flows based on 2, 10, and 100-year, 1-hour design storms created from the National Oceanic and Atmospheric Administration's (NOAA) Atlas 14 point precipitation frequency estimates (NOAA Precipitation Frequency Data Server, 2012).

Prior to running the models several data layers and climate data were collected including, topography (http://viewer.nationalmap.gov), soil (http://soildatamart.nrcs.usda.gov), land cover (http://gapanalysis.usgs.gov/), and daily precipitation and temperature (http://www.ncdc.noaa.gov) values. Since the reliability of the modeling results will depend highly on the quality of the input data, a thorough examination of each data layer is included describing the potential benefits and limitations of each.

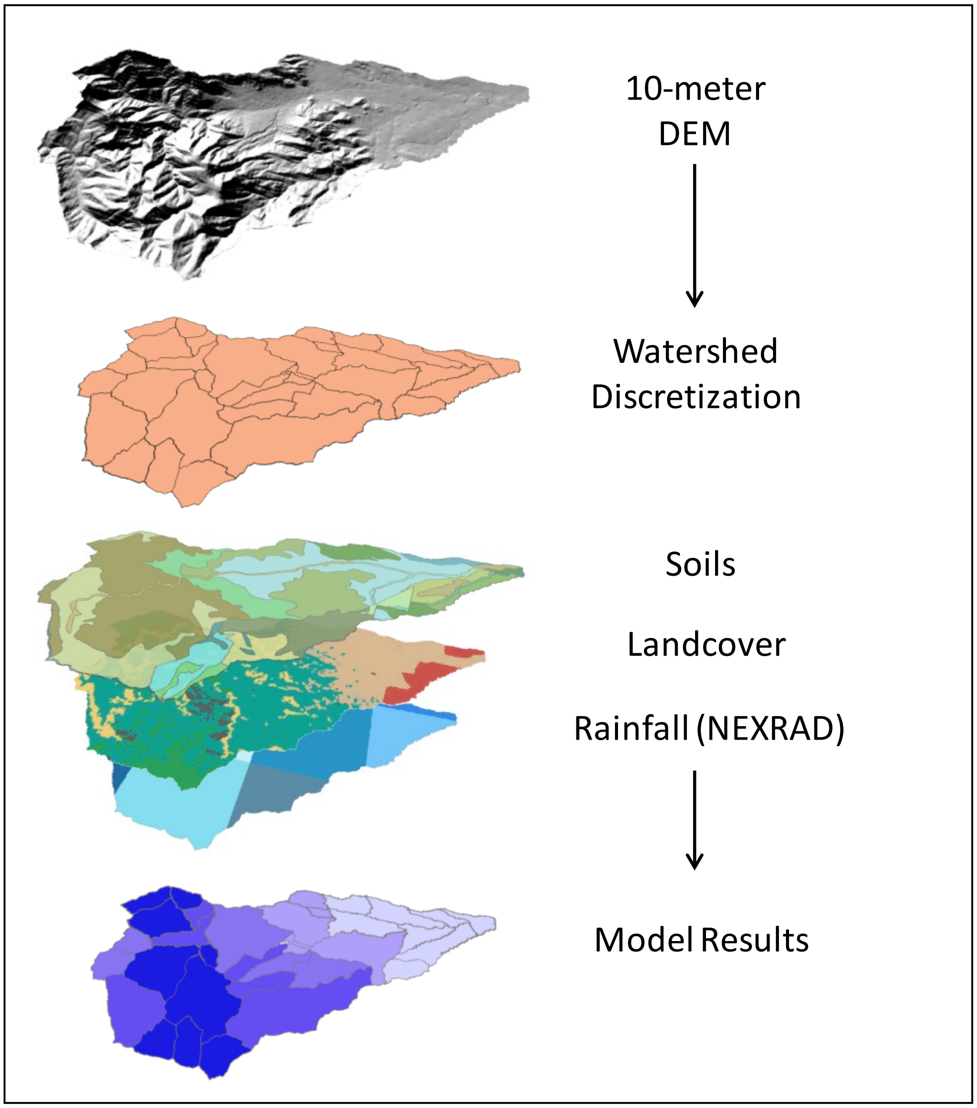


Figure 3. Diagram of AGWA workflow.

3.4 Watershed delineation and discretization

A tiled mosaic of Digital Elevation Model (DEM) raster data layers was necessary to delineate watershed boundaries and determine the flow routes needed to run the models. The United States Geological Survey (USGS) provides bare earth DEM data from the National Elevation Dataset (NED) of 1/3 arc-second (approximately 10-meter) resolution for the contiguous United States that has been corrected to remove artifacts, match edges, and account for missing data (Gesch *et al.,* 2002). The 10-meter DEM data was deemed appropriate for use in this project as it captures the level of detail necessary to determine stream pathways, though some variance is expected, especially in areas of low relief. AGWA allows users to fill DEMs in order to remove any erroneous values (sinks). Then it is used to create a flow directional grid, a flow accumulation grid, and stream representation layer.

The size and shape of each watershed boundary was determined by the location of the watershed outlets that were chosen by overlaying the installation boundaries over the stream map. Some personal expertise was required in determining outlet locations due to the predominantly linear boundaries of the study areas not corresponding with the natural flow pathways and large parts of some watersheds being located outside the study areas. This resulted in two different classes of watershed sizes. The first class represents areas that are completely contained within the study area's borders and whose outlet location was based as close as possible on the USGS's Watershed Boundary Dataset for 12-Digit Hydrologic Units (HUC12). The second class is considerably smaller due to only a small portion of a watershed being located within the study area. The focus of the work is on the larger watersheds that predominantly lie within the study boundaries but may also incorporate some portions of the surrounding watersheds.

Upon delineation of the watershed boundary the user decides which model will be used before proceeding to discretize the watershed into the smaller subwatersheds, referred to as hydrologic response units (HRUs) within SWAT and planes within KINEROS2, due to each model having a different method for routing flow through the steam channels. SWAT uses a command structure to route runoff through the watershed by computing surface runoff and infiltration for each HRU before adding the runoff to each downstream stream segment (Arnold & Fohrer, 2005). KINEROS2 conceptualize subwatersheds into rectangular overland planes and then routes flow to the channel from planes on either or both sides of the channel before routing it to the next downstream channel segment (Woolhiser *et al.,* 1990). It is during the discretization that the user decides on the size of the individual HRUs or planes and their associated stream segments by defining the contributing source area (CSA), which is adjusted to reflect the level of model complexity desired (Goodrich *et al.*, 2011). For this study the CSA was set to a flow accumulation area of 10,000 m^2, which was deemed an appropriate scale needed to meet the project's objectives.

3.5 Soil and land cover parameterization

The next step was to intersect soil and landcover data to each model element polygon and its associated stream segment. The soil databases used in this study include the Soil Survey Geographic (SSURGO) and the State Soil Geographic (STATSGO) databases, both created and maintained by the USDA's Natural Resource Conservation Service (Soil Survey Staff [SSS] Natural Resources Conservation Service [NRCS], 2011). The SSURGO dataset comes from digitized county-level maps that were created following standardized field methodologies and vary spatially from 1:12,000 to 1:63,360 (SSS NRCS, 2012). The STATSGO dataset is a coarser version of the soil survey maps, generalized to a scale of 1:250,000 to be more appropriate for state and regional uses (SSS NRCS, 2011). Comparing the differences between modeled runoff results in a more temperate area of the United States has shown that SSURGO-based results tend to be closer to observed values, whereas STATSGO-based results tend to underestimate runoff (Mednick, 2010). However, STATSGO has also been observed to be more accurate than SSURGO in some uncalibrated runs, although both were found to be within reasonable ranges (Geza & McCray, 2008). Evaluating which soil database will prove to be the more accurate for areas covered in this study was not part of the original scope of this project and remains to be explored. Due to its availability at the time of the study, the finer resolution the SSURGO database was used at Fort Huachuca and most of Fort Bliss and Fort Irwin and the STATSGO was used at Yuma Proving Grounds and where SSURGO data was unavailable.

Land cover information on vegetation and land use patterns was acquired from the USGS's Gap Analysis Program (GAP) National Land Cover dataset (USGS National Gap Analysis Program, 2012). The GAP land cover data combines data generated by regional GAP projects with LANDFIRE data to provide information on the distribution of native vegetative types, modified and introduced vegetation, developed areas, and agricultural areas in a seamless coverage for the entire Unite States (USGS GAP, 2012). The southwest portion of the dataset was derived through the classification of 30-meter, multi-seasonal Landsat Enhanced Thematic Mapper Plus (ETM+) satellite images that were acquired between 1999-2001 (Lowry *et al.,* 2007). The imagery was classified into 590 land use classes following the NatureServe's Terrestrial Ecological Systems Classification framework for natural and semi-natural land cover (Comer *et al.,* 2003). Training data were used to validate the classification based on field work samples, aerial photography, digital orthophotoquads, or other remotely sensed imagery and agreement between the validation samples and map ranged in accuracy from 50-70% for the entire Southwest region (Lowry *et al.,* 2007). The GAP land cover data are available online and was downloaded for the 'Desert' Landscape Conservation Cooperative region from the GAP land cover data portal (USGS GAP, 2012).

In AGWA the vegetation type, interception, Manning's N, percent impervious, and curve number values based on the hydrologic soil group (A, B, C, and D) are all obtained from the land cover layer using a land cover data look up table that is included within the AGWA2 data package (Burns *et al.,* 2007). These values were determined for each of the vegetation classes from expert opinion and previously published look-up tables (Miller *et al.,* 2002a). The original table included with AGWA, however, covers only parts of the Southwest and excluded some of the ecological classes in Southern California needed for this study. As a result, a new lookup table was created that incorporated these missing classes by assigning values from similar classes based on their physical description.

3.6 Precipitation input

Following the assignment of soil and landcover data to each HRU, the next step in running AGWA is to prepare the precipitation input data for the desired model. Accurate representation of precipitation events requires a high degree of spatial coverage and both rain gage and radar data were explored to assess which could most accurately simulate real world conditions. The representation of rainfall from rain gauge observations varied at each site depending on the number of gauges found in close proximity to the military installations. The finer resolution NEXRAD-MPE data were also used at all four installations to supplement for some of the areas with limited rain gage coverage.

SWAT precipitation input requires a table of daily precipitation (mm) values arranged chronologically by year and Julian calendar day that are associated with each rain gauge location. For multiple gauges, AGWA uses a built in tool that distributes the values using Thiessen polygons to compute the weighted rainfall depth falling on each subwatershed (Miller *et al.,* 2007). The daily climate data needed to run SWAT was obtained from the NOAA National Climatic Data Center's (NCDC) Global Historical Climatology Network (GHCN) Daily, Version 2 dataset accessed via the online interactive map application (NOAA GHCN, 2010). This dataset contains a composite of climate records from numerous sources that were merged and subjected to a suite of quality assurance reviews (NOAA GHCN, 2010). The dataset provides daily maximum and minimum temperatures, snowfall, and 24-hour precipitation totals that were obtained primarily from state universities or cooperatives and reported as part of the United States Cooperative Summary of the Day (NOAA GHCN, 2010).

Daily precipitation and temperature data were compiled for those rain gauges that were within a close proximity to the four study areas. Due to the relatively remote locations of the study sites only a limited number of rain gauges have been installed and maintained over the years. Some of the gauges have changed location or have been removed completely resulting in varied spatial coverage of the study areas. From the data available only the years with overlapping recorded observations will be used and any gaps or erroneous values will be replaced with averaged values from adjacent stations.

The following reports the number of the gauges with years available for each study site: eight gauges with 55 years of data (1956-2011) at Fort Huachuca, nine gauges with 51 years (1960-2011) at Fort Bliss, five gauges with 55 years (1956-2011) at YPG, and six gauges with 57 years (1954-2011) at Fort Irwin. Given that relatively few of the rain gauges recorded data continuously throughout these time periods, different subsets of years will be used at each installation, each with a varying number of rain gauges available.

Due to the limited spatial coverage of the GHCN rain gauge data additional precipitation estimates were obtained from next-generation radar (NEXRAD) data and from local meteorological stations at Fort Huachuca. NEXRAD data are collected through a network of 159 high-resolution Weather Surveillance Radar-1988 Doppler (WSR-88D) radars that constantly scan the near surface detecting precipitation and atmospheric movement using a Precipitation Processing System (PPS) algorithm described in detail in Fulton *et al.* (1998). The data are organized to provide spatially continuous precipitation estimates over a 4x4 km^2 grid projected in the Hydrologic

Rainfall Analysis Project (HRAP) coordinate system. The quality of NEXRAD data has evolved through various stages (I-IV), as new algorithms have been developed to remove bias and enhance accuracy (Young *et al.,* 2000). NEXRAD Stage IV observed precipitation data, also known as Multisensor Precipitation Estimation (NEXRAD-MPE) data, were downloaded from the NOAA Advanced Hydrologic Prediction Service as a series of daily shapefiles from 2005-2012 for the conterminous United States. An open source Python script designed by Mehmat Ercan at the University of South Carolina (http://grg.engr.sc.edu/mehmet/scripts.html) was used to create a table of daily precipitation values for the central point of each HRAP grid cell that intersected any part of the study area watersheds. These center points were then used as virtual rain gauge locations and used to drive SWAT. Fort Bliss NEXRAD-MPE data were obtained using HydroDesktop, a GIS program that allows a spatial query of hydrologic data sources and allows for the download and export of MPE data from the NWS regional River Forecasting Centers (Ames *et al.,* 2012).

In addition to the NEXRAD-MPE and rain gauge data sources, an array of six meteorological towers (met towers) located at Fort Huachuca within the installation boundaries provided precipitation and temperature data from 2000-2011 in 15-minute intervals. These data were evaluated as an input for SWAT and were used to create design storms needed for the KINEROS2 calibration efforts at Upper Garden and Huachuca Canyons.

To assess the impacts of climate change on the flow regime, climate projection data were obtained from the World Climate Research Programme's (WCRP's) third

Coupled Model Intercomparison Project (CMIP3). These data have the advantage of previously being bias-corrected and spatially and temporally downscaled (Maurer *et al.,* 2010). Created by the United States Department of the Interior's Bureau of Reclamation (Research and Development Office) and the Lawrence Livermore National Laboratory (LLNL) with the help from other federal agencies and the Santa Clara University Civil Engineering Department, these data are currently available for use in climate change studies including those that study changes in watershed hydrology. The Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4) incorporates the work of several climate modeling groups who have developed and produced hundreds of simulations of past and future climates (Parry *et al.,* 2007). Different scenarios have been developed based on various population and economic growth forecasts and technological advances that have been grouped into 4 different scenarios (A1, A2, B1 and B2) and subdivided into three groups (A1a, A1b, A1c etc.), each with a varying degree of CO_2 concentrations (Nakićenović *et al.,* 2000). For this study, climate projection data will be used based on the high forcing A2 scenario, where carbon emissions increase to 820ppm from 2000 to 2100 with an average global warming of 3.4°C (Meehl *et al.,* 2007). Of the various climate models included in the CMIP3 dataset, NOAA's Geophysical Fluid Dynamics Laboratory Climate Model version 2.1 (GFDL CM2.1) was shown to have a good representation of the multi-model ensemble mean for the Southwest and is one of the few models that provide continuous daily temperature and precipitation outputs (Seager *et al*., 2007; Cayan *et al.,* 2010). These data have a scale of 1.8° or approximately 12 km resolution and was accessed for free from the LLNL Green Data Oasis data storage website (http://gdo-dcp.ucllnl.org). The GFDL CM2.1 data were obtained for both historical (1981-2000) and future (2081-2100) time periods and were assigned to “virtual” rain gauge locations at grid centers before being used to create necessary SWAT precipitation input files.

Precipitation data required to run the KINEROS2 model were entered as depths (in) from a pre-defined table of precipitation frequency estimates based on a specific return interval and duration. NOAA’s Precipitation Frequency Data Server (PFDS) allows for the input of geographical coordinates to determine precipitation depths based on a frequency analysis of partial duration series (NOAA PFDS, 2012). Design storms based on 2, 10, and 100-year, 1-hour storms were created from the PFDS data using the centroid coordinate for each watershed in the study areas. Applying a design storm created from a single point estimate across an entire watershed tends to result in an overestimation of runoff due to the failure to account for spatial heterogeneity of the input data (Miller *et al.,* 2002a). To account for discrepancies, an aerial reduction factor developed from paired rain gauge study in Southern Arizona (Osborn *et al.,* 1980) and expanded for other parts of the Southwest in NOAAs Technical Memorandum NWS HYDRO-40 (Zehr & Myers, 1984) was applied to the design storm depth estimates.

3.7 Simulations and model execution

Writing the SWAT simulation file involves selecting the appropriate precipitation and temperature files and the desired simulation start date and time period. Temperature data for the historical runs using rain gauge and NEXRAD-MPE were created from weather generator station data included within the program. Included with SWAT, the weather generator files contain statistical data for gauge locations that are used to estimate daily maximum and minimum temperature values by selecting the station closest to the watershed (Burns *et al.,* 2007). Temperature data included with GFDL CM2.1 projection data were formatted to match the temperature (.tmp) file structure used by SWAT at each virtual rain gauge location and were selected based on proximity to watershed center. Lastly, a daily output frequency was selected to report streamflow data on a daily time-step, necessary for determining flow permanence.

KINEROS2 simulation files are written by selecting the discretized watershed and the desired design storm previously created. A saturation index slider allows the user to set the amount of soil moisture present prior to the model run and was adjusted based on the presence and duration of previous storms. A series of multipliers also make it possible to adjust hydraulic conductivity (Ks) and Manning's N in both the planes and channels and were determined from the calibration efforts. After creating the simulation files the desired model was chosen and executed and results were then imported back into the GIS viewer where AGWA allows for visual display of the modeling results using a graduated color ramp.

3.8 Calibration and validation of SWAT at Fort Huachuca

Calibration and validation were performed in order to improve model accuracy by adjusting several of the model input parameters until modeled and observed streamflow were in agreement. Calibration of SWAT was possible by comparing simulated and monitored streamflow values at the watershed outlet for yearly, monthly and daily time-steps. Streamflow observations are limited to two U.S. Geological Survey (USGS) stream gauges found on perennial streams in the higher elevations of Garden and Huachuca Canyons and are the only locations where calibration and validation of model output were possible. Daily discharge totals in cubic feet per second (cfs) were downloaded from the USGS Water Data website (http://waterdata.usgs.gov) for USGS 09470800 Garden Canyon and USGS 09471310 Huachuca Canyon stream gauges and average totals were calculated for a calibration and validation time period. The sums were then converted to depth by dividing by the watershed area (km^2) for comparison to SWAT simulated results. Subsurface flows were determined using a Baseflow Filter Program based on methodology outlined in an Arnold and Allen (1999) study that reports a fraction used to separate surface and subsurface flow of the USGS data.

Compared to initial SWAT average annual basin outputs, it was determined that model parameter changes would be needed in order to better match actual streamflow conditions. Past studies in similar settings have indicated that the Curve Number (CN) parameter has the strongest influence on runoff values and can be adjusted to improve model efficiency (Hernandez *et al.,* 2000; Miller *et al.,* 2002a). CN is an empirical parameter that describes the amount of runoff or infiltration that occurs from rainfall excess and ranges from 30-100, with high numbers indicating greater runoff and low numbers indicating less runoff (United States Soil Conservation Service, 1983). Following the SWAT user guide instructions for calibration, surface flow estimates were adjusted by changing CN and soil available water content (SOL_AWC) values in the input model files until surface flow estimates and observations were similar. Baseflow contributions were then adjusted by changing the groundwater “revap” coefficient (GW_REVAP) until baseflow estimates and observations were similar. Adjustments were made incrementally and then assessed using common statistical tests at monthly and daily time-steps.

Calibration and validation was carried out at Upper Garden and Upper Huachuca Canyons for SWAT-rain gauge, SWAT-NEXRAD-MPE (from here on referred to as just NEXRAD), and SWAT-met tower simulations to compare and to assess the accuracy of each. Specifically, the SWAT-NEXRAD derived output was compared against the SWAT-rain gauge output to determine if it was a viable substitute for areas with a sparse rain gauge network. Calibration and validation of the climate projection simulations were not performed due to the down-scaled data for the 1981-2000 time period showing little relation to actual observations and the goal of the study to look at the relative difference in flow permanence between different parts of a watershed under a climate change scenario.

3.9 Calibration and validation of KINEROS2 at Fort Huachuca

Calibration for the KINEROS2 model was attempted at Fort Huachuca at both Upper Garden and Huachuca Canyons based on USGS peak flow stream gauge reports and 15-minute met tower precipitation data. From 2000-2011 the Garden Canyon stream gauge reported twelve high-flow events from which seven had matching met tower data and were chosen for calibration. For the same time period, the Huachuca gauge reported eleven high-flow events from which three were used for calibration. Calibration was performed using AGWA multipliers to adjust several input parameters for KINEROS2 including saturated hydraulic conductivity (Ks) and Manning's N estimates for both planes and channels. Several model iterations using various multipliers were performed to calibrate the peak flows of one storm and were then applied to separate storms to determine if the changes were valid.

3.10 Statistical analysis

Agreement between observed and modeled streamflow values were assessed using a variety of statistical methods including a paired t-test, a linear regression, and the Nash-Sutcliffe model efficiency (NSE), with the latter two considered the most widely used statistics used for reporting hydrologic calibration and validation (Gassman *et al.,* 2007). The paired t-test was used to assess the null hypothesis of zero difference between the mean of the observed and simulated data sets at a 0.05 significance level ($\alpha = 0.05$). A standard linear regression statistic was used to evaluate the strength of the linear relationship between the observed and simulated data using the coefficient of determination (R^2) to report the degree of correlation between simulated and observed regression lines. R^2 values can range from 0 to 1, with 0 indicating no correlation and 1 indicating the two lines are equal (Krause *et al.,* 2005). The NSE measures how well the simulated versus observed data match a regression line with a slope of 1 and ranges in values from $-\infty$ to 1. Values less than 0 indicate that the mean of the observed data is a better predictor than the model output and a value of 1 indicate a perfect fit (Krause *et al.,* 2005). Accuracy assessment will follow the Moriasi *et al.* (2007) evaluation standard that model simulation results are satisfactory if R^2 and NSE values are > 0.5 at the monthly time-step. The increased sensitivity of R^2 and NSE values to outliers and insensitivity to a consistent over- or under-estimation can often limit the reliability of these statistical results despite meeting the acceptable limit (Legates and McCabe, 1999). To address this and further assess model accuracy line plots were created to compare simulated variation to observed variation.

3.11 Flow permanence

For this study, flow permanence refers to the percent of time of the year where surface flow is present for each stream reach. Presence was determined using the SWAT reach (.rch) output file, which reports daily runoff values for each modeled stream reach. Prior to formatting it was deemed necessary to add a ‘YEAR’ column to the reach output files and was accomplished running a C# script to append a year to each record. The tables were then imported into Excel and sorted by date and reach and then a series of Excel formulas were used to capture the number of days where flow was present in each reach. Threshold values reported in section 4.3 were assigned such that values that were greater were designated as having "flow present" and those that were less as "flow absent" for each reach on each day. A simple ratio of the number of days with flow present to the total number days of the year resulted in annual percent time with flow that was calculated for each stream reach, both for the total year and wet season only. Average flow permanence was calculated for the entire period of record and the resulting table was joined to the stream feature class then exported and merged into a final spatial layer that covered each installation.

3.12 Flow permanence cutoffs

Due to SWAT's inability to simulate zero flow conditions (Kirkby *et al.,* 2011) it was necessary to establish cutoff values equivalent to zero to accurately describe flow permanence. Because of the large variation in stream channel sizes it was decided that the cutoff values would need to vary based on the contributing watershed area. In this study, a correlation between flow permanence and watershed area was performed at stream gauge and Tidbit sensor locations in Fort Huachuca. Tidbit data sensors log temperature data from within the channel at 15-minute intervals and have been shown useful in detecting the onset and cessation of streamflow using a thermograph interpretation technique (Gungle, 2006; Figure 4). Data from the Gungle (2006) study reported the timing and duration of flows over an 18-month time period in 2001-2002 from several locations in and around Fort Huachuca. Two locations in particular, one in Lower Garden and one in lower Huachuca Canyons, were especially important because they provided flow permanence observations for the low-lying alluvium dominated channels where more recent sensor data was unavailable. Additional Tidbit sensor data was also acquired from an active SERDP project being conducted by the Stromberg research group, which provided data from 2011 that was used to assign the flow cutoff-watershed area classes for higher elevation, mountainous stream reaches. For each Tidbit sensor data location average annual flows were determined and compared to SWAT results. Flow presence cutoffs were increased in small increments until they were in close agreement with the observed and used to define the different classes based on contributing watershed area.

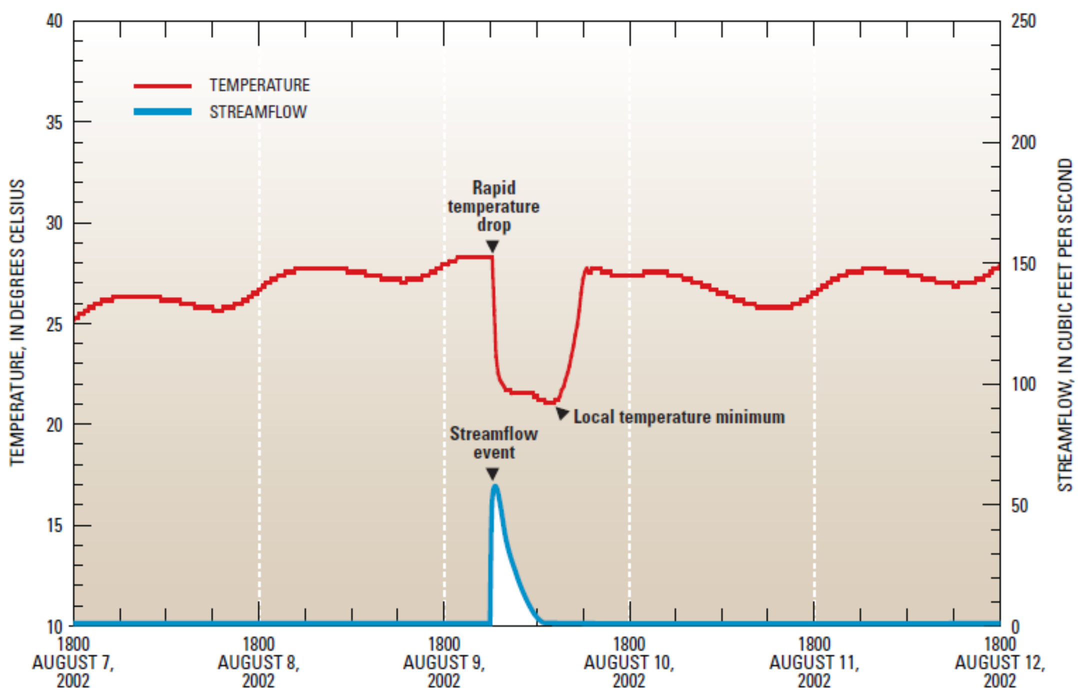


Figure 4. Graphical representation of thermal interpretation of streamflow from Gungle, 2006.

3.13 Peak flows

For each watershed center an aerial reduction factor was determined using area relationships developed from a paired rain gauge study at the Walnut Gulch Experimental Watershed by Osborn *et al.* (1980) for 2, 10, and 100-year, 1-hour storm events (Figure 5). These values were applied to each of the design storms created from NOAA's precipitation frequency maps prior to running KINEROS2. Following model execution peak flow (m^3/s) results were displayed in AGWA and individual spatial layers were then exported and merged to create a final coverage for each of the four study areas.

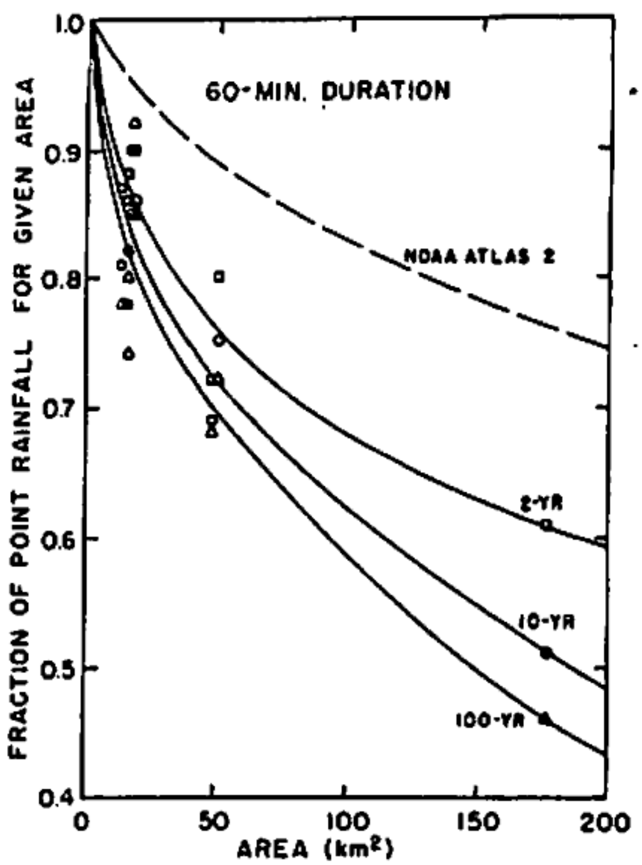


Figure 5. Depth-area ratios at Walnut Gulch for 2, 10, and 100-yr, 1-hour storms (Osborn *et al.,* 1980).

4. RESULTS

4.1 Calibration and validation of SWAT at Garden and Huachuca Canyons

Early SWAT-rain gauge, SWAT-NEXRAD, and SWAT-met tower simulations all displayed excessive surface runoff at Upper Garden Canyon. To correct for this a 20% decrease in CN values was applied to each subwatershed unit to increase infiltration within the subwatersheds. Further decreases to surface runoff were applied to the SWAT-NEXRAD runs by increasing the soil available water content (SOL_AWC) 0.08 at each soil horizon. Groundwater contributions were increased by adjusting the depth of groundwater evaporation (GW_REVAP) values from the default value of 0.2 to 0.02 for SWAT-rain gauge and NEXRAD simulations and to 0.08 for SWAT-met tower simulations.

To assess the accuracy of the model simulations, statistical analyses were performed for average monthly totals and daily totals for both calibration and validation time periods. At Upper Garden Canyon, results from the paired T-test failed to reject the equal mean hypothesis for average monthly totals of all three precipitation inputs, but only SWAT-NEXRAD simulations failed to reject for daily totals (Table 1). Both SWAT-NEXRAD and SWAT-rain gauge simulations obtained acceptable levels of accuracy based on R^2 and NSE values for average monthly totals during both calibration and validation time periods (Table 2). However, upon plotting the data a trend of overprediction of large flow events and underprediction of small events was observed for both SWAT-NEXRAD simulations [Figures 6 (a) and (b)] and SWAT-rain gauge simulations [Figures 7 (a) and (b)]. The poor performance of the SWAT-met tower simulations at the monthly calibration time period (Table 2) may have been the result of data gaps in the met tower dataset considering that acceptable results were achieved during the validation period (Table 2).

At Upper Huachuca Canyon, results from the paired T-test also failed to reject the equal mean hypothesis for average monthly totals for each of the simulations minus the SWAT-NEXRAD validation time period; whereas all three simulations were rejected for the daily totals (Table 3). Acceptable R^2 values were obtained for both SWAT-NEXRAD and SWAT-rain gauge simulations at both time periods; however, NSE values were below the 0.5 limit (Table 4). Line plots revealed an over-prediction for small events and under-prediction for large events for the SWAT-NEXRAD simulations [Figures 8 (a) and (b)]; whereas SWAT-rain gauge simulations under-predicted small events and over-predicted large events [Figures 9 (a) and (b)]. The similarity between rain gauge and radar results observed at Upper Garden and Huachuca Canyons suggest that the NEXRAD-MPE data can serve as an accurate substitute for field observations where rain gauges are absent or possibly achieve better results where they are scarce.

Table 1. Paired T-test results from Upper Garden Canyon calibration and validation simulations.

Precipitation Data	Calibration					Validation				
	Years	Ave Monthly Total		Daily Total		Years	Ave Monthly Total		Daily Total	
		P-value	Reject H_Θ	P-value	Reject H_Θ		P-value	Reject H_Θ	P-value	Reject H_Θ
NEXRAD-MPE	2005-2008	0.81	No	0.17	No	2009-2012	0.17	No	0.17	No
Rain gauge	2000-2005	0.19	No	1.36E-15	Yes	2006-2011	0.97	No	0.27	No
Met tower	2000-2004	0.062	No	0.01	Yes	2005-2008	0.7	No	0.01	Yes

Table 2. Statistical results for Upper Garden Canyon SWAT-NEXRAD and SWAT-rain gauge simulations with coefficient of determination (R^2) and Nash-Sutcliffe Efficiency (NSE) values for calibration and validation time periods.

Precipitation Data	Calibration					Validation				
	Years	Daily		Monthly		Years	Daily		Monthly	
		R^2	NSE	R^2	NSE		R^2	NSE	R^2	NSE
Nexrad-MPE	2005-2008	0.50	-0.01	0.80	0.80	2009-2012	0.57	-0.38	0.90	0.86
Rain gage	2000-2005	0.46	0.44	0.95	0.92	2006-2011	0.34	-0.24	0.97	0.73
Met Tower	2000-2004	0.02	-6.9	0.06	-0.3	2005-2008	0.37	-0.21	0.99	0.78

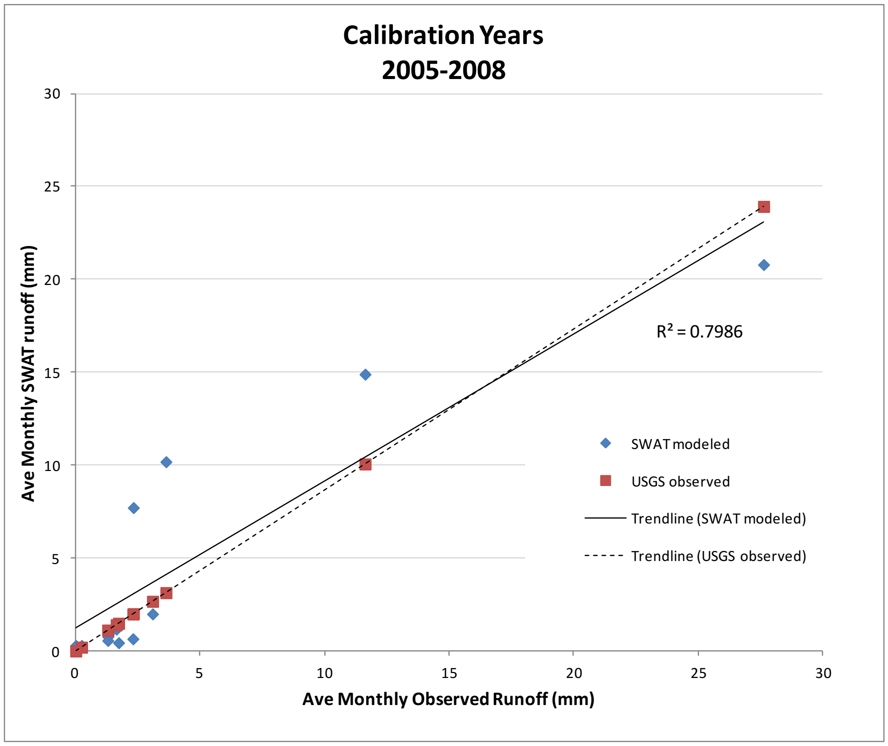
Table 3. Paired T-test results from Upper Huachuca Canyon calibration and validation simulations.

Precipitation Data	Calibration					Validation				
	Years	Ave Monthly Total		Daily Total		Years	Ave Monthly Total		Daily Total	
		P-value	Reject H_Θ	P-value	Reject H_Θ		P-value	Reject H_Θ	P-value	Reject H_Θ
NEXRAD-MPE	2005-2008	0.22	No	8.42E-07	Yes	2009-2012	0.02	Yes	3.79E-13	Yes
Rain gauge	2005-2007	0.18	No	2.24E-14	Yes	2008-2011	0.25	No	9.39E-07	Yes
Met tower	2005-2006	0.21	No	0.04	Yes	2007-2008	0.52	No	3.82E-09	Yes

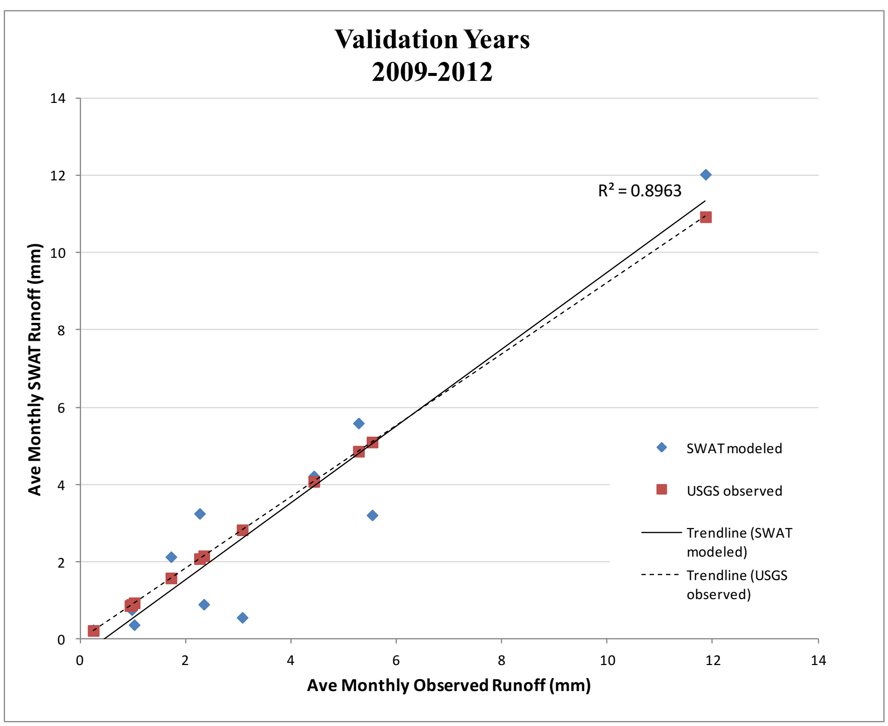
Table 4. Statistical results for Upper Huachuca Canyon SWAT-NEXRAD and SWAT-rain gauge simulations with coefficient of determination (R^2) and Nash-Sutcliffe Efficiency (NSE) values for calibration and validation time periods.

Precipitation Data	Calibration					Validation				
	Years	Daily (<1mm)		Monthly (<5mm)		Years	Daily (<1mm)		Monthly (<5mm)	
		R^2	NSE	R^2	NSE		R^2	NSE	R^2	NSE
Nexrad-MPE	2006-2008	0.12	0.02	0.53	0.14	2009-2012	0.05	-0.22	0.86	0.12
Rain gage	2005-2007	0.49	-1.05	0.97	-9.71	2008-2011	0.07	-7.08	0.83	-3.22
Met Tower	2005-2006	0.06	-2.56	0.66	-107	2007-2008	0.51	-20.4	0.16	-1.06

(a)

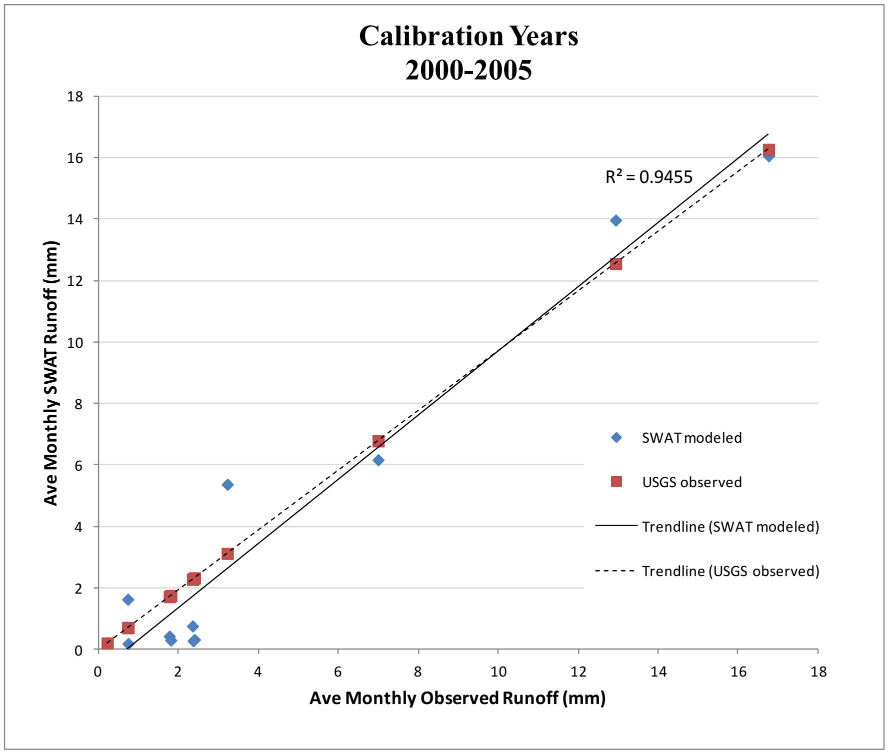


(b)



Figures 6 (a) and (b). Plot of simulated vs. observed average monthly volume totals at Upper Garden Canyon using NEXRAD-MPE precipitation input for (a) calibration and (b) validation time periods.

(a)



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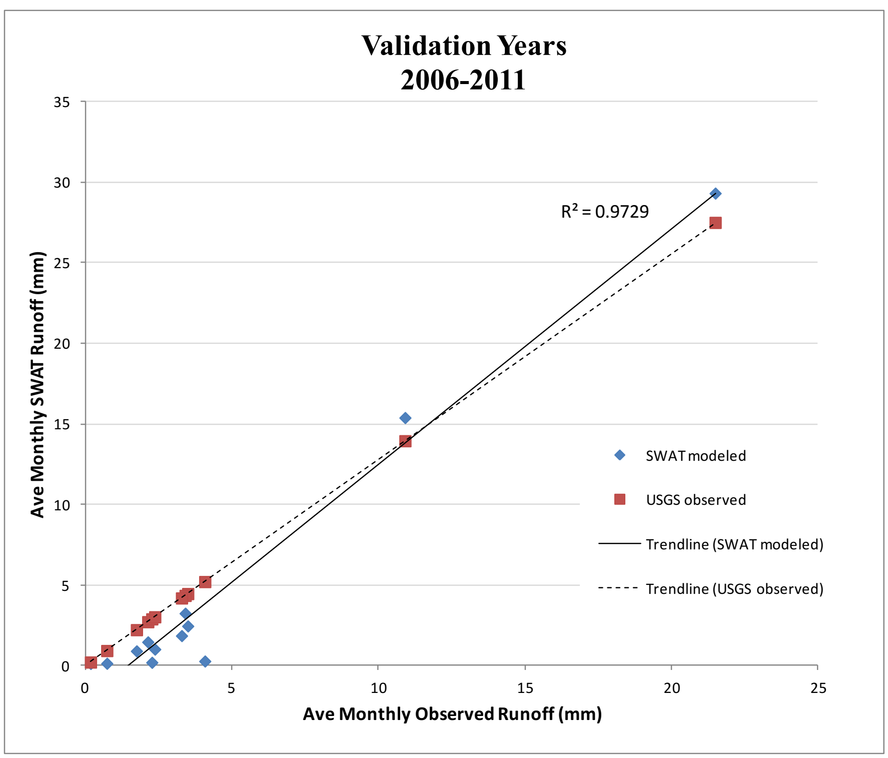
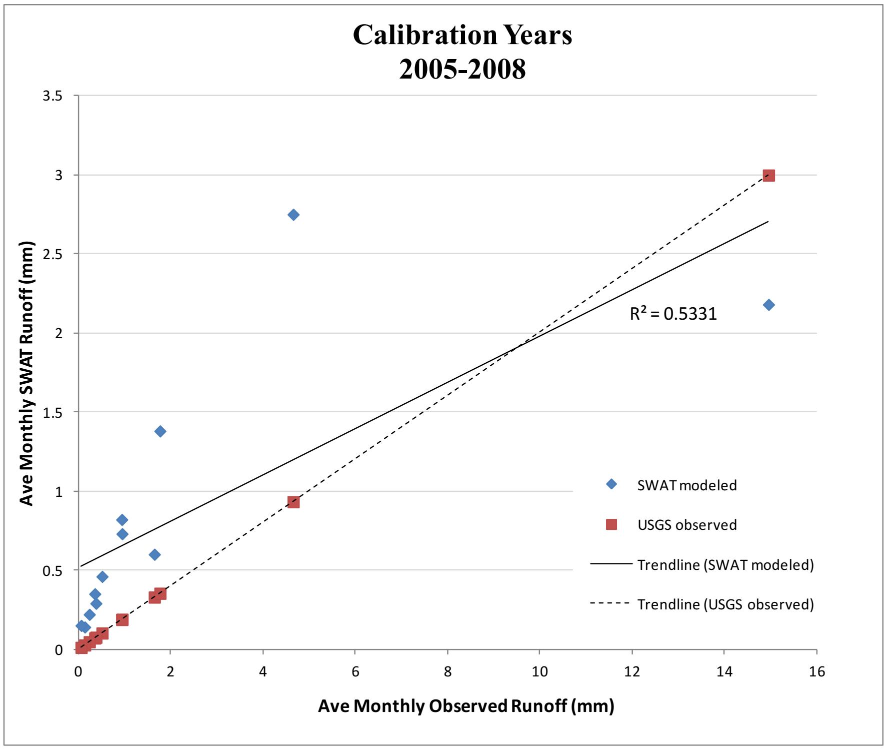
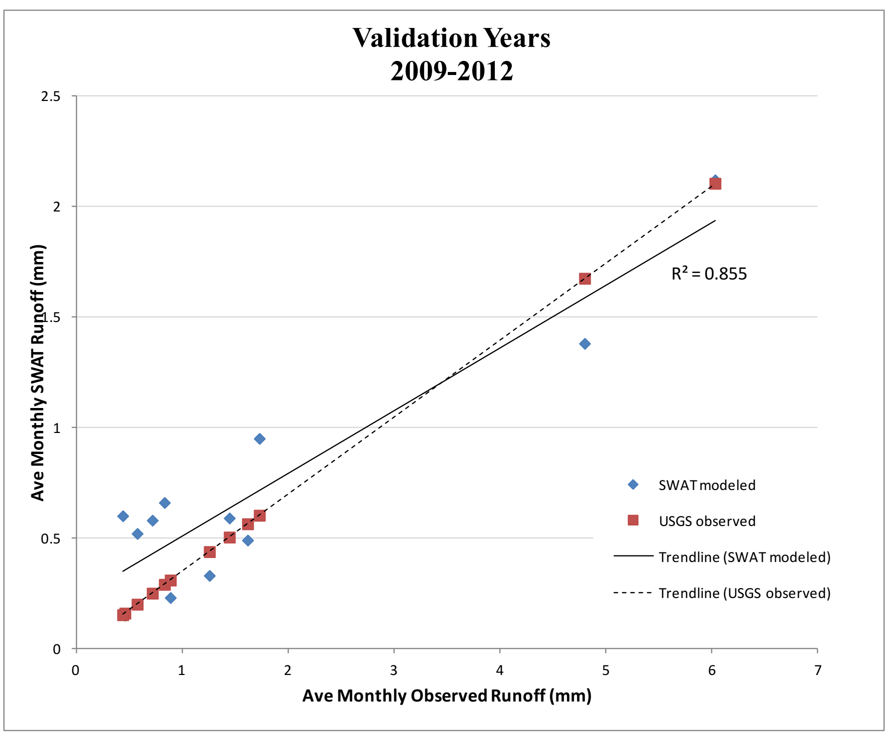


Figures 7 (a) and (b). Plot of simulated vs. observed average monthly volume totals at Upper Garden Canyon using rain gauge precipitation input for (a) calibration and (b) validation time period.

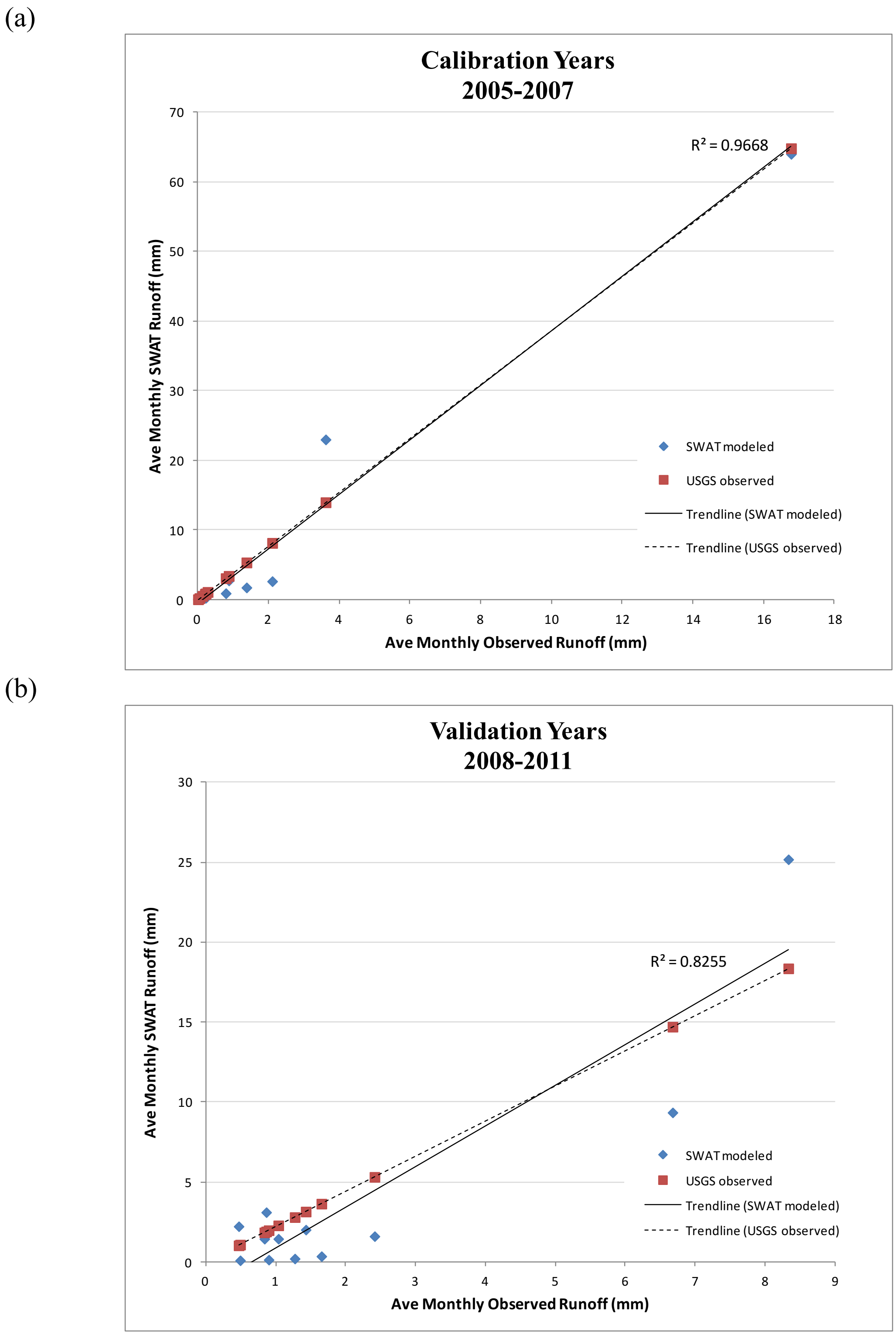
(a)



(b)



Figures 8 (a) and (b). Plot of simulated vs. observed average monthly volume totals at Upper Huachuca Canyon using NEXRAD-MPE precipitation input for (a) calibration and (b) validation time periods.



Figures 9 (a) and (b). Plot of simulated vs. observed average monthly volume totals at Upper Huachuca Canyon using rain gauge precipitation input for (a) calibration and (b) validation time periods.

4.2 *Calibration and validation of KINEROS2 at Fort Huachuca*

At Garden Canyon, non-calibrated simulations of KINEROS2 showed that of the nine high-flow events with met tower data, four showed under estimations of peak flows, two were marginally overestimated and two events (08/09/2007 and 08/05/2008) were largely overestimated. For Upper Huachuca Canyon met tower data for three high-flow events exist, however the closest met tower was found outside of the watershed and showed poor agreement between the timing of storm events and streamflow and were not considered practical for calibration. After considerable attempts of calibration it was determined that obtaining agreement between the observed and simulated peak flows was not possible given the wide range of estimated values. This was perhaps due to the high spatial variability of the summer thunderstorms with high rainfall intensities that often result in high-flow events. Another possibility is changing conditions in soil moisture within the watershed, though attempts were made to account for varying conditions by adjusting the saturation index in KINEROS2 based on whether any precipitation was recorded in the preceding days. Despite not being able to accurately calibrate KINEROS2 simulations, the relative difference of peak flows of each stream reach can still be useful in differentiating channels that see large magnitude flows from those that only experience low-flow events.

4.3 Flow permanence

Flow permanence values were successfully assigned to each stream reach within the four study areas using the SWAT-rain gauge and SWAT-NEXRAD results. Flow cutoffs, or the minimum streamflow values where flow was considered present in the channel, were established for the mountainous areas of Fort Huachuca based on the 2011 Stromberg Tidbit data sensors (Table 5) located in the upper and middle parts of Garden Canyon, the middle tributary of the Buena School Area watershed, the southern tributary of Soldier Creek watershed, the upper part of Huachuca Canyon, and Upper Slaughterhouse Wash. Flow cutoffs were established for alluvium reaches of Garden Canyon, Woodcutters Wash, Graveyard Gulch, Soldier Creek, and Huachuca Canyons based on the Gungle 2001-2002 Tidbit sensor results. Three watershed size classes were assigned different flow cutoffs based on their contributing watershed area. Watersheds with an area <10 km^2 were assigned a cutoff of 0.0001 m^3/sec; between 10-34.9 km^2 a cutoff of 0.001 m^3/sec; and >35km^2 a cutoff of 0.35 m^3/sec. A statistical comparison between the Tidbit and SWAT flow permanence values revealed acceptable R^2 values for the SWAT-NEXRAD simulations for entire year 2011 (Figure 10) and SWAT-rain gauge simulations for the summer of 2011 (Figure 11). SWAT derived flow permanence values were assigned to stream reaches located within each of the four military installations based on these same cutoff values and divided into ten classes based on Jenks natural breaks (Figure 12, Appendix A).

Flow permanence values were also obtained using the 1981-2000 and 2081-2100 GFDL CM2.1 climate data at each of the four installations with absolute and percent differences calculated between the two time periods. Results varied among the different watersheds but overall indicated that higher elevation portions of watersheds would be most affected by decreased precipitation and increased temperatures predicted for the Southwest (Figure 13, Appendix B).

Table 5. Stromberg research team's 2011 Tidbit Sensor flow permanence and SWAT derived flow permanence percentages at Fort Huachuca (Monsoon time period includes Julian calendar days 166-258)

Watershed	TidBit Sensor			NEXRAD-MPE		Rain Gauge	
	Location ID	Annual %	Monsoon %	Annual %	Monsoon %	Annual %	Monsoon %
Buena School Area	GN	7.9	15.08	7.95	16.13	9.32	6.45
Soldier Creek	HN	7.47	12.12	1.37	4.3	0.27	1.08
Huachuca Canyon	HU	28.81	86.31	24.38	54.84	43.01	54.84
Garden Canyon	GU	88.74	84.95	69.59	74.19	56.71	60.22
Garden Canyon	GL	14.69	40.96	30.41	56.99	56.44	60.22
Ramsey Canyon	RU	82.33	53.76	90.14	82.8	71.78	65.59
Ramsey Canyon	RL	9.04	27.99	57.81	63.44	24.93	25.81

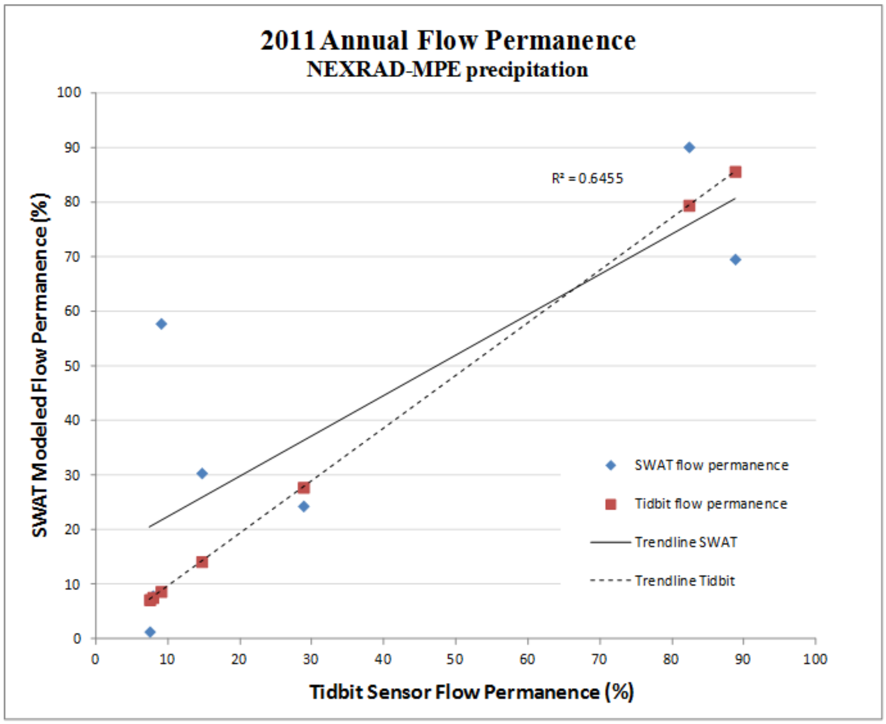


Figure 10. Line plot of Tidbit sensor derived flow permanence compared to SWAT-NEXRAD derived flow permanence percentages for 2011.

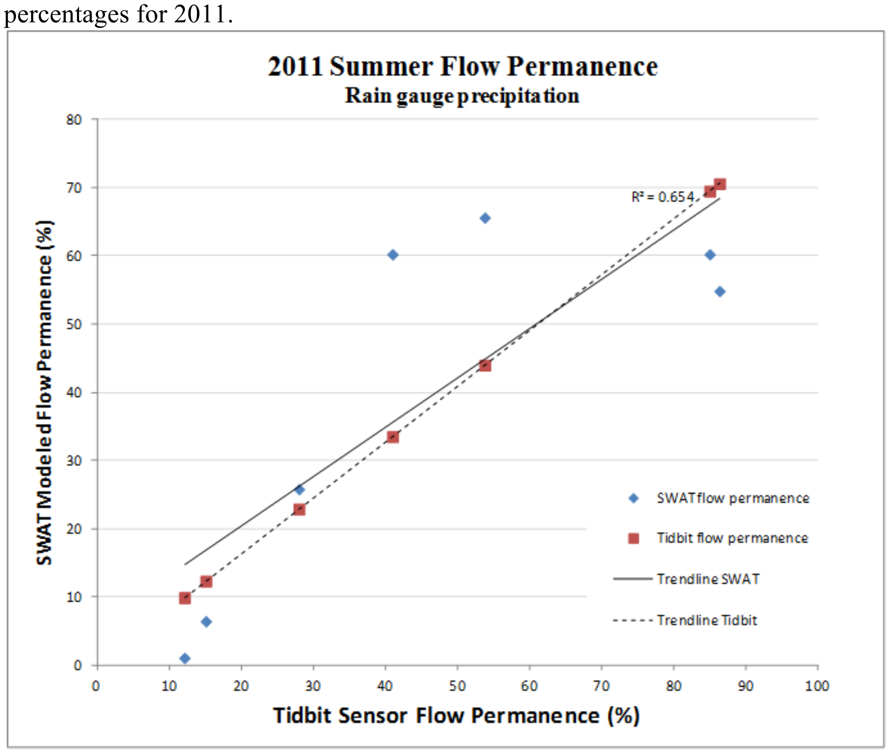


Figure 11. Line plot of Tidbit sensor derived flow permanence compared to SWAT-rain gauge derived flow permanence percentages for the summer of 2011.

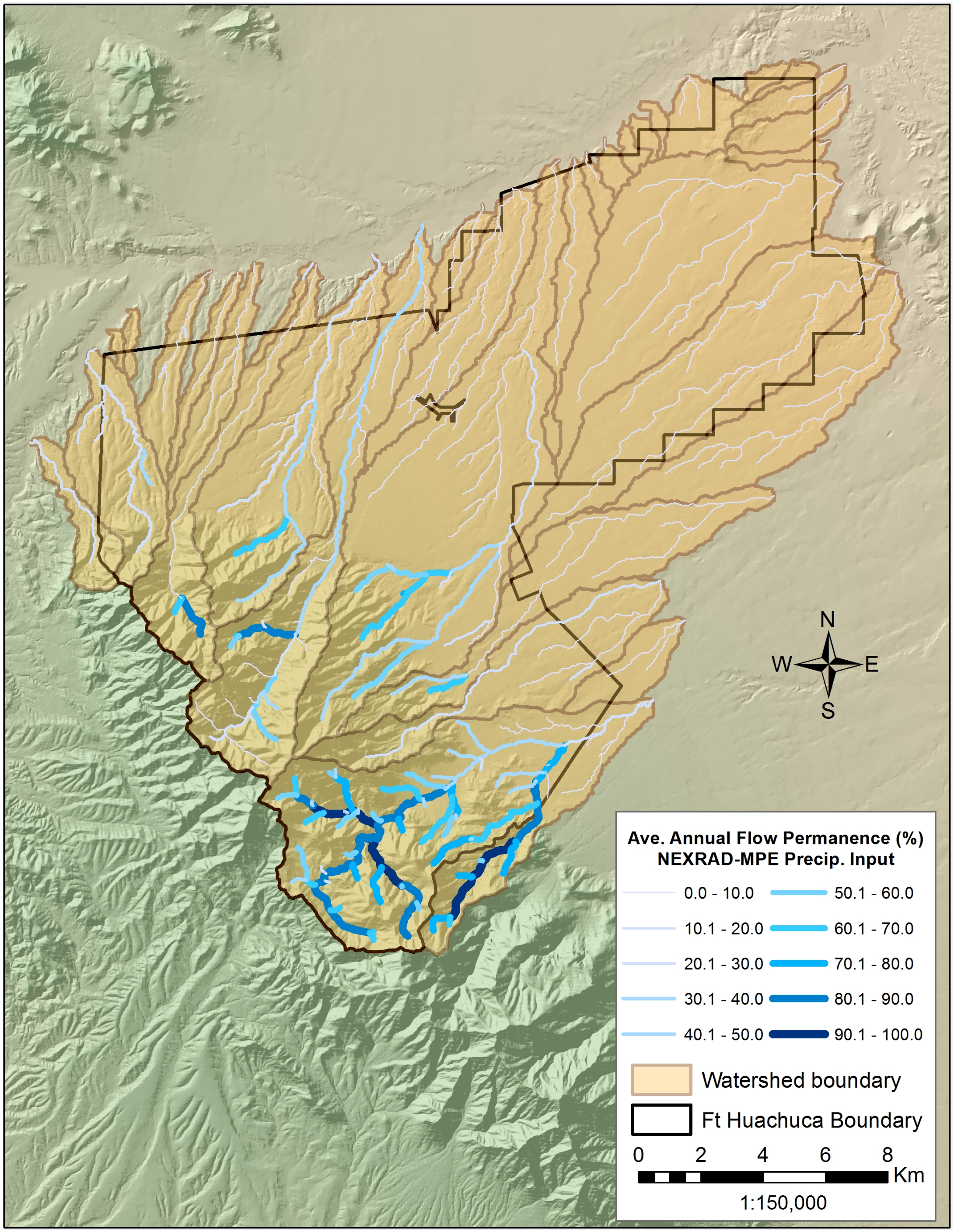


Figure 12. Flow permanence at Fort Huachuca using NEXRAD-MPE data and flow cutoffs.

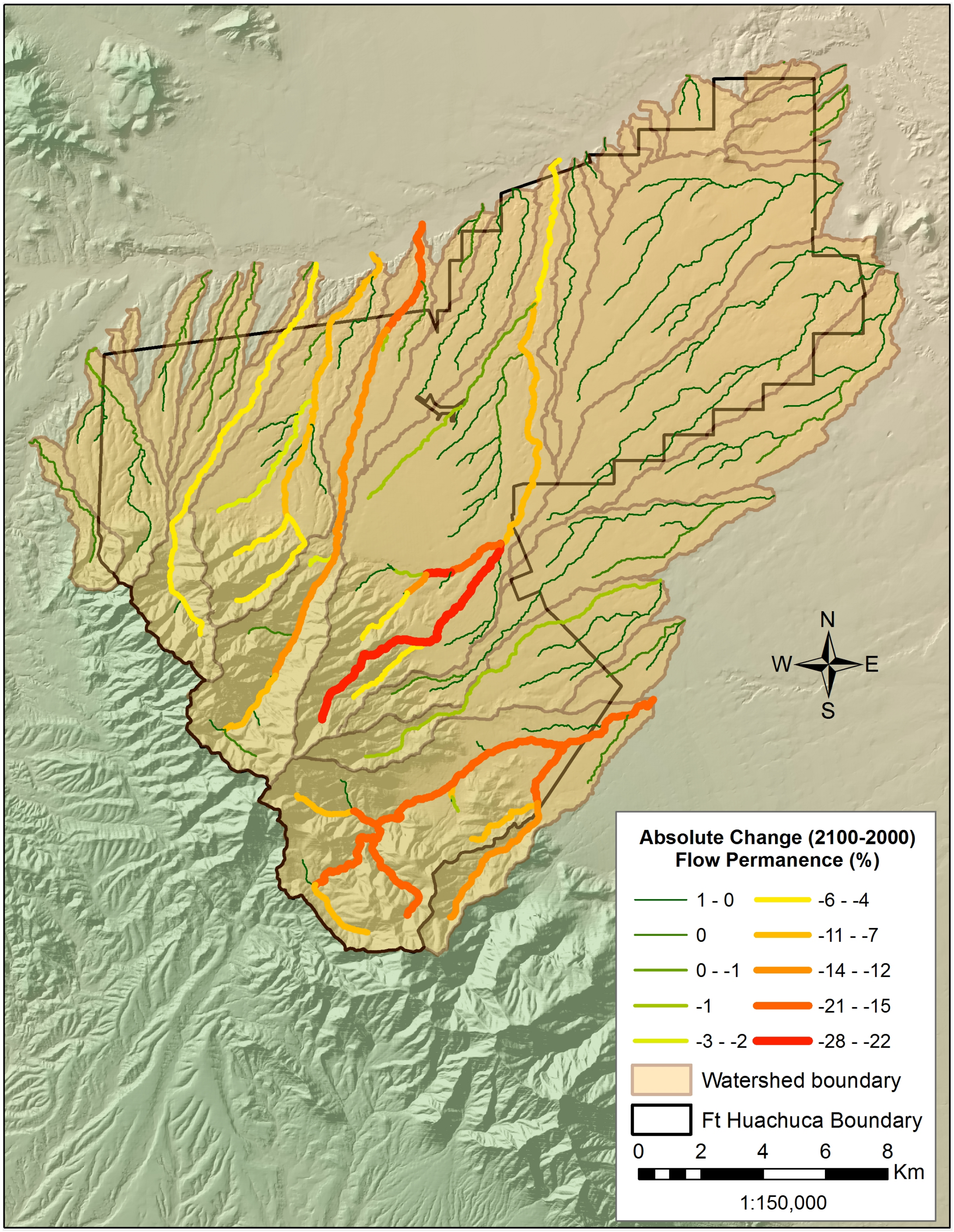


Figure 13. Absolute change in flow permanence between 1981-2000 and 2081-2100 at Fort Huachuca using GFDL CM2.1 climate projection data.

4.4 Peak flows

Due to the inability to calibrate KINEROS2, analysis of the peak flow model results were based on visual cues made during field operations. Indicators such as width of channel and height of flood debris on banks were examined for evidence of large flow events. At each of the installations the stream reaches with the highest simulated peak flows were often found to have wide braided channels indicating large magnitude flows. Figure 14 shows photographs from the Bug Scuffle watershed at Fort Bliss where channel width was approximately 15-meters and flood debris on a mid channel tree had a height over 1-meter. The modeled 100-year, 1-hour peak flow associated with this reach was 1,912 m^3/sec, which was the highest estimate for the entire watershed. Figure 15 shows evidence from Mojave Wash at Yuma Proving Grounds where channel width was approximately 50-meters with 1-meter high flood debris encountered on a mid-channel tree. The modeled 100-year, 1-hour peak flow associated with this stream reach was 2,094 m^3/sec, also the largest estimate for this watershed.

Figure 14. Photographs from Bug Scuffle watershed at Fort Bliss showing large channel and flood debris on tree.

Figure 15. Photographs from Mojave Wash at Yuma Proving Grounds showing large channel and flood debris on tree.

5. DISCUSSION

In the southwestern United States the ecological function of riparian areas is largely determined through the interaction between hydrological and ecological processes that take place within the hyporheic and parafluvial zones. Quantifying the flow regime of ephemeral and intermittent streams is a critical first step in establishing ecohydrological relationships within riparian environments. The methodology presented here attempts to advance the current knowledge of semiarid stream hydrology by examining how the timing, frequency, and magnitude of streamflow events vary throughout different parts of a watershed. By incorporating topographical relief, soil properties, and land cover patterns in rainfall-runoff model simulations, valuable insights were made on soil moisture distribution. This knowledge can be used to explore associations between hydrologic connectivity and sediment transport, seed dispersal, or aquatic species distribution. Furthermore, it can be used as a measure of how often flow pulses act as a catalyst for biogeochemical reactions that can influence the amount of nutrients available for plant uptake. This characterization of streams based on their flow regime can be used to gauge the ecological sensitivity of the adjacent riparian areas and be used to guide land use activities away from more vulnerable environments.

5.1 Errors and assumptions

The work described here is not without error and where observed data were available attempts were made to measure accuracy, but the inherent nature of certain types of error are largely unquantifiable. As with any modeling effort the level of accuracy is much dependent on the correctness of the input data. The high degree of spatial variability associated with summer thunderstorms remains one of the key sources of error in rainfall measurements and biggest challenge to modeling efforts. Even fine resolution radar and local met tower data can fail to account for the variability of rainfall especially in areas with large elevation gradients related to orographic features. At the Walnut Gulch Experimental Watershed nearly 100 precipitation and runoff gages are required to accurately assess hydrologic conditions of a watershed that is approximately 150 km^2 (Garcia *et al.,* 2008).

Errors may also have been introduced as a result of equipment failure. Large gaps were often observed in some of the meteorological and rain gauge data and zero flow days reported by the stream gauges on days where rainfall was recorded. The various resolutions of the DEM, soil, and landcover data often result in an oversimplification of real-world conditions that can affect modeling results. A comparison of SWAT's performance in semiarid verses more mesic landscapes indicated that the model does not perform as well in dry conditions and that it had trouble reproducing short-term rainfall events (Van Liew *et al.,* 2007) This was due to a combination of factors including the need for a shorter computational time-step than one day and the inability of the model to accurately account for antecedent soil moisture conditions immediately prior to precipitation events, which affected the curve number method of partitioning rainfall into runoff (Van Liew *et al.,* 2007). Many of the parameters changed during model calibration and validation corrected most of the discrepancies within the different data layers; however, the accuracy of applying these same changes to different watersheds cannot be fully assessed due to the absence of observed data. The accuracy of using the Tidbit data to establish flow presence cutoff values may also have been affected by the placement of the sensor within the channel as high-flow events may alter channel morphology and resulted in a shift of the main channel away from the sensor's location. Also, the persistence of soil moisture long after flow has ceased may result in an overestimation of time when flow was considered to be present.

5.2 Flow permanence

The results of this research indicate that determining flow permanence values using the SWAT model is a viable procedure that can quickly assess hydrologic conditions over large areas. The results at Fort Huachuca demonstrate that the accuracy of the simulated results can be established when field observations are available to allow calibration and validation of the model. However, in failing to establish acceptable statistical results below the monthly time-step indicates some uncertainty in the flow permanence values calculated on a daily time-step. Nevertheless these results, as well as those from the other installations, highlight the relative differences in flow permanence within a watershed that serve as a good measure of which areas are more sensitive to land-use change. For example, if a base manager was tasked with choosing a new site for ground training activities, they could choose areas that have streams with low flow permanence knowing that these areas would be associated with less riparian abundance and less potential wildlife habitat. Such information can be used to justify land management decisions that direct disturbance activities away from ecologically sensitive areas. It also allows land managers to evaluate hydrologic connectivity and assess how upstream activities could impair downstream ecohydrological processes.

5.3 Peak flows

KINEROS2 modeling efforts were able to determine peak flows using 2, 10, and 100-year, 1-hour storm events for all stream reaches within the four study sites. The relatively few peak flow events reported for the time period prevented a successful calibration and determination of model accuracy at the stream gauge locations. However, field observations of channel morphology established that channel reaches with the highest modeled peak flows were typically the wider, more braided stream channels that form during large magnitude flow events. In addition, the reliability of results from the 100-year, 1-hour simulations can be assumed to be relatively accurate due to high volumes overwhelming any watershed or channel characteristics. These results provide a good indication of which parts of the watershed are most susceptible to high flow events and where channel geomorphology is most dynamic. This information can be used to assist base managers in road maintenance activities as well as in future site development assessments.

5.4 Climate projection simulations

Agreement among climate model projections indicates that a global rise in temperature will likely affect regional and local weather patterns. How these changes will be manifested in local precipitation patterns remains uncertain. Using spatially and temporally down-scaled climate data offers one look at how these changes will influence ephemeral and intermittent streamflow in the Southwest. The results of the comparison of the GFDL CM2.1 climate data for the historical and projected time periods show a wide variance in absolute and percent changes of flow permanence values. One pattern that emerged was a noticeable decrease in flow permanence in the higher elevation mountainous areas. These patterns indicate that these areas might be more sensitive to climate change and could be used to justify the directing of adaptation management strategies to focus on species located in these areas first.

5.5 Suggestions for improvements

The methodology described within this paper was designed using the appropriate rainfall-runoff models with best available geospatial data, but there exists areas where improvements can be made in both the modeling results and flow permanence determination. Model results are only as good as the input data used to run them and the scant amount of data in the Southwest limits calibration, validation, and assessment of the model output. A coarse representation of rainfall patterns is created from the scarce and infrequent scattering of rain gauges across the desert Southwest. Though improvements in radar and satellite detection of precipitation are being made, a local network of meteorological towers could deliver superior spatial and temporal scaled data that could be used to drive the models.

More streamflow measurements are needed to guide the calibration process and assess the accuracy of runoff models. With the exception of the two stream gauges in the upper watersheds of Ft Huachuca, no stream gauge data was available for model calibration forcing an analysis that looks at relative differences alone. Installing stream gauges at various points within some of the key tributaries would deliver data needed for accurate representation of streamflow volumes and make possible a measurement of sediment transport. Another less-costly option would be to expand this methodology to areas of similar terrain outside the study areas where streamflow data are available and then apply those results back to the study areas with the assumption that any differences between the areas would be minor.

Additional Tidbit sensor data are currently being collected in watersheds throughout Fort Huachuca and should soon become available. The addition of this data could lead to more accurate cutoffs for flow detection and determination of flow permanence. Additionally, creating smaller subwatersheds with shorter stream segments by setting smaller CSAs during the discretization stage of modeling would create a more detailed stream representation for which flow permanence values could be assigned. The use of a CSA of 10,000 m^2 may have been appropriate for the larger study sites (Irwin, Bliss, and YPG); however a finer level of detail may be more appropriate for the smaller Fort Huachuca.

5.6 Future development and uses

The next phase of the SERDP study is to establish a relationship between the hydrologic characteristics collected in this study with both riparian vegetation and geomorphologic characteristics to develop an ecohydrologic classification of ephemeral and intermittent streams. Correlating channel geomorphology with the flow data can provide insight into how channel patterns influence the hydrologic budget. It can also highlight which parts of the landscape are more susceptible to change due to erosional and depositional processes. Hydrologic data can also be correlated to vegetation metrics derived from remotely sensed data. A combination of aerial imagery and LiDAR datasets can be used to measure the three-dimensional distribution of vegetation canopies and bare-ground topography allowing for accurate assessments of vegetation height, cover, and canopy structure. Correlating vegetation metrics from riparian areas to the flow regime could be used as an indicator of vegetation response to hydrologic change. A combination of these results could be used to create an ecohydrologic classification of ephemeral and intermittent streams that would provide a holistic understanding of some of the potential feedbacks that could occur from land use disturbances. Placing this knowledge in the hands of land managers would present them with a greater level of information that can be used to guide future base operations.

6. CONCLUSION

In semiarid to arid environments traditional stream measurements fail to fully describe the hydrology due to the ephemeral and intermittent nature of most flows. Despite the absence of continuous flow, an abundance of ecohydrological interactions are known to occur within these stream channels that require an improved method for characterizing the hydrologic flow regime. While frequency and magnitude of flows can determine hydrologic connectivity within the watershed and limit the amount of soil moisture and nutrients available for vegetation uptake, little observational data exists to accurately describe these parameters.

The results show that it is possible to use rainfall-runoff models to capture flow permanence and peak flow data that better characterizes the flow regime of ephemeral and intermittent streams. It demonstrates how the AGWA toolkit was used to setup and run the continuous simulation SWAT model, from which daily flow values were derived, and the event orientated KINEROS2 model, from which peak flows were estimated. Calibration and validation of both models were performed at two sites in Fort Huachuca that contained active stream gauges. Acceptable results were achieved for the SWAT simulations on a monthly time-step using NEXRAD-MPE precipitation data. The methodology developed herein illustrated using daily flow data it is possible to obtain average annual and wet season flow permanence using flow cutoff values based on Tidbit temperature sensor data from several stream channels at Fort Huachuca. These flow cutoff values can then be assigned to the unmonitored stream reaches based on the contributing watershed area. Additional model simulations using climate projection data were able to identify stream reaches that are most vulnerable under a hotter, drier scenario. While quantifiable results were achieved at the calibrated watersheds, an analysis of the relative differences between different reaches within the watersheds provides enough information to guide decision-making.

This research demonstrates that it is possible to use free and easily obtainable datasets within AGWA to setup and simulate a rainfall-runoff time series to characterize stream hydrology in unmonitored watersheds. These results can be correlated to vegetation metrics to identify areas with increased ecological sensitivity. Such associations would make it possible to make vegetation change predictions that occur in response to hydrologic changes from future land-use development or climatic changes. Such knowledge would promote ecologically sensitive land management decisions that direct development away from critical habitat areas thereby preserving the integrity of the ecosystem.

APPENDICES

APPENDIX A: FLOW PERMANENCE MAPS

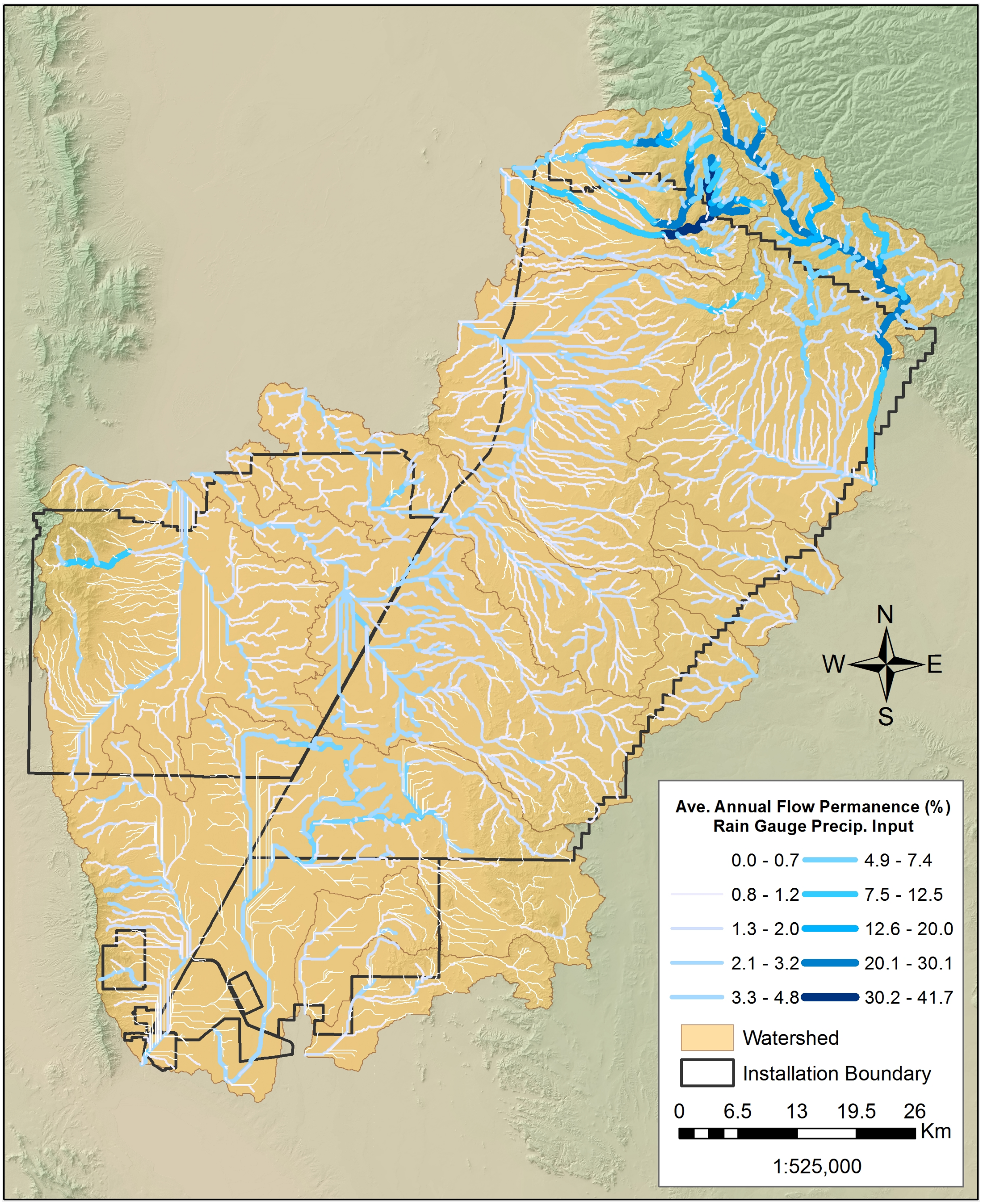


Figure A1. Flow permanence at Fort Bliss using rain gauge precipitation data.

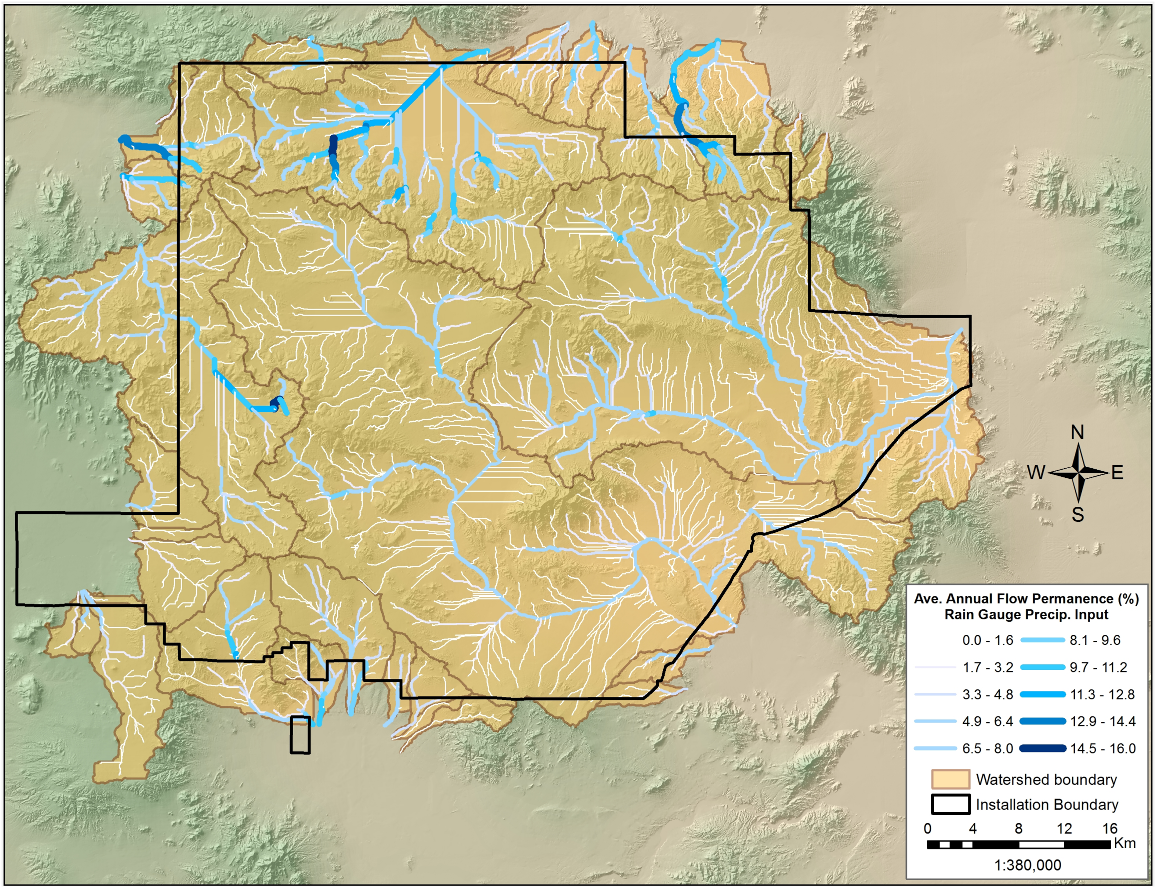


Figure A2. Flow permanence at Fort Irwin using rain gauge precipitation data.

Figure A3. Flow permanence at Yuma Proving Grounds using rain gauge precipitation data.

APPENDIX B: ABSOLUTE CHANGE FLOW PERMANENCE MAPS

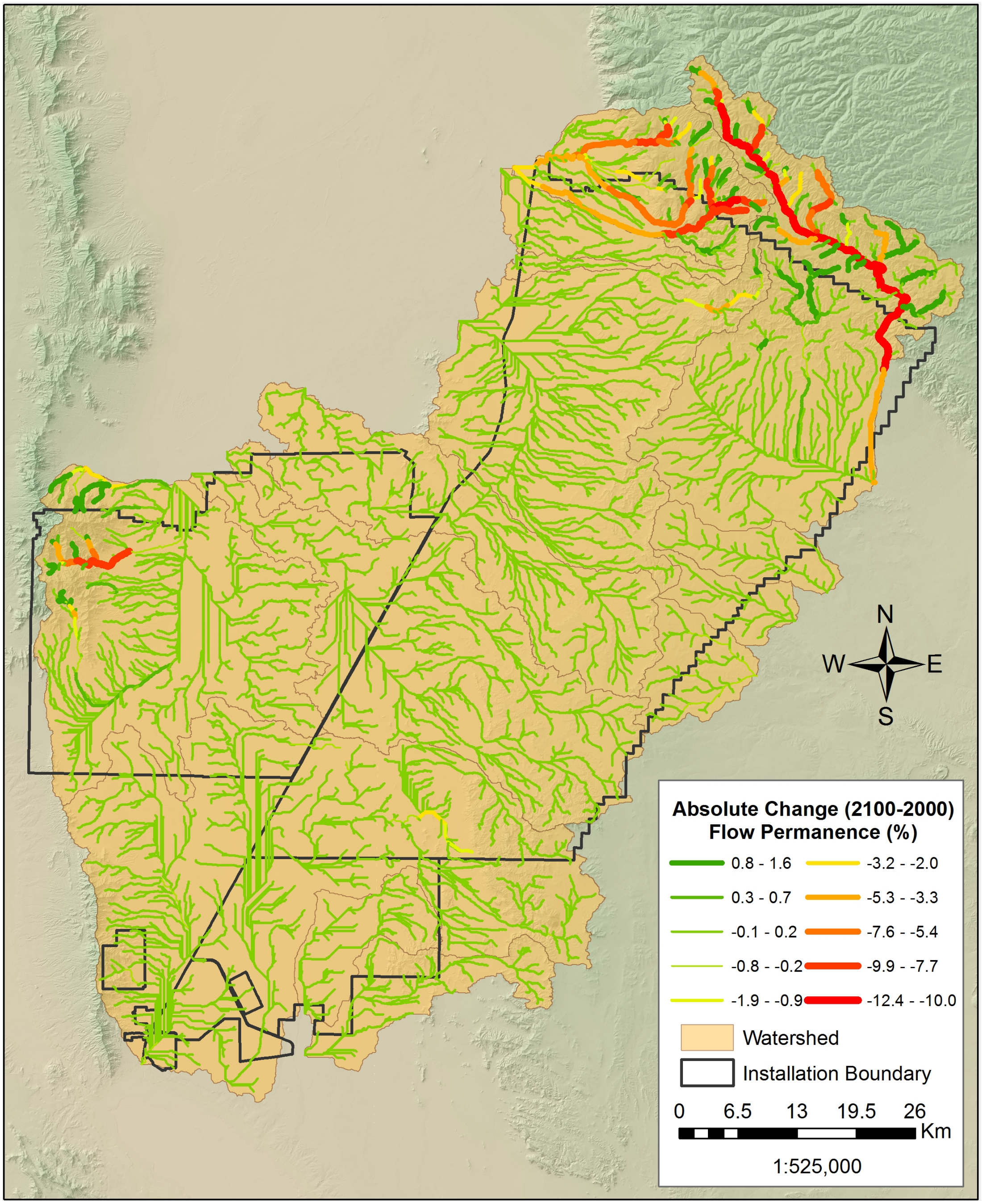


Figure B1. Absolute change in flow permanence between 1981-2000 and 2081-2100 at Fort Bliss using GFDL CM2.1 climate projection data.

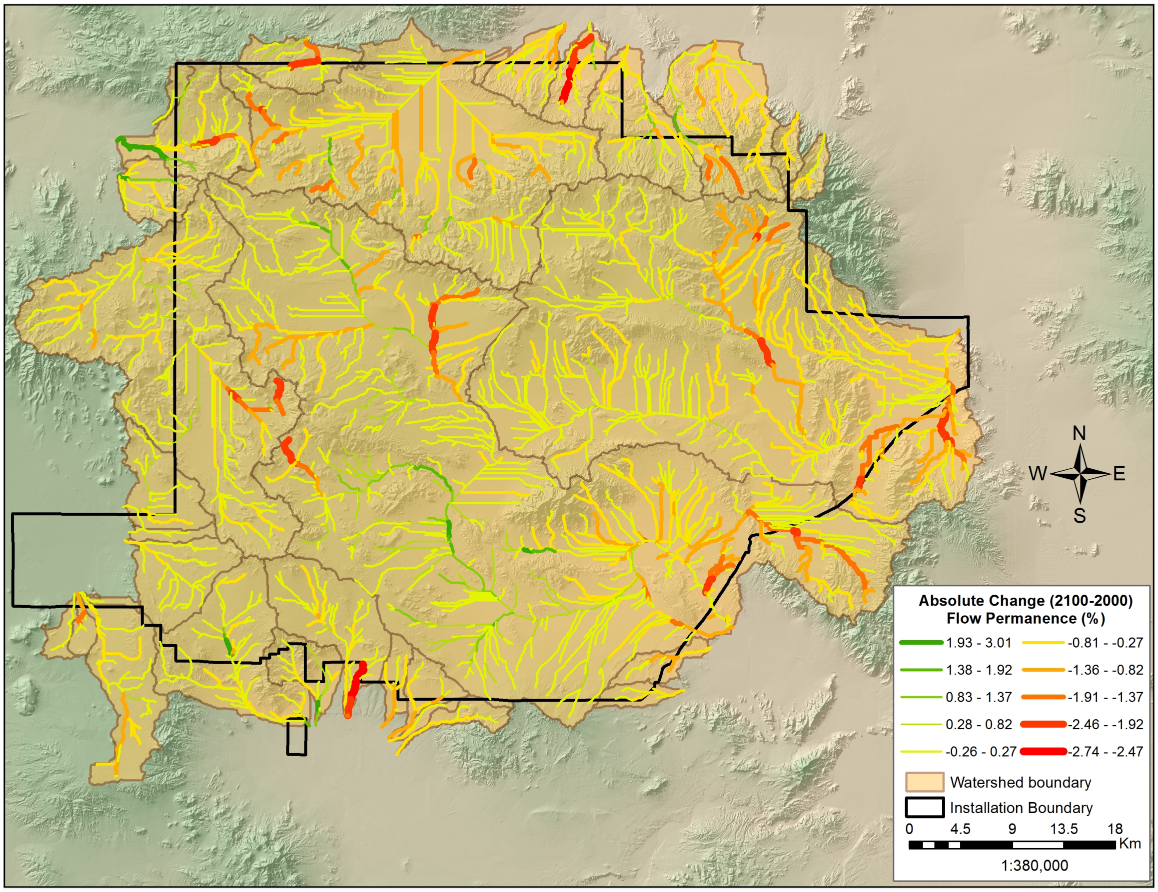


Figure B2. Absolute change in flow permanence between 1981-2000 and 2081-2100 at Fort Irwin using GFDL CM2.1 climate projection data.

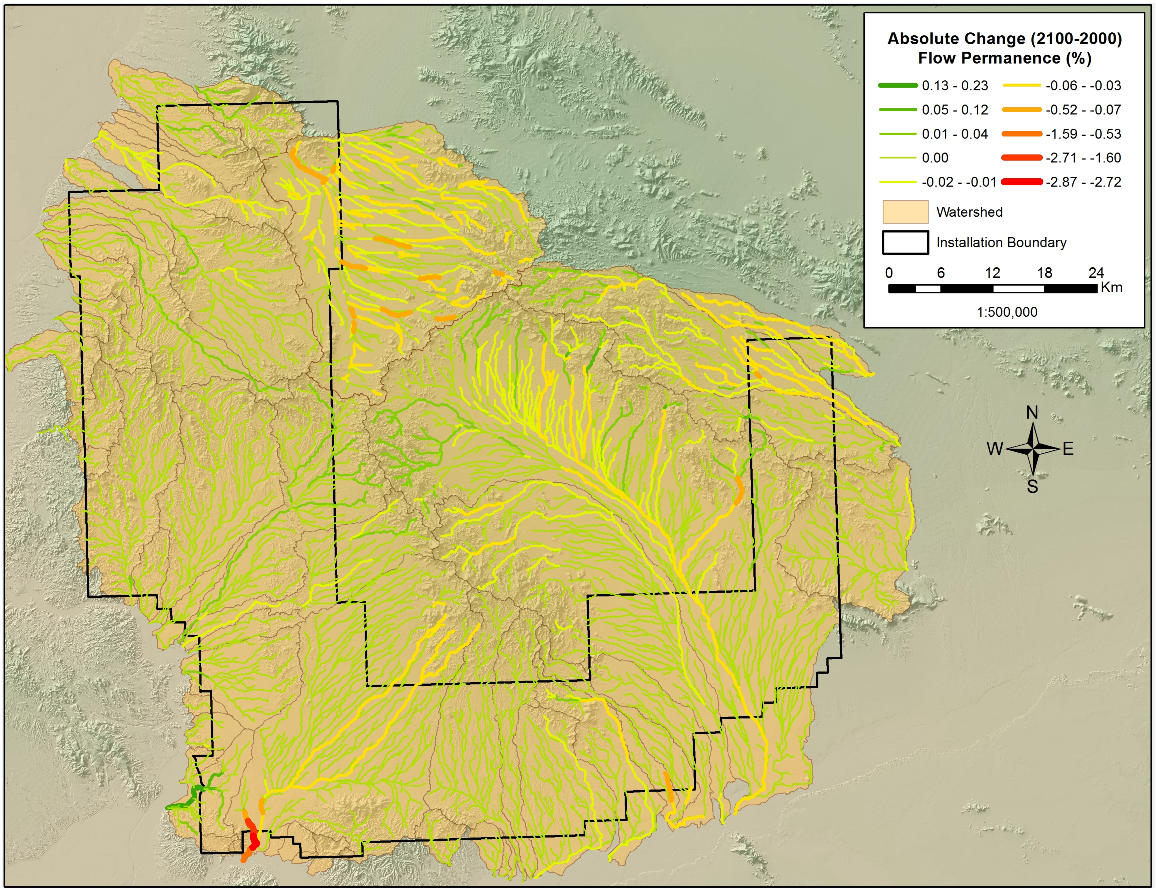


Figure B3. Absolute change in flow permanence between 1981-2000 and 2081-2100 at Yuma Proving Grounds using GFDL CM2.1 climate projection data.

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