Final Report: Phase II Nevada Water Resources Data, Modeling, and Visualization (DMV) Center

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II. OVERVIEW

Water is unquestionably a critical resource throughout the United States. In the semi-arid west -- an area stressed by increase in human population and sprawl of the built environment -- water is the most important limiting resource. Crucially, science must understand factors that affect availability and distribution of water. To sustain growing consumptive demand, science needs to translate understanding into reliable and robust predictions of availability under weather conditions that could be average but might be extreme. These predictions are needed to support current and long-term planning. Similar to the role of weather forecast and climate prediction, water prediction over short and long temporal scales can contribute to resource strategy, governmental policy and municipal infrastructure decisions, which are arguably tied to the natural variability and unnatural change to climate. Change in seasonal and annual temperature, precipitation, snowmelt, and runoff affect the distribution of water over large temporal and spatial scales, which impact the risk of flooding and the groundwater recharge. Anthropogenic influences and impacts increase the complexity and urgency of the challenge.

The goal of this project has been to develop a decision support framework of data acquisition, digital modeling, and 3D visualization. This integrated framework consists of tools for compiling, discovering and projecting our understanding of processes that control the availability and distribution of water. The framework is intended to support the analysis of the complex interactions between processes that affect water supply, from controlled availability to either scarcity or deluge. The developed framework enables DRI to promote excellence in water resource management, particularly within the Lake Tahoe basin. In principle, this framework could be replicated for other watersheds throughout the United States.

Phase II of this project builds upon the research conducted during Phase I, in which the hydrologic framework was investigated and the development initiated. Phase II concentrates on practical implementation of the earlier work but emphasizes applications to the hydrology of the Lake Tahoe basin. Phase 1 efforts have been refined and extended by creating a toolset for geographic information systems (GIS) that is usable for disparate types of geospatial and geo-referenced data. The toolset is intended to serve multiple users for a variety of applications.

The web portal for internet access to hydrologic and remotely sensed product data, prototyped in Phase I, has been significantly enhanced. The portal provides high performance access to LANDSAT-derived data using techniques developed during the course of the project. The portal is interactive, and supports the geo-referenced display of hydrologic information derived from remotely sensed data, such as various vegetative indices used to calculate water consumption. The platform can serve both internal and external constituencies using inter-operating infrastructure that spans both sides of the DRI firewall. The platform is intended grow its supported data assets and to serve as a template for replication to other geographic areas. An unanticipated development during the project was the use of ArcGIS software on a new computer system, called the IBM PureSytems, and the parallel use of the systems for faster, more efficient image processing.

Additional data, independent of the portal, was collected within the Sagehen basin and provides detailed information regarding the processes that control hydrologic responses within mountain watersheds. The newly collected data include elevation, evapotranspiration, energy balance and remotely sensed snow-pack data.

A Lake Tahoe basin hydrologic model has been developed, in part to help predict the hydrologic impacts of climate change. The model couples both the surface and subsurface hydrology, with the two components having been independently calibrated. Results from the coupled simulations involving both surface water and groundwater processes show that it is possible to fairly accurately simulate lake effects and water budget variables over a wide range of dry and wet cycles in the historical record. The Lake Tahoe basin is representative of the hydrology, topography and climate throughout the Sierra Nevada Range, and the entire model development is prototypical of the efforts required to replicate the decision support framework to other locales. The Lake Tahoe model in particular, could allow water managers to evaluate more accurately components of the water budget (ET, runoff, groundwater, etc) and to answer important questions regarding water resources in northern Nevada. This report discusses the geographic scale and the hydrologic complexity of the calibrated model developed as part of this project, as well as simulation results for historical and future climate projects

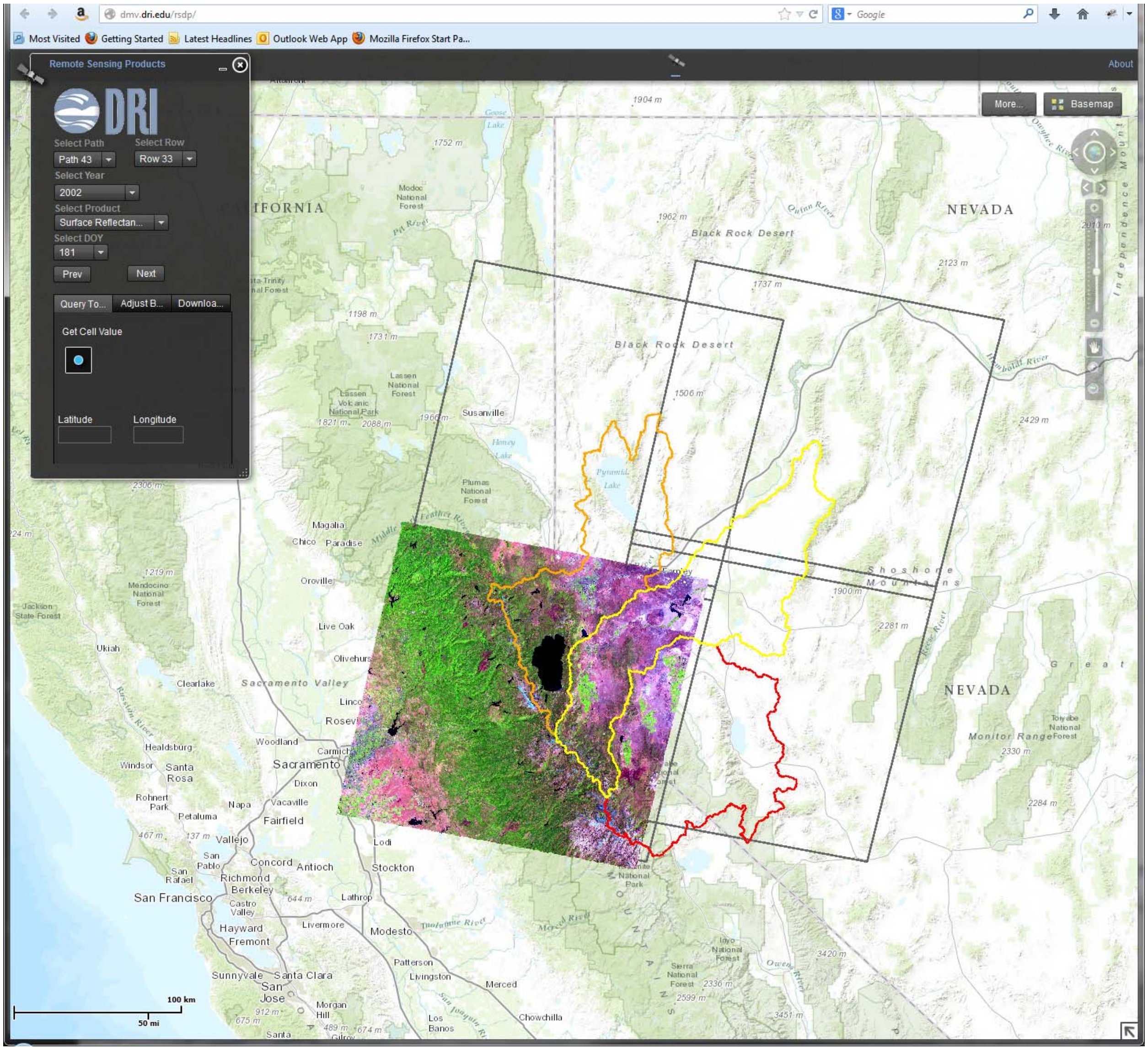
To enable human-driven data exploration and discovery, de novo software for a globalized rendering module that extends the capability of our evolving custom visualization engine from Phase I (called SMEngine) has been developed. The new rendering component, called Horizon, supports terrain rendering capable of displaying and interrogating both remotely sensed and modeled data. The development of Horizon necessitated adaptation of the visualization engine to allow extensible integration of components such as the global rendering module and support for associated features. The resulting software is general in its GIS capability, but a specific Lake Tahoe visualization application suitable for immersive decision support in the DRIVE6 virtual reality facility has been developed. During the development, various features to enhance the value of the visualization experience were explored, including the use of hyperspectral image overlays. An over-arching goal of the visualization aspect of the project has been to develop and demonstrate the CAVE (CAVE Automatic Virtual Environment) as a practical tool for hydrologic research.

The three components of this project – Data, Modeling and Visualization – had independent milestones and worked as independent but coordinated teams over the term of the project. Reports from the three teams are discussed in the following sections.

III. DATA

Development of a Web Portal for Historical Remote Sensing Products Related to Hydrologic and Environmental Monitoring in the Truckee River Basin

DRI’s data team continued development efforts towards a live web portal for serving historical remote sensing products for the Truckee River Basin (Figure III-1.) Landsat Thematic Mapper (TM) data collected from 2001 through 2011 were used to develop the derivative products. The derivative products focus on hydrologic and environmental monitoring data sets outside users can implement in their own research in the Basin. Necessary modifications were made to the Phase I computer-based framework (hardware and software) that hosts the large set of remote sensing derivative products available through the web portal (over 4,000 images) so that the data could be made available to outside users. Modifications were made to the original data formats of the derivative products to make their observation in the portal more efficient and faster. DRI scientists tested the web portal outside the DRI firewall, evaluating both the interface and download capabilities of the portal.



dmv.dri.edu/rsdp/

Remote Sensing Products

Select Path: Path 43

Select Row: Row 33

Select Year: 2002

Select Product: Surface Reflectan...

Select DOY: 181

Figure III-1. Web portal interface for hydrologic and environmental monitoring in the Truckee River Basin using historical remote sensing products. Image shown is a surface reflectance product from the Landsat 5 satellite for early spring, 2008.

The web portal was designed with a tool set and graphical user interface similar to image visualization and download sites such as the Global Visualization Viewer (GLOVIS) website published by the U.S. Geologic Survey (USGS). Tools were provided for both spatial and temporal selection of a variety of remote sensing products, including surface reflectance, surface albedo, surface temperature, and the following vegetation indices,: Enhanced Vegetation Index (EVI); Modified Soil Adjusted Vegetation Index (MSAVI); Normalized Difference Vegetation Index (NDVI); and Normalized Difference Water Index (NDWI). Table III-1 contains lists the remote sensing products now offered on the portal. As in Phase I, the web application was developed primarily using ArcServer, ArcSDE, and Flex 4 software, with modifications described below. The web application allows users to avoid time consuming downloading and preprocessing steps; these steps are performed by DRI on the front end. All products are geometrically aligned to a common area and pixel size (30 meters). Data can be quickly collected and analyzed for each scene; sample cells may be selected for each particular scene, time series of various parameters can be developed for all available Landsat TM scenes, and the user can sample within a user defined area of interest. Finally, the user can easily download products for further analysis. Figure III-2 shows an example of the EVI product for an area in northwestern Nevada. EVI is related to evapotranspiration (ET) and can be used to quantify and analyze water consumption by phreatophytes and agricultural crops in arid environments. Figure III-3 shows a change detection application using the surface reflectance product. By comparing surface reflectance data from the same scene footprint over time, scientists can evaluate urban growth and the reduction in wetlands and agricultural production.

Table III-1. Description of the remote sensing data products available on the DMV web portal.

Data	Description	Source	Spatial Extent
Image Data (Rasters)			
Landsat Thermatic Mapper (TM) Imagery	Multi-date Landsat Thematic Mapper satellite imagery for years 2001 to 2011 – corrected to surface reflectance composites by DRI	USGS, DRI	Eastern California / Western Nevada
Landsat TM Surface Temperature	Multi-date surface temperature derived from Band 6 of Landsat TM data	DRI	Eastern California / Western Nevada
Landsat TM Surface Albedo	Multi-date surface albedo derived from Landsat TM visible and NIR bands	DRI	Eastern California / Western Nevada
Landsat TM NDVI	Multi-date Normalized Difference Vegetation Index derived from red and NIR Landsat TM bands	DRI	Eastern California / Western Nevada
Landsat TM MSAVI	Multi-date Modified Soil Adjusted Vegetation Index derived from Landsat TM bands	DRI	Eastern California / Western Nevada
Landsat TM EVI	Multi-date EVI Enhanced Vegetation Index derived from Landsat TM bands	DRI	Eastern California / Western Nevada
Landsat TM NDWI	Multi-date NDWI Normalized Difference Water Index from Landsat TM bands	DRI	Eastern California/ Western Nevada

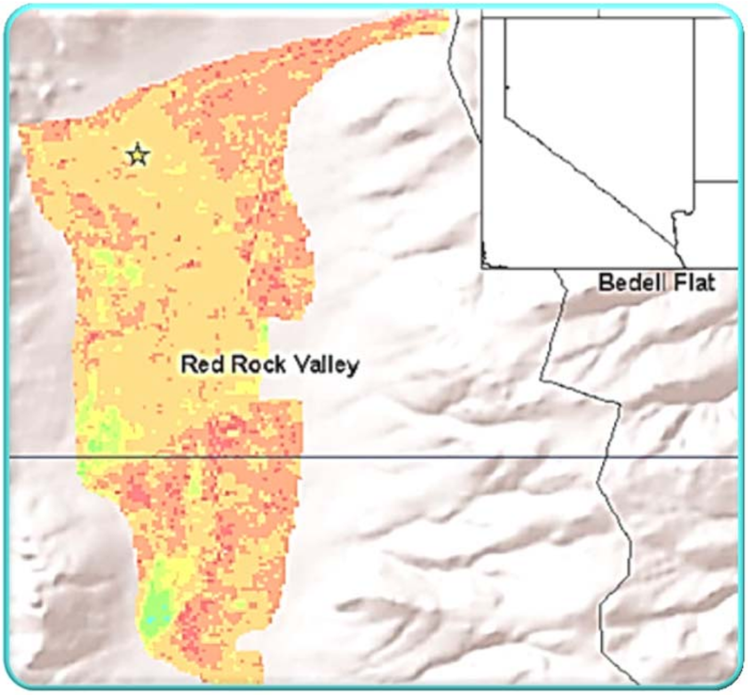
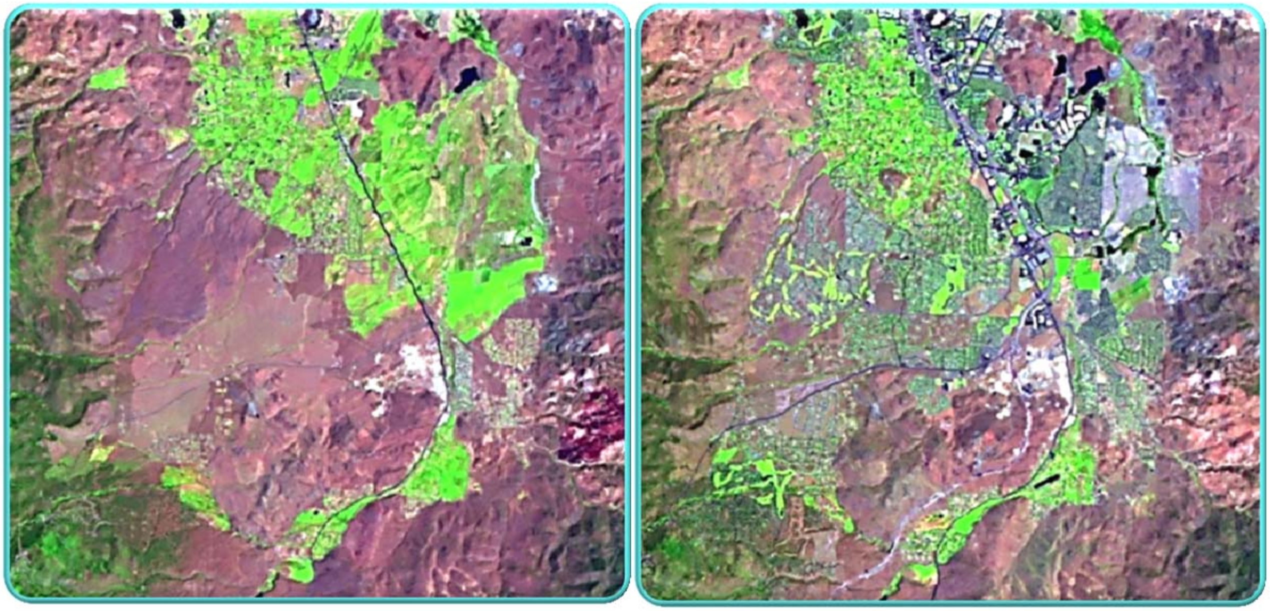


Figure III-2. Enhanced Vegetation Index (EVI) results for the Red Rock Valley in Northwestern Nevada. High EVI in green, low EVI in orange.



July 17, 1985 **July 6, 2010**

Figure III-3. Surface reflectance products from two different dates for the southern Reno/Truckee Meadows area showing land use change from 1985 to 2010.

In Phase II of the DMV project, DRI scientists attempt to add additional remote sensing data products to the web portal content beyond those developed in Phase I, however these efforts were unsuccessful due to hardware and software limitations presented by DRI servers and ESRI software.

Web Portal Hardware and Software Modifications

The DMV Remote Sensing Data Portal (Http://dmv.dri.edu/rsdp) developed in Phase 2, now consists of two virtual servers; one server hosting the ArcGIS Server site and data while the other virtual machine is outside of DRI's firewall acting as a reverse proxy pass thru for the ImageServices request and access to the download the data. Both servers are running Windows Server 2008, while only the internal server running ArcGIS Server 10, ARCSDE 10, Flex 4.6 development site, and Microsoft SQL Server 2008. The internal server has also been upgrade with 192 gigabytes of RAM and an external storage device with six terabytes of capacity. These improvements were required to host 4,535 Landsat derivative ImageServices processed from the 2001 to 2011 Landsat scenes.

During the iterations conducted in the prototype phase of this design effort, hardware limitations restricted how many ImageServices could be hosted at one time. This number was far below the total number of scenes need to serve the portal. Solving this problem was accomplished by upgrading the internal machine and configuring it to run as a virtual server.

Through the prototype phase two ESRI ArcGIS software suites were tested with the upgraded hardware configuration: ArcGIS version 10.0 and ArcGIS version 10.1. Initially, DRI scientists installed the newest version of ArcGIS version 10.1 once the hardware reconfiguration was completed. Unfortunately, significant issues occurred during the implementation of ArcGIS version 10.1, mainly the inability to publish ImageServices in a batch process mode where multiple years could be added. Once one year was added to the portal the next year would fail after publishing the first scene for that year. This issue did not exist with the ArcGIS version 10.0 so a decision was made to revert back to version 10.0 and reestablish the ImageServices. After reinstalling ArcGIS version 10.0 all batch publishing issues were resolved.

Data Format Modifications for Derivative Data Products

To improve the speed of displaying the image data products on the web portal, DRI scientists used the Institute's new IBM Pure Systems (PureApplication System) to convert and compress each image. This reduced the size of each image file, and therefore reduced the display time required for users to load the image into the graphical user interface. The image files were converted from 32 bit floating point data to integer format. For all of the vegetation indices products, the data values were multiplied by 1000 and then rounded to the nearest integer, so that each cell would have an integer value but retain precision to three decimal points. For surface temperature images the cell values were multiplied by 50, since the approximate bit resolution of the raw thermal data is ~0.5 degrees Kelvin and because the values are on the order of 300 degrees Kelvin, as opposed to -1.0 to 1.0 for the vegetation indices. Finally, to compress the file sizes of each image and increase the display speed for each in the portal, image pyramids were built for all output raster images.

The process of conversion and compression on such a large number of floating point images would normally have taken several weeks to complete on DRI's server constellation, but running the functions on the new PureApplication System only took approximately four to five hours. The combination of solid state drives, very fast CPU, and an abundance of RAM made the difference in performance.

Live Testing of Web Portal Functionality

After solving the batch publishing issues, creating the appropriate ImageServices for the historical derivative remote sensing data sets, and setting up the reverse proxy for DRI's firewall with the second virtual machine, access to the web portal from outside of DRI's website was tested from remote machines. Using the URL Http://dmv.dri.edu/rsdp, access to the graphical user interface was successfully tested by DRI scientists; the users were able to display the various data products available for different Landsat TM paths and rows (Paths 42 and 43, Rows 32 and 33) covering the Northern Nevada study area.

The download capability was also tested successfully; users were able to download zip format versions of each individual derivative data product: Surface Reflectance, surface albedo, surface temperature, NDVI, MSAVI, EVI, and NDWI. After adding the scene and date of interest to the download list, the user selects the product of interest and a dialog box appears that allows the user to select the location on their local machine or the network as to where they want to store the zip file. Once the zip file is stored, the image files and headers can be extracted using WinZip or WinRAR. The image files themselves are unpacked as ERDAS Imagine image files with associated header files

Geospatial Data Support of CAVE Visualization Tasks using High Resolution Optical Remote Sensing Imagery and LiDAR data of the Lake Tahoe Basin.

In support of DRI's visualization tasks in the CAVE, the DMV Data Team processed high spatial and spectral resolution hyperspectral imagery and high spatial resolution Light Detection and Ranging (LiDAR) data of the Lake Tahoe Basin. The Data Team also processed high resolution multispectral WorldView-2 satellite imagery of the Basin. These data were processed and converted into formats compatible with the CAVE hardware and software architecture. The hyperspectral imagery, WorldView-2 and LiDAR bare earth data will be integrated to create a terrain surface in the CAVE with imagery draped over the terrain model.

Using 0.5 meter and 1.0 meter Eagle/Hawk hyperspectral data flown by SpecTIR, Inc. in the summer of 2011, DRI created spatial and spectral subsets of the data for the Tahoe City, CA and Incline Village/Eastern Shore, NV areas of the Lake Tahoe Basin in TIF format (Figures III-4, III-5, and III-6). The high resolution images allow the user to discern individual trees, automobiles, and detect different patterns of sediment density and bottom cover in the shallow near-shore zone of the lake. Subsequent processing produced customized band combination images to enhance the analysis of the shallow near-shore zone water column with the purpose of discerning sediment content density and concentrations (Figure III-7). This was done by combining the "water bands" of the SpecTIR Eagle-Hawk sensor, i.e. spectral bands that can sense reflected energy from the lake bottom as well as the water column.

Figure III-4. True color composite image of Tahoe City hyperspectral imagery at 0.5 meter resolution.

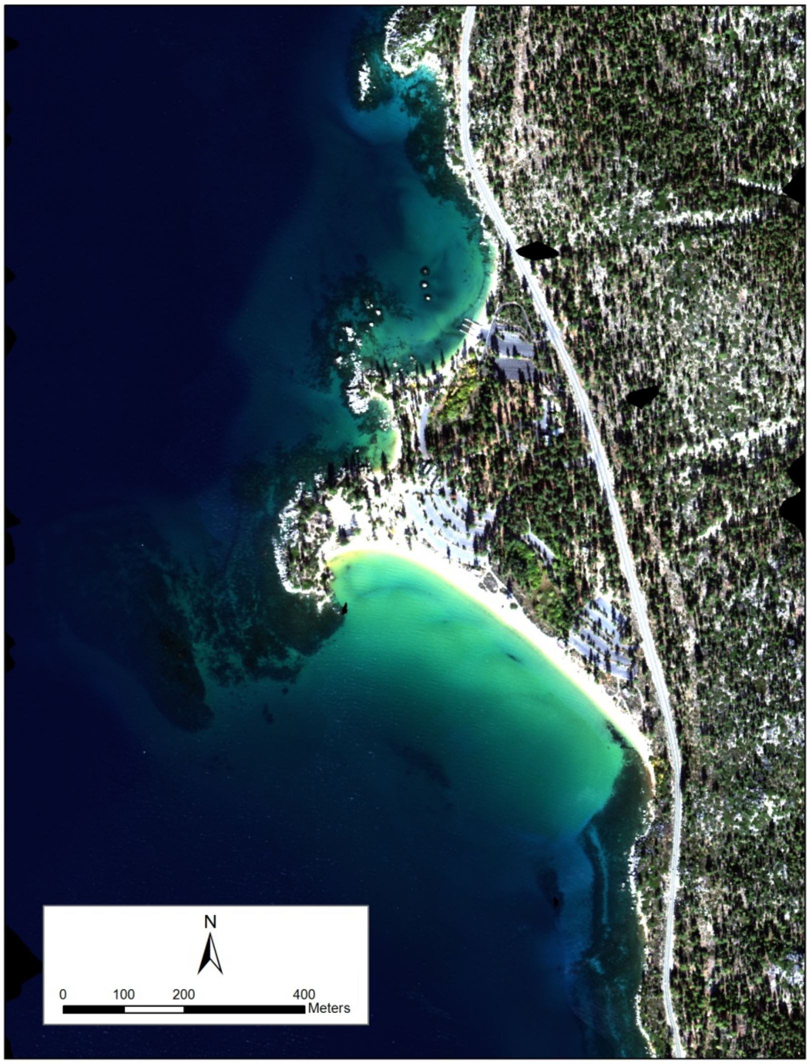


Figure III-5. True color composite image of Sand Harbor hyperspectral imagery at 1.0 meter resolution.

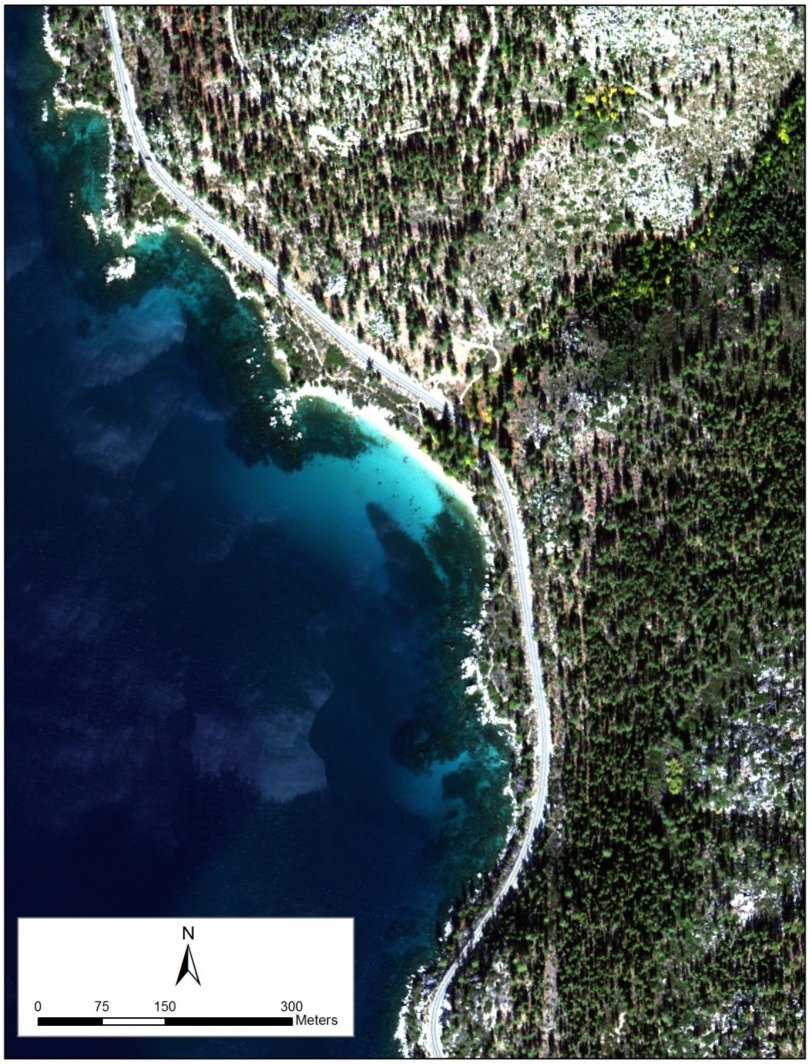


Figure III-6. True color composite image of Tunnel Creek hyperspectral imagery at 1.0 meter resolution.

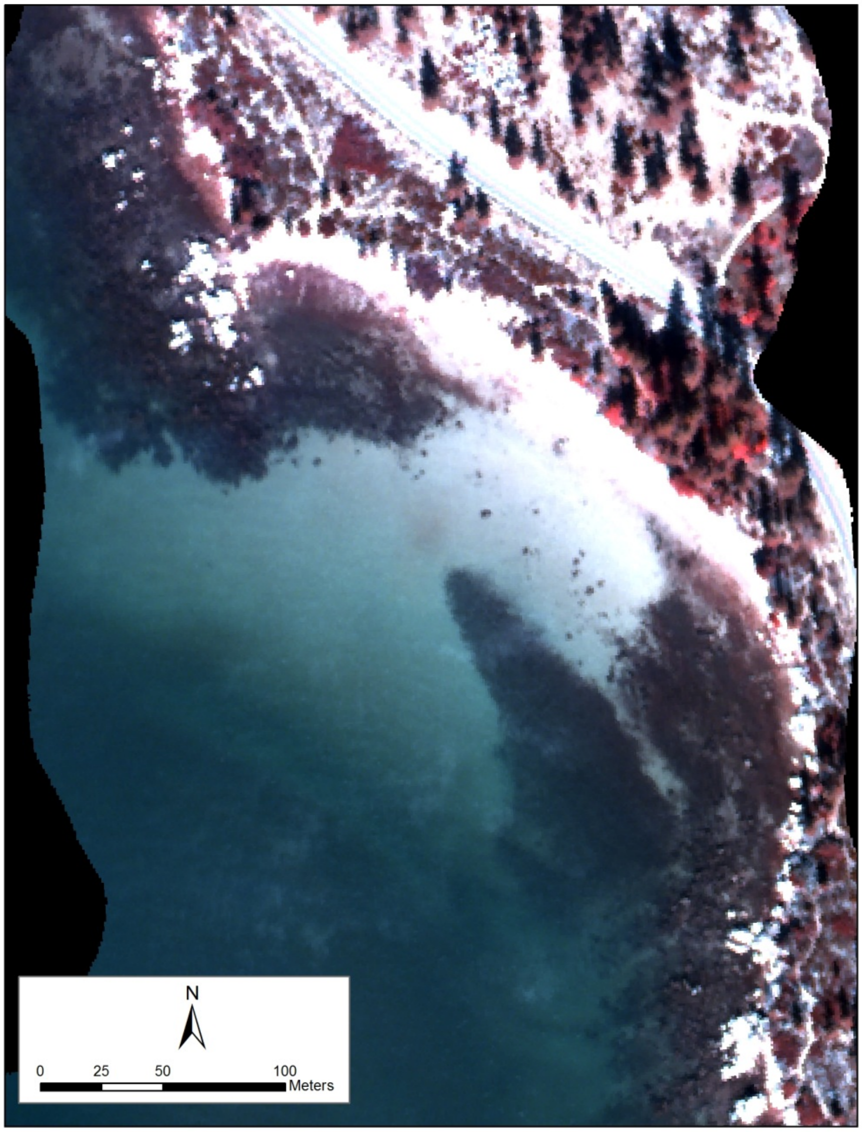


Figure III-7. Water band composite (SpecTIR Eagle-Hawk bands 36 (0.5635um), 18 (0.4818um), and 9 (.4413um) in RGB) for the mouth of Tunnel Creek as it runs into Lake Tahoe.

The DMV data team processed high resolution LiDAR data collected over the Lake Tahoe Basin in the summer of 2010 to provide the DMV Visualization team with a derivative DEM product that could be used with CAVE hardware and software architecture. The data were originally collected by Watershed Sciences, Inc. from August 11th to August 24th, 2010. The data team utilized the hydro-enforced bare earth model of the Basin produced by Watershed Sciences, as it more accurately represents the actual drainage flow through the use of hard breaklines to account for culvert and other artificial impediments to flow (Figure III-8).

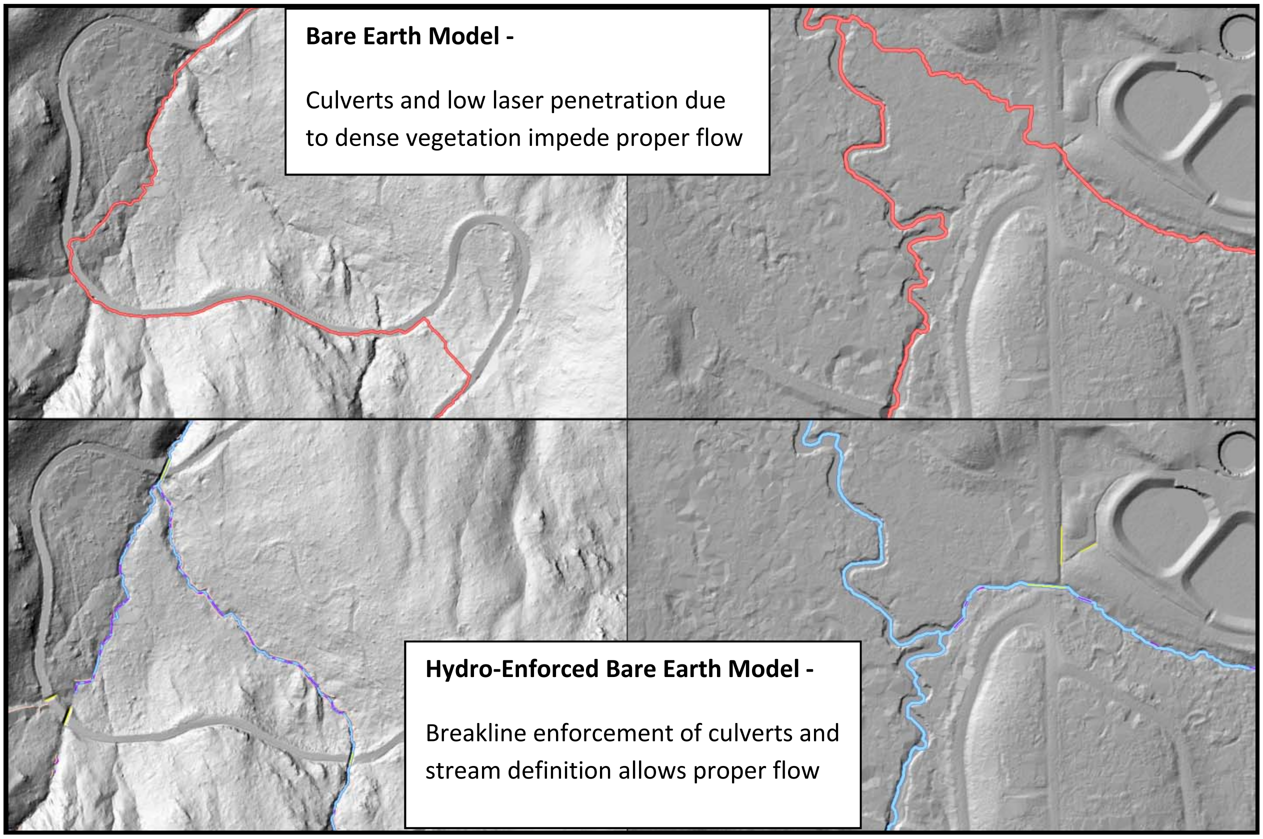


Figure III-8. Examples of bare earth to hydro-enforced bare earth model improvements for stream drainage systems in the Lake Tahoe Basin.

The derivative hydro-enforced DEM product the Data team produced for the Visualization team was a 10.8 gbyte subsection of the northern third of the Lake Tahoe Basin, subsectioned at full resolution (0.5 meter horizontal resolution). This data set included all of the north shore the lake, the Incline Village area, and south to Ward Creek on the west side of the Lake and to Skunk Harbor on the east side (Figure III-9).

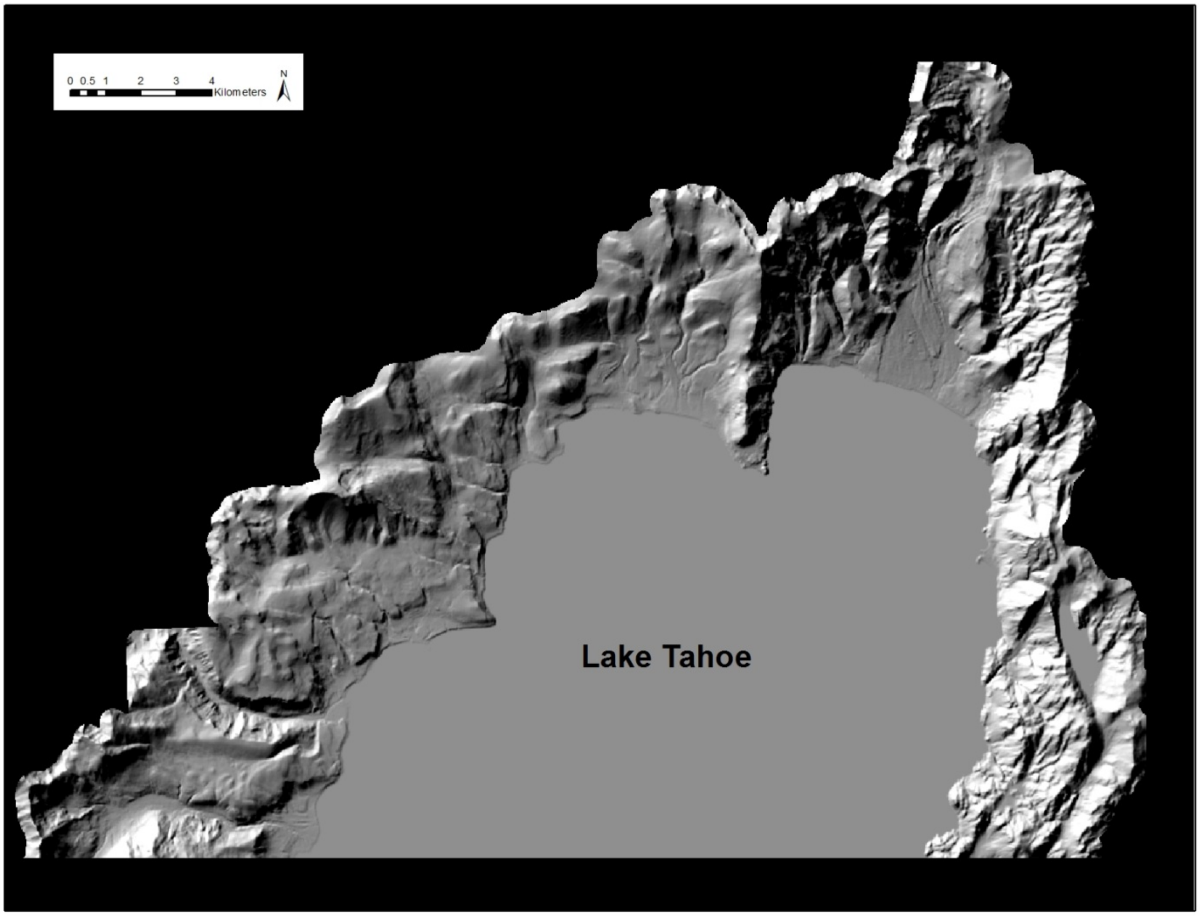


Figure III-9. Hillshade of the northern Lake Tahoe Basin hydro-enforced DEM.

The DMV data team also provided the DMV visualization team with a high resolution WorldView2 satellite based image of the same area (northern third of the Lake Tahoe Basin). WorldView 2 is a commercial satellite platform at 770 km in space owned and operated by DigitalGlobe, Inc. Imagery of the Lake Tahoe Basin (excluding the deepest parts of the Lake) were collected at approximately the same time as the Watershed Sciences, Inc. LiDAR data collect, August and September of 2010. These data were purchased by a consortium of agencies and institutions led by the Tahoe Regional Planning Authority (TRPA). WorldView2 has a unique band configuration: It has a broadband panchromatic (black and white) channel (0.45 to 0.80um) with a horizontal spatial resolution of 0.46m, and an eight band multispectral imaging system that includes bands from the blue portion of the spectrum (0.4 to 0.45um for bathymetric and vegetation studies) to the shortwave infrared (0.86 to 1.04um for vegetation and biomass studies) at 1.84 horizontal spatial resolution. Several products were developed by DigitalGlobe for the study area, the DMV team utilized the “pansharpened” product, which is a fusion of the 0.46m panchromatic data and the 1.84m multispectiral data. The panchromatic band is used to “sharpen” the coarser resolution multispectral data; the resultant product has finer spatial resolution but still contains all the spectral information of the multispectral bands. Figure III-10 is a three band composite (bands 5, 3, 2 or Red, Green, Blue (true color) in RGB color space) showing the subsection the DMV data team extracted from the master data set for use in the CAVE. The data set provided to the DMV visualization team included all eight multispectral bands.

Figure III-10. WorldView2 three band composite (bands 5,3,2 in RGB) for the northern Lake Tahoe Basin area.

Development of Sagehen Study Area Remotely Sensed Data Sets Related to Snow Cover and Evapotranspiration

The Sagehen Creek watershed in the Sierra Nevada Mountains of California is a long-term regional research area used by many scientists to study hydrology and forestry (Figure III-11). As part of DMV Phase II, DRI scientists have continued to collect data that will verify processes that control hydrologic responses within mountain watersheds such as Sagehen. Data collected include high resolution LiDAR remote sensing data processed to derive bare earth elevation values for the watershed. These data can be used to image and model surface geology, snow-water equivalent (SWE) crown-bulk density, and fluvial geomorphology. LiDAR data were collected on two different dates. One data set was collected during the summer of 2006 for the UC Berkeley Center for Forestry by Sanborn, Inc. , with pre-processing performed by the National Center for Airborne Laser Mapping (NCALM) (Figure III-12). A second LiDAR data set was collected by the NCALM in February of 2008 for a DRI scientist working on the DMV project (Figure III-13). The purpose of this second collection was to develop an elevation surface that represents the snow cover surface present at the time of the collect. With a summer and winter collect, post-processing can be performed to subtract one bare earth data set (summer collect, ground surface) from the other (winter collect, snow surface) to determine snow depth and thus SWE.

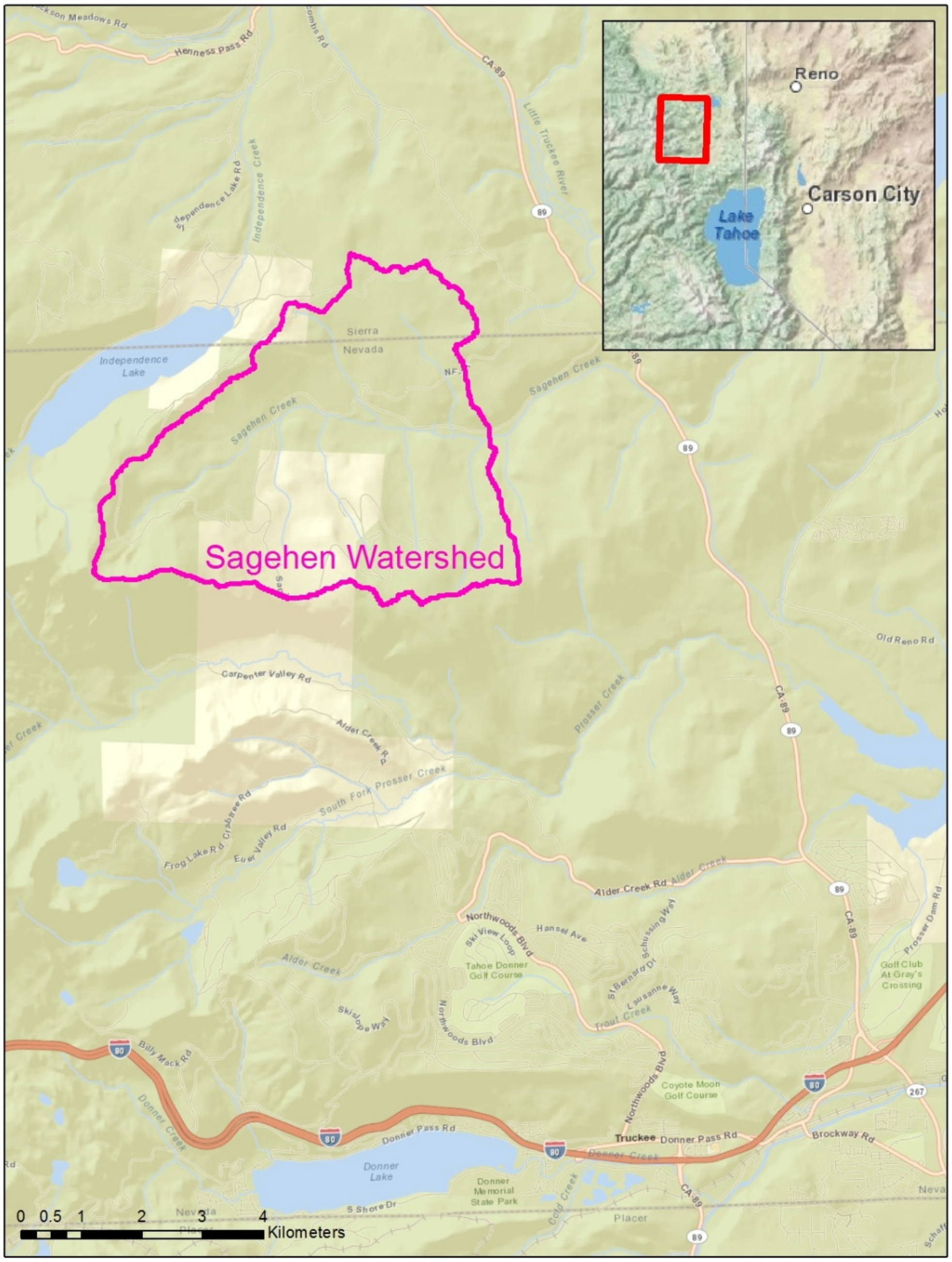


Figure III-11. Location of Sagehen watershed in the Sierra Nevada Mountains, CA.

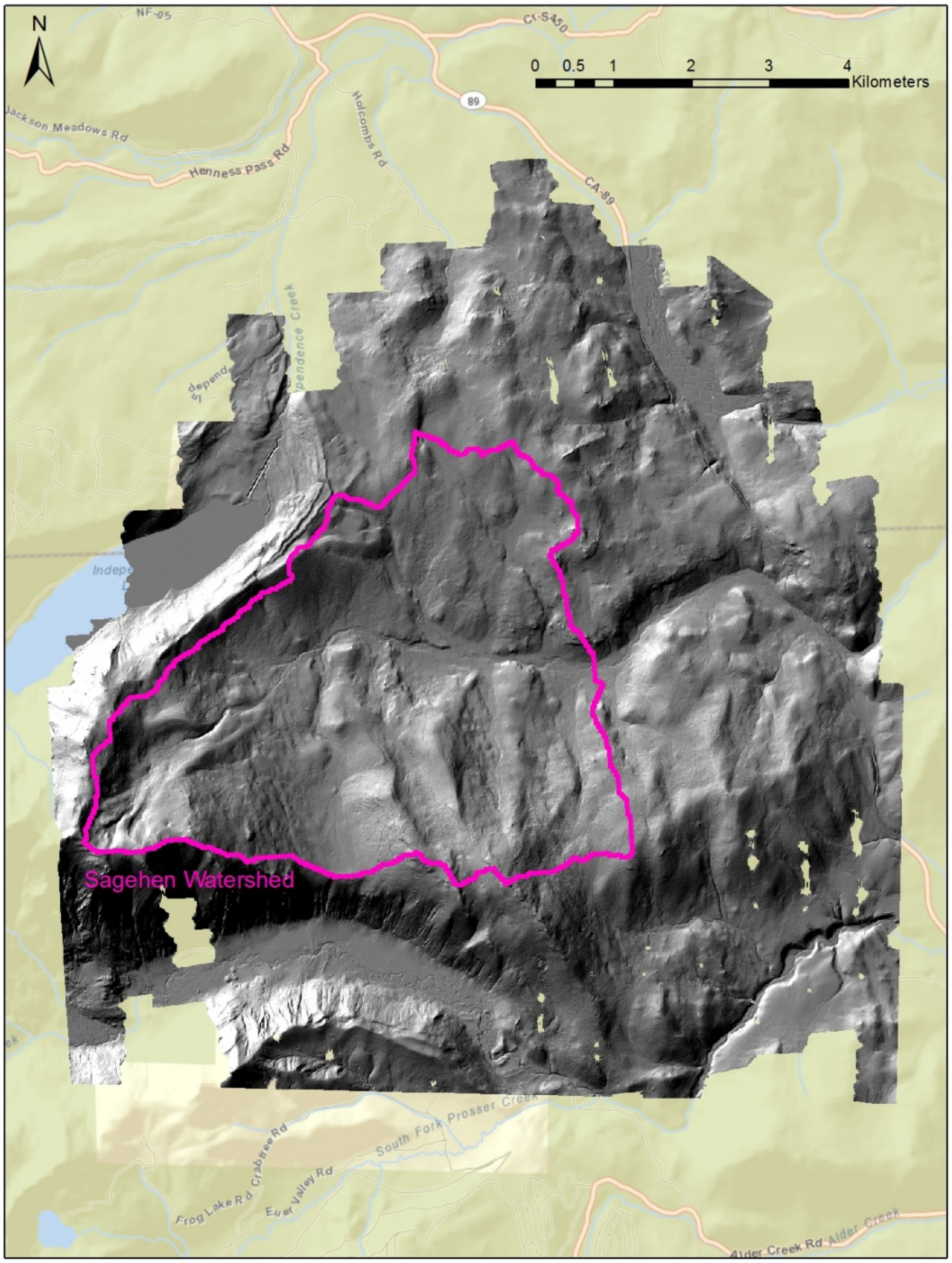


Figure III-12. Bare earth DEM of the Sagehen region derived from LiDAR data collected in the summer of 2006.

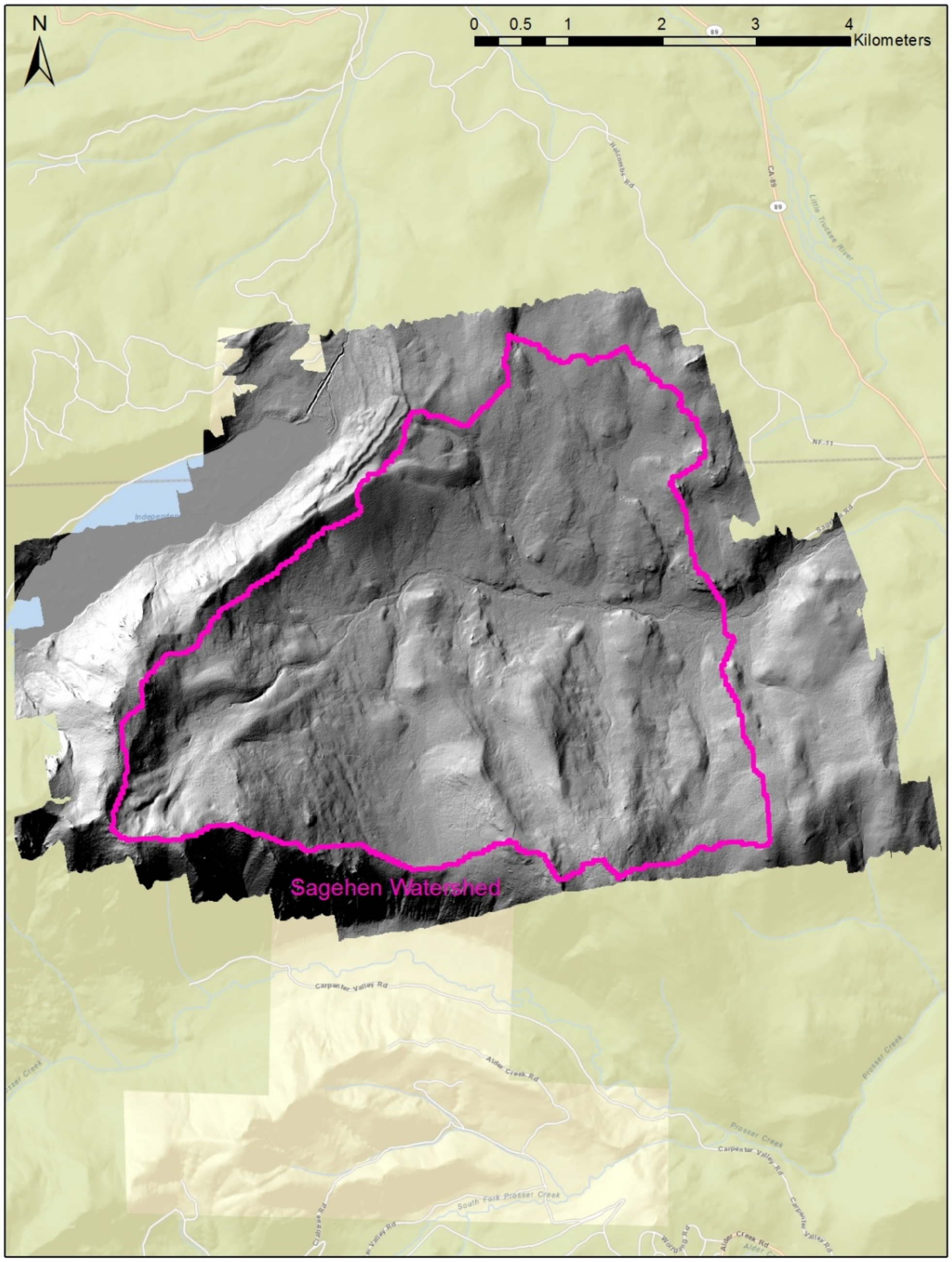


Figure III-13. Bare earth DEM of the Sagehen region derived from LiDAR data collected in the winter of 2008.

In order to provide an efficient means of storage and retrieval for the Sagehen LiDAR data and its derivative products, an ArcGIS geodatabase was developed that contains all the rasters and feature classes for both LiDAR collection dates. Rasters include the floating point DEM and hillshade representation of the 2006 summer data, as well as a vegetation canopy heights raster and a hillshade representation of the canopy heights, and a grey shade representation of the canopy density. Raster data from the 2008 winter collect include the filtered and unfiltered floating point grids and hillshade representations of the bare earth surface. Feature classes include topographic contour data derived from the LiDAR data at three interval levels: 2 meters, 10 meters, and 50 meters.

Appendix B contains a description of additional data collected and processed in the Sagehen watershed related to evapotranspiration (ET), snow cover as derived from MODIS remote sensing data, precipitation, and water levels near Sagehen Creek.

Development of a Publication that Describes the Web Portal Development Effort

Appendix A contains an abstract for a publication that details the development and implementation of the web portal for historical remote sensing products for the Truckee River Basin. The completed manuscript will be submitted to a peer-review publication specializing in scientific web applications and/or geographic information systems (GIS) web applications.

DMV Data Summary and Conclusions

In Phase II of the DMV project, the "Data" part of the project focused on three primary project tasks: Development of a web portal for historical remote sensing projects related to monitoring in the Truckee River Basin, geospatial data support of CAVE visualization tasks; and development of Sagehen study area remotely sensed data sets developed from LiDAR data.

The historical remote sensing web portal developed in Phase I was made more efficient on the visualization side (user interface), with quicker turnaround on image display times and added functionality. Both the graphical user interface and the data product download capabilities were successfully tested outside the DRI firewall. The web portal will provide outside users from academic and government institutions the capability to perform image visualization of various derivative raster products used in a wide variety of environmental and hydrological applications, as well as utilize the tools provided for spatial and temporal query of the products. Users will have direct access to these products through the download option available within the portal, saving the time required to process these derivative products themselves for complex modeling and analysis.

High spatial and spectral resolution hyperspectral image data were processed and analyzed to produce CAVE-compatible data sets for use in terrain rendering and visualization applications for the Lake Tahoe near-shore areas. High spatial resolution satellite imagery and LiDAR data were processed to produce CAVE-compatible data sets for use in terrain rendering and visualization applications for the entire Lake Tahoe Basin land surface (excluding the lake itself).

High resolution remote sensing data (LiDAR data) were acquired, processed and integrated for the Sagehen Creek watershed research area. Data from two different dates were integrated into an ArcGIS geodatabase for use by DRI researchers. The two different dates of data provided a means of analyzing the differences between land surface elevations from a summer collect and those elevations observed for the snowpack in the winter collect. Contour lines derived from the

LiDAR bare earth data were also included in the geodatabase. In addition, vegetation canopy elevations derived from the LiDAR data were integrated into the geodatabase.

IV. MODELING

Section Overview

The U.S. Department of Interior (DOI) is currently initiating a historical and future water supply and demands investigation in the Truckee River basin as part of the WaterSMART (Sustain and Manage America's Resource for Tomorrow) program. Snowmelt runoff from the Sierra Nevada is a multibillion dollar resource that is critical to the region's economy, forest health, aquatic ecosystems, and agriculture. Snow melt runoff and storage water from Lake Tahoe is a primary water supply to the Truckee River, Reno, NV, and surrounding agricultural areas. Significant shifts in the timing of snowmelt and streamflow, and reductions in summer streamflow have recently been observed in the Lake Tahoe basin and larger Sierra Nevada region (Coats, 2010; Kim and Jain, 2010). Groundwater in the Tahoe region has recently been identified as vulnerable to changing climate (Singleton and Moran, 2010).

Groundwater will be pivotal for future water supplies and the health of groundwater dependent ecosystems (GDEs), yet our understanding of climate change impacts on surface water and groundwater (SW/GW) supply and exchange is very limited. The majority of water in the Truckee River basin emanates from high-altitude mountain catchments, thus a better understanding of how climate change affects hydrology in mountain catchments is essential for long-term water and biological resources planning in the region. Hydrologic modeling capabilities of mountain catchments are not very well developed. Most climate change hydrologic modeling studies of mountain catchments have relied on simple bucket and linear reservoir representation of groundwater, while either ignoring or over simplifying the effects of the unsaturated zone. These models calculate recharge independently of dynamic groundwater levels and SW/GW interactions. Furthermore, the important interplay between snowmelt-derived streamflow and SW/GW interactions are not simulated in a coupled manner, which is essential for evaluating climate-change impacts on summertime flow (baseflow) and GDEs in snow-dominated regions (Huntington and Niswonger, 2012).

Recent developments of integrated hydrologic models provide a means of simulating coupled hydrologic processes in mountain catchments. Integrated hydrologic models can provide greater insight into climate change effects on watershed hydrologic processes due to their ability to more realistically simulate feedback between hydrologic processes that occur above and below land surface (Maxwell and Kollet, 2008; Ferguson and Maxwell, 2010; Sulis et al., 2011; Huntington and Niswonger, 2012). In this report, we present an application of the integrated hydrologic model, GSFLOW (Markstrom et al., 2008) to simulate climate change effects on the hydrology in all the mountain catchments tributary to Lake Tahoe hydrographic area. The regional scale and hydrologic complexity of these catchments pose difficult challenges for hydrologic modeling; however, we have constructed useful models through innovative methods and automated calibration procedures. Century-long simulations of surface water and ground water flow provide unique insights into the feedbacks between climate and hydrologic fluxes that drain from the Sierra-Nevada to the Truckee River. For this report, we focus on conceptual model development and calibration of GSFLOW, and present modeling results for historical and future climate projections that demonstrate the unique hydrologic conditions of these mountain catchments.

Conceptual and Numerical Model Development

Maintaining a balance between adequate horizontal and vertical grid discretization, while honoring known stream, wetland, and lake locations and elevations (i.e., heads), is particularly difficult in mountain catchments due to complex topography and geology. Generally, the geology in the Sierra Nevada is characterized by low-permeable mountain block overlain by thin, high-permeable alluvium and glacial deposits near stream channels that gradually thicken in the down-valley direction. We developed grid-block representations of the alluvium and mountain block subsurface geology using deductive reasoning and a combination of data-driven automated and manual interpolation to observed lithologies, cross sectional and surficial geologic maps, and geophysical surveys, while explicitly considering known stream and wetland locations. Key to the development of the model grid is the conditioning of the model grid-scale digital elevation model to ensure proper location of streams and wetlands, and their sub-grid scale geometries. This conceptual model, which merges data-driven hydrostratigraphic interpolation with conceptual understanding of the surface water and groundwater systems, is useful for constructing integrated models in data limited mountain block regions.

The Lake Tahoe basin is largely representative of typical topography, geology, climate, and hydrology of the greater Sierra Nevada region. Important characteristics that are shared among the upland watersheds of the region are the large topographic relief, high precipitation gradients with significant winter snowfall, and relatively impermeable shallow bedrock that accentuates the dominance of shallow groundwater-flow paths in the regional system. Because the alluvial aquifers are typically small and have limited storage, they are likely to be more sensitive to climate fluctuations as compared to thick valley aquifers. Mean annual precipitation over the model domains ranges from 380 to 1,650 mm, with 90 percent of the precipitation occurring between November and March. Monthly average extreme temperatures range from 30oC in August to -10oC in January. Vegetation consists of subalpine and conifer forest, with some deciduous riparian and meadows association. Mountain block geology is primarily composed of granitic and volcanic rocks, overlain with glacial moraines and stream deposits in low-elevation areas that primarily make up the alluvial aquifers, while soils are generally shallow and derived from parent rock consisting of mostly sand and silts. Gridded datasets of elevation, geology, vegetation, soils, and land use were used to discretize and parameterize GSFLOW. Precipitation and temperature was distributed spatially across model domains (1,900–3,000 m above Mean Sea Level, AMSL) using the Parameter-elevation Regression on Independent Slopes Model

(PRISM) monthly precipitation spatial distributions (Daly et al., 1994), and daily temperature and precipitation recorded at the Mt. Rose, Squaw Valley, and Tahoe City Cross SNOTEL stations, and Tahoe City cooperative-observer weather station.

Tahoe PRMS and model development and calibration

a) Spatially distributing Precipitation

The PRMS model is the surface hydrology model that provides the boundary flux (recharge) for the ground water model. To distribute climate (precipitation and temperature) we take the approach of using one station and using ratios between monthly mean values from the chosen station with a PRISM (*Daly et al., 1994*) map to spatially distribute the climate. The method of selecting the one station for the Tahoe basin is described in the phase one report. Here we present how well this methodology works in application. It is important to make this comparison between model simulated precipitation and observed gauged precipitation since only a hand full of observations are available in the Tahoe basin, but to simulate the hydrology we need to have values of precipitation even in the ungauged sub watersheds. Figures IV-1-5 show the comparison between the observed precipitation and the simulated precipitation at the co-located PRMS grid cell. It can be observed from these figures that the simulated precipitation agrees well with the observations at multiple timescales viz. daily, annual, monthly and climatologically.

GSFLOW is typically calibrated using a 3-step process, where PRMS is calibrated independent of MODFLOW-NWT, and MODFLOW-NWT is calibrated for a steady state stress period, and lastly, PRMS and MODFLOW-NWT are calibrated jointly for transient daily stress periods in GSFLOW. In this work, we calibrated PRMS by matching observed streamflows as discussed above. MODFLOW calibration is discussed later.

(Figure, next page)

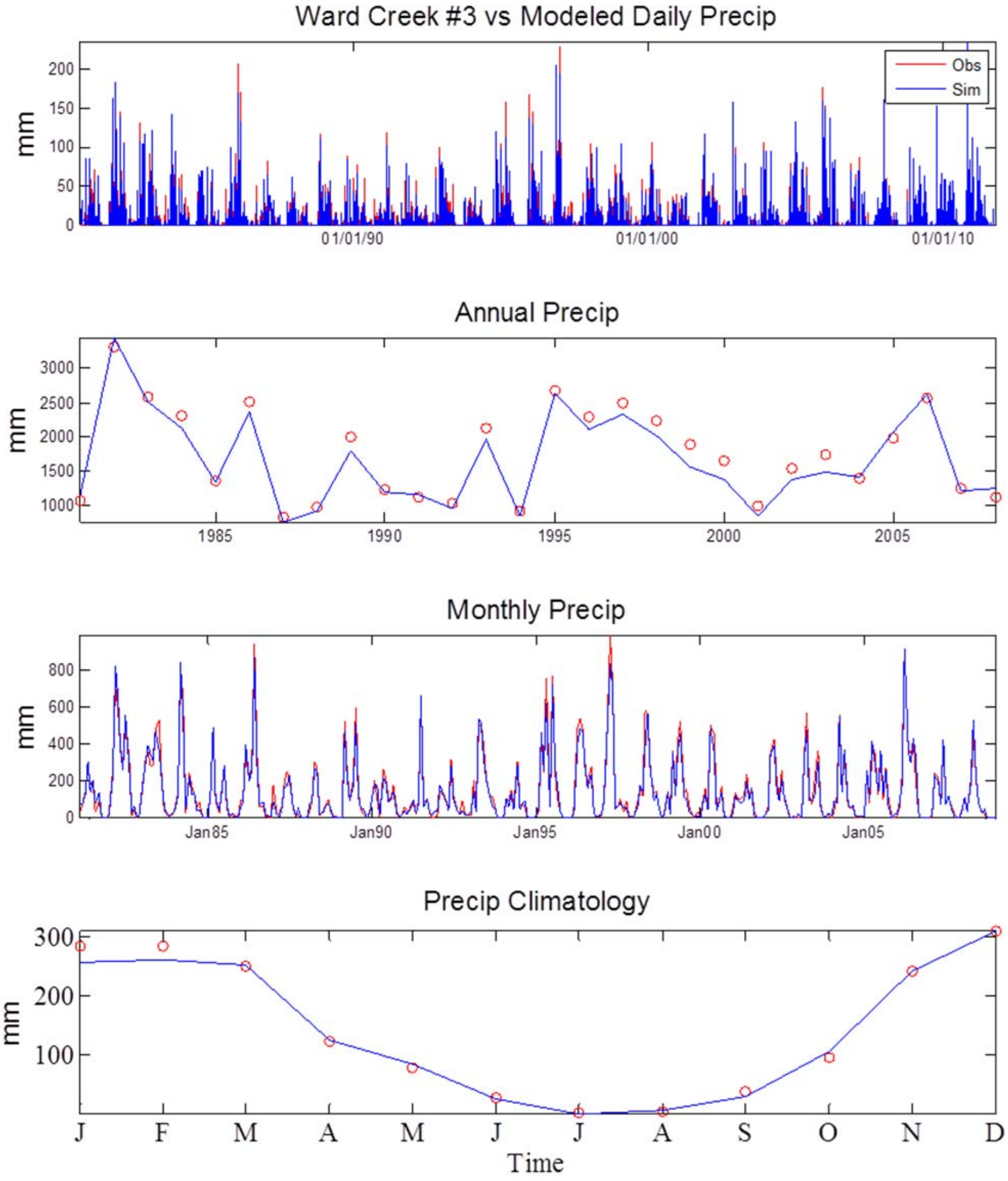
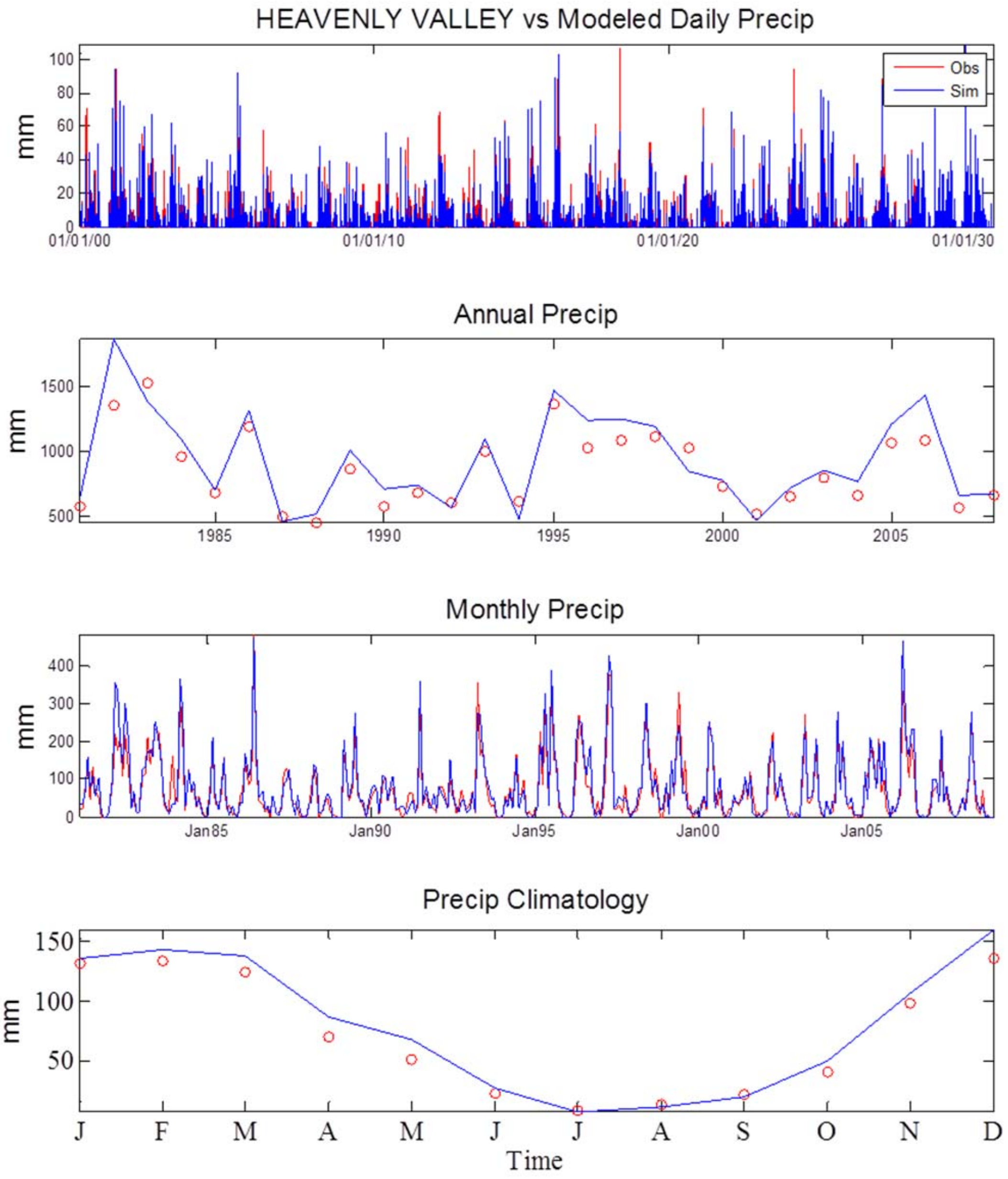


Figure IV-1. Model simulated Precipitation comparison with actual station observed precipitation at Ward Creek #3.



HEAVENLY VALLEY vs Modeled Daily Precip

Annual Precip

Monthly Precip

Precip Climatology

Figure IV-2. Same as previous figure, but for Heavenly Valley.

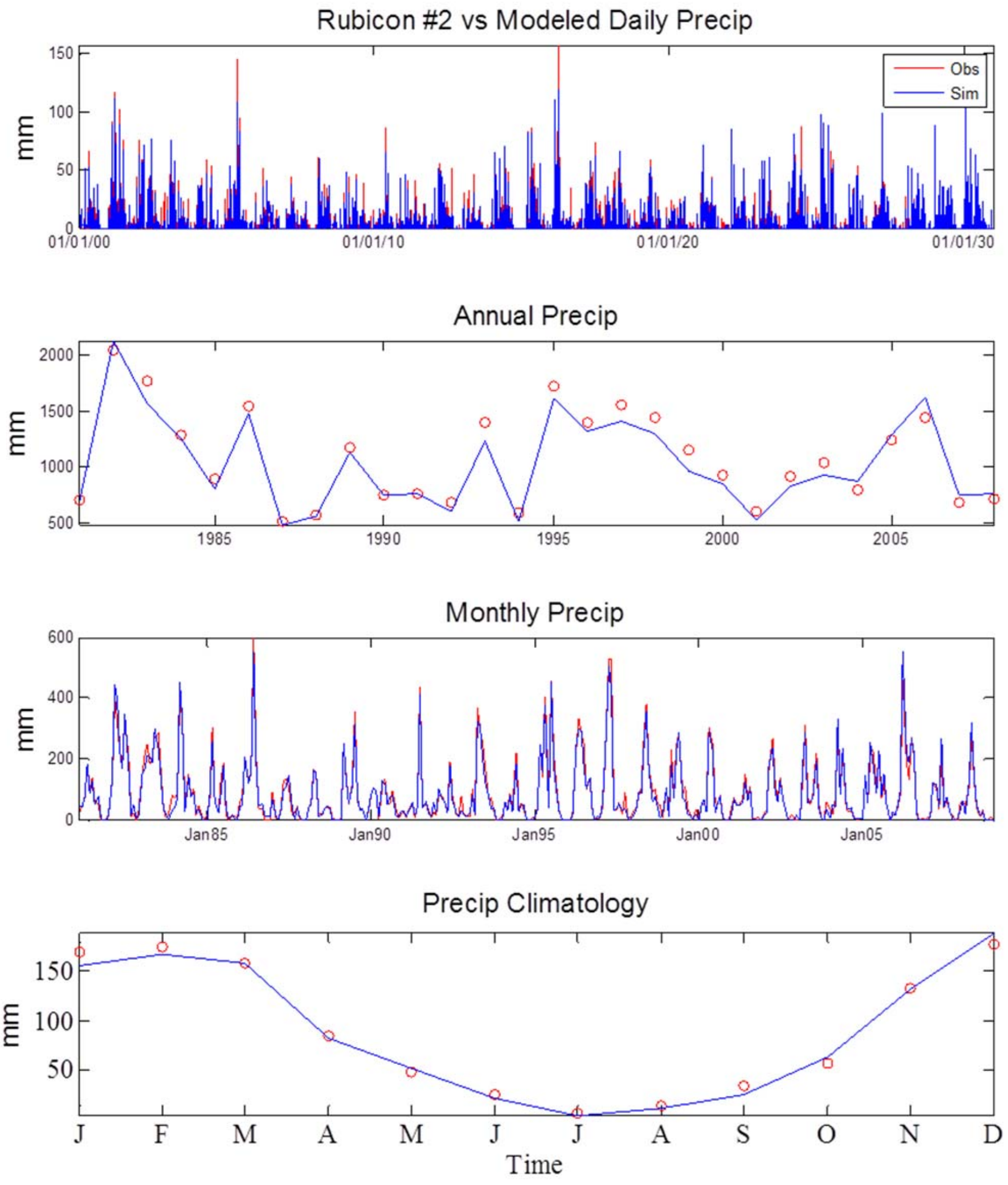
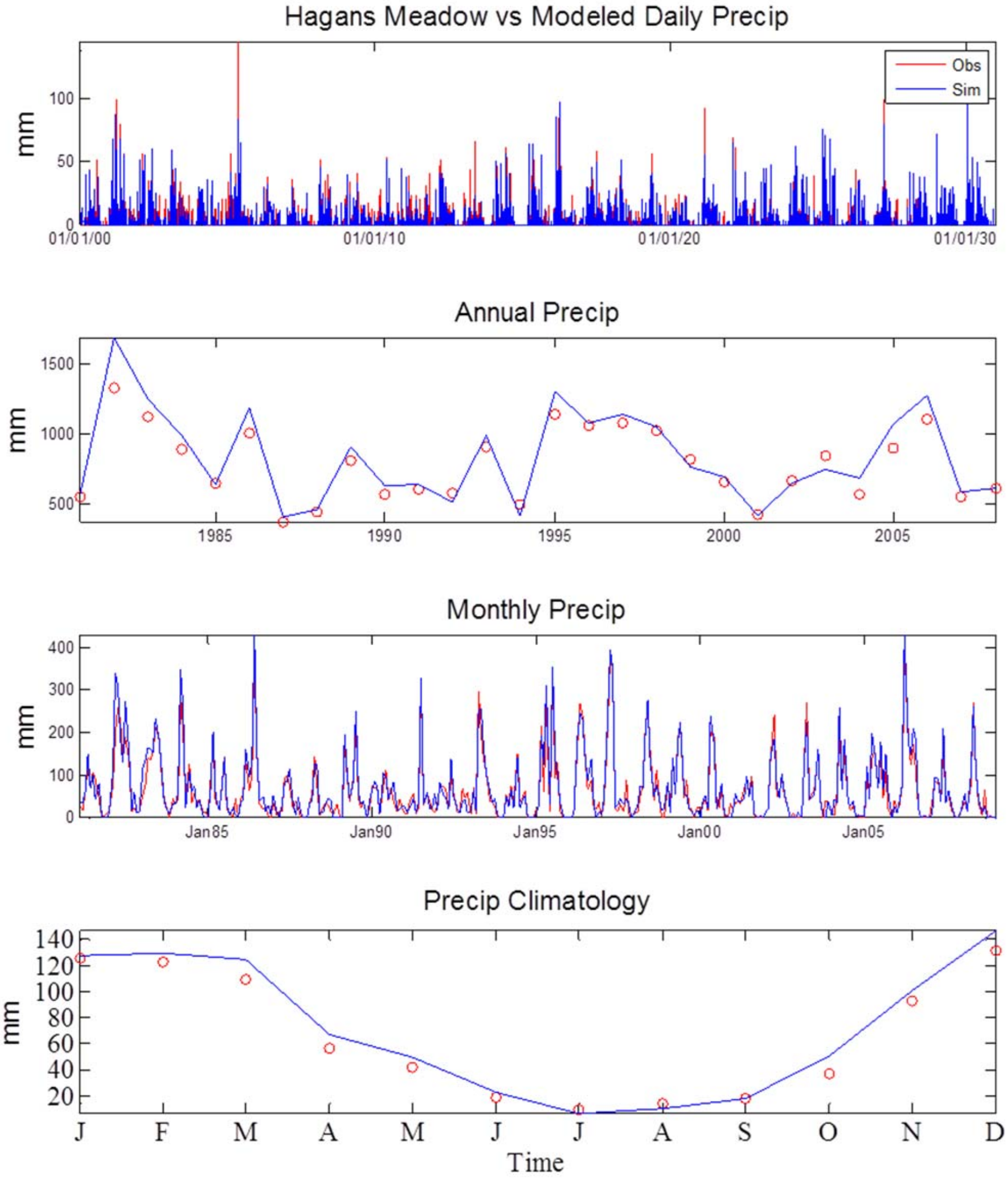


Figure IV-3. Same as previous figure, but for Rubicon #2.

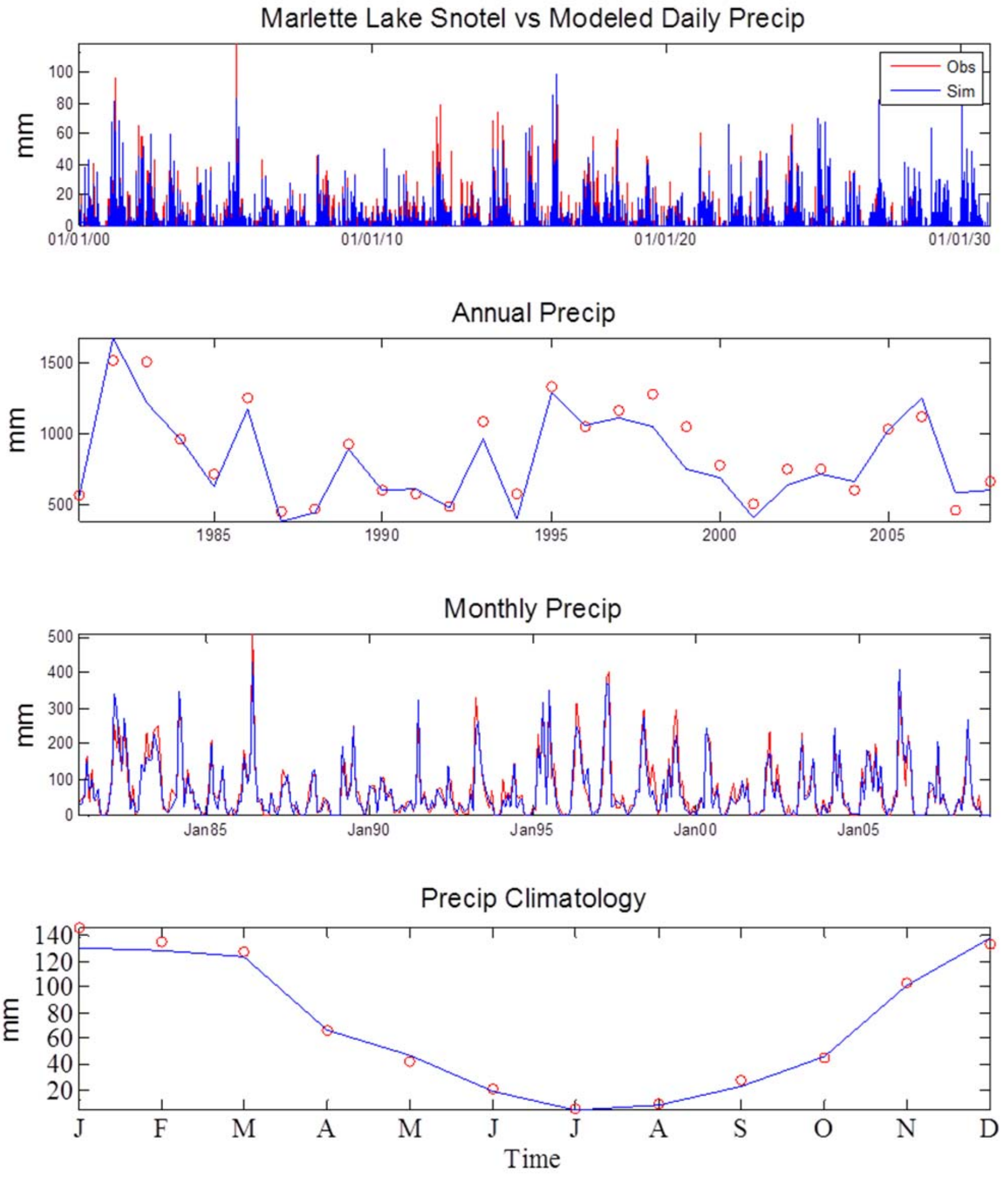

Hagans Meadow vs Modeled Daily Precip

Annual Precip

Monthly Precip

Precip Climatology

Figure IV-4. Same as previous figure, but for Hagan Meadow.


Marlette Lake Snotel vs Modeled Daily Precip

Annual Precip

Monthly Precip

Precip Climatology

Figure IV-5. Same as previous figure, but for Marlette Lake Snotel station.

b) Calibrating solar radiation and evapotranspiration (ET)

The model parameter (degree day intercept) was adjusted to match solar radiation at the Tahoe City Coast guard pier. Figure IV-6 shows the comparison between the model simulated shortwave radiation and the observations. These values are averaged over 2000-2009.

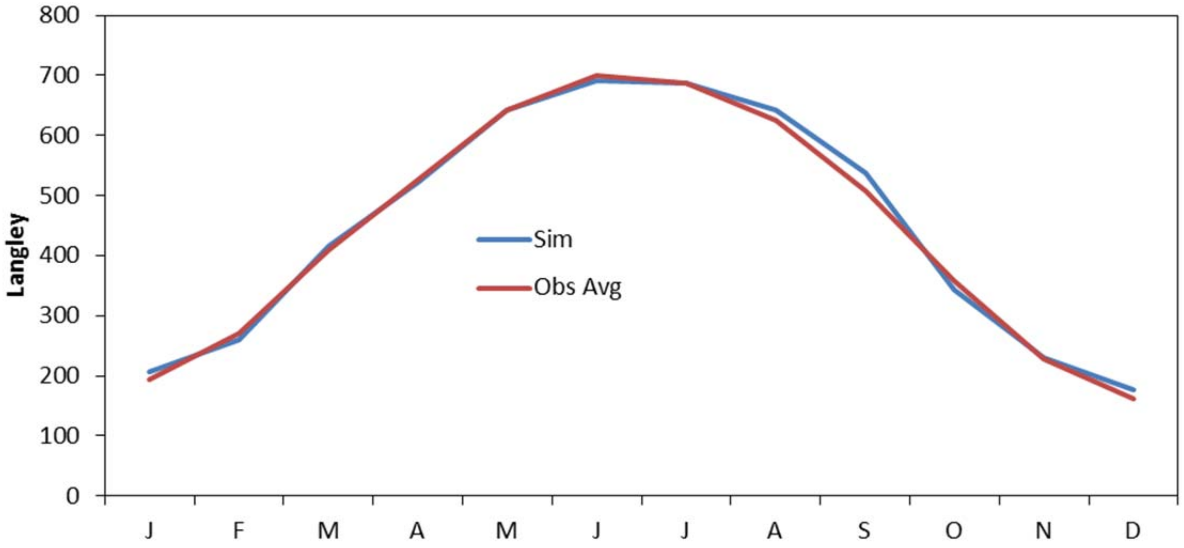


Figure IV-6. Observed and simulated solar radiation.

While no observation of ET exist in the modeling domain, we adjusted the modeled ET to be similar to the reference ET at three different locations. Figures IV-7-9 show the model fit between simulated ET and reference ET at these locations. We want to point that that while parameters can be adjusted to fit these values perfectly one does not want to do this, because the reference ET is based on a well-watered alfalfa plant, which is different from the forested area of the Tahoe basin.

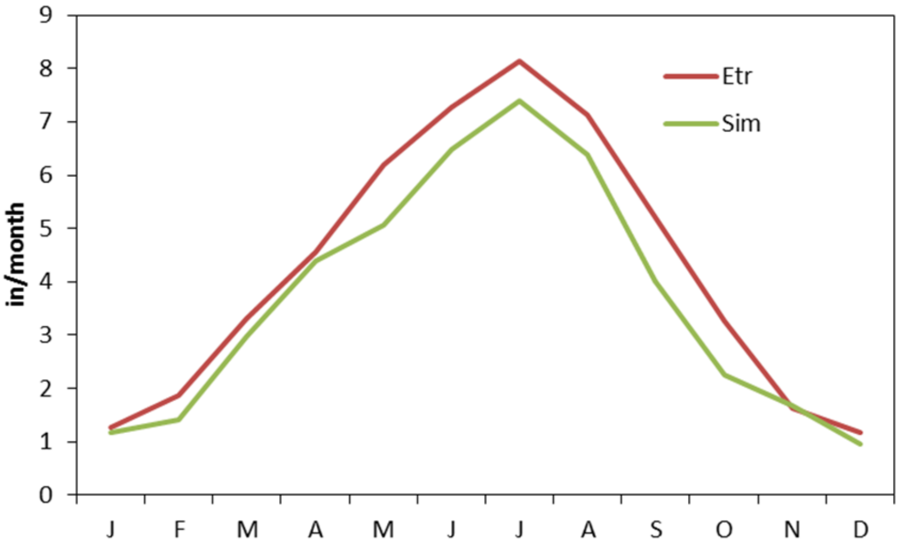


Figure IV-7. Model simulated potential ET comparison to ETr at Glenbrook.

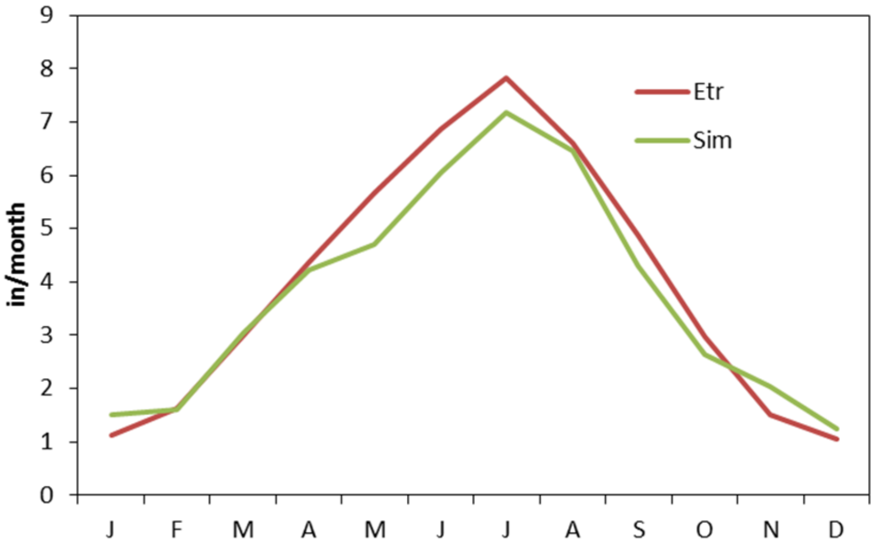


Figure IV-8. Model simulated potential ET comparison to ETr at Dagget Pass.

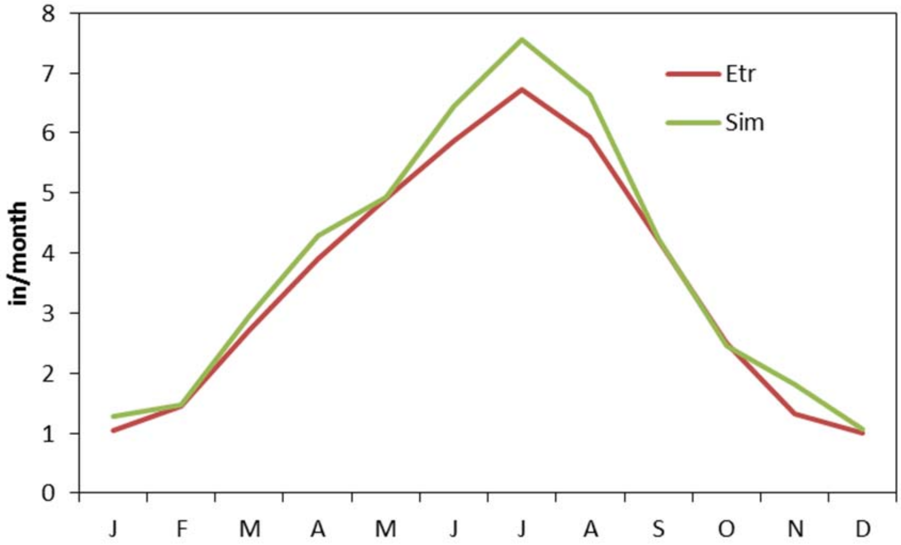


Figure IV-9. Model simulated potential ET comparison to ETr at Marlette.

c) Treatment of ungauged catchments

The Tahoe Basin consists of a total of 60 sub-catchments that all drain into Lake Tahoe. Of the 60 sub-catchments, only 10 have observed values of streamflow that can be used for model calibration. The PRMS model was used to derive synthetic streamflow at the ungauged catchments. The model was parameterized (see phase I report) to accurately describe catchment physical properties such as:

1) Catchment dimensions

2) Shape

3) Topography (Slope, Aspect)

4) Geology and soils

5) Drainage Density and stream gradient

6) Vegetation

7) Climate (precipitation and temperature)

8) Land use

In the present study; of the above physical catchment descriptors, only catchment area was used as a metric to regionalize model parameters. This choice was made since all the other descriptors are unique to the catchment and are derived based on available data. Another metric that was calculated to help with the model baseflow parameterization was the ratio of annual precipitation to ratio of annual baseflow. Baseflow in this context was defined as the average flow between Aug-Oct in the gauged records. Figure IV-10 shows a graph of the basin area vs. sub-catchment id. From this figure one can observed that one could potentially make many groups of sub-catchments based on area. However, for simplicity we only derived three such groups. Table 1 presents the ratio of precipitation to baseflow for the gauged catchments.

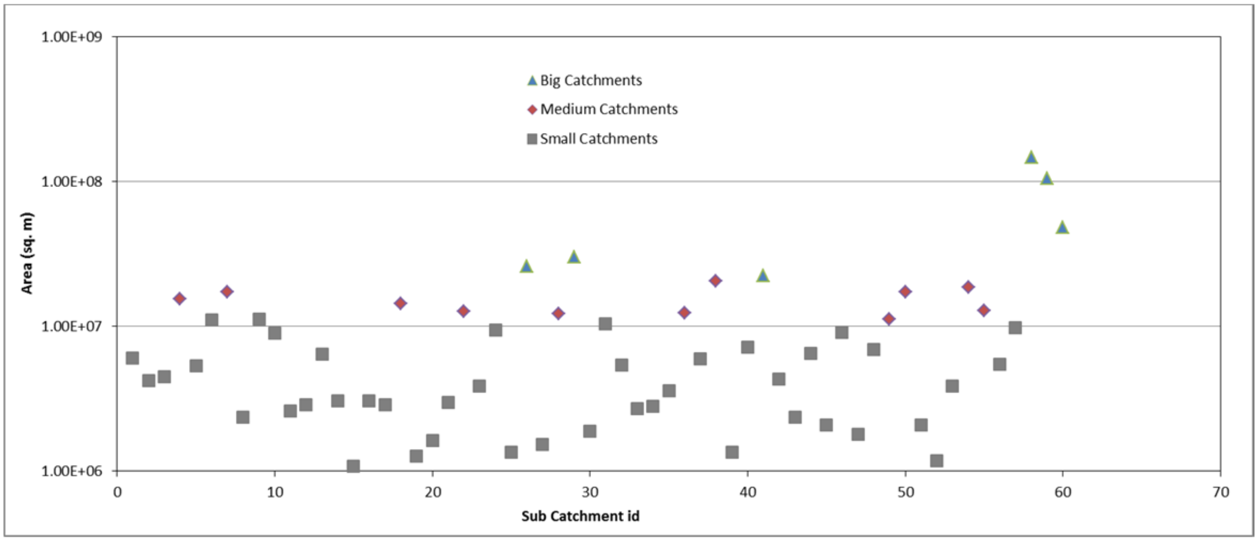


Figure IV-10. Catchment size vs. catchment id.

Table IV-1. Percentage of annual precipitation to annual baseflow and streamflow values

Gage Name	Baseflow as percent of Annual Precipitation %	Streamflow as percent of annual precipitation %
Ward Creek at Highway 89	0.039	0.502
Blackwood Creek	0.067	0.635
General Creek	0.050	0.560
Taylor Creek	0.154	0.544
Upper Truckee River	0.065	0.480
Third Creek	0.145	0.351
Incline Creek	0.191	0.385
Marlette Creek	0.022	0.197
Edgewood Creek	0.233	0.362
Trout Creek	0.174	0.338

d) PRMS annual streamflow simulations

Based on the above calibrations, the PRMS model was used to simulate streamflow at the observed gauges. Figure IV-11-12 show the performance of the PRMS model simulated and observed streamflow at the annual timestep.

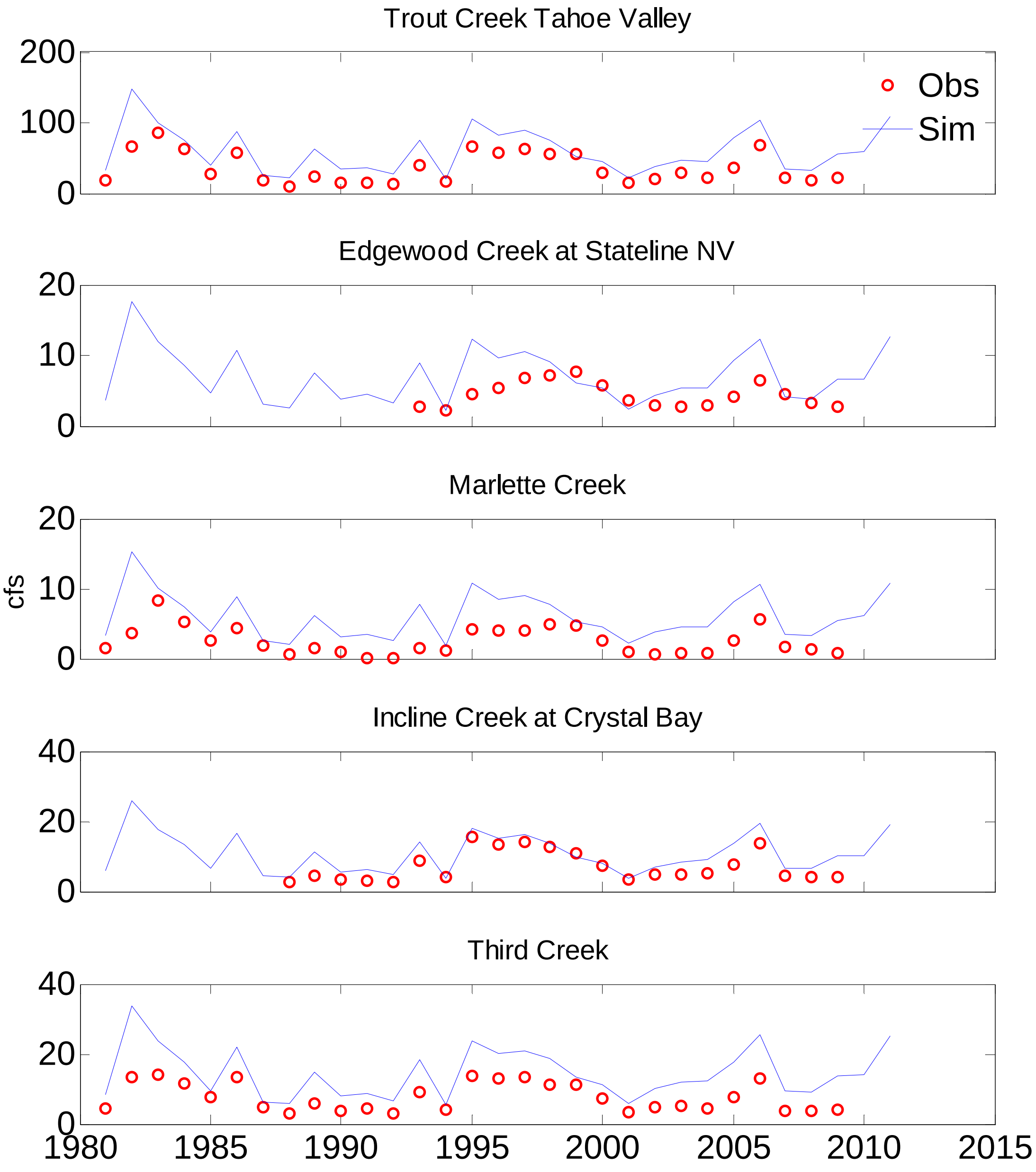


Figure IV-11. Annual streamflow comparison between model simulated and observed values.

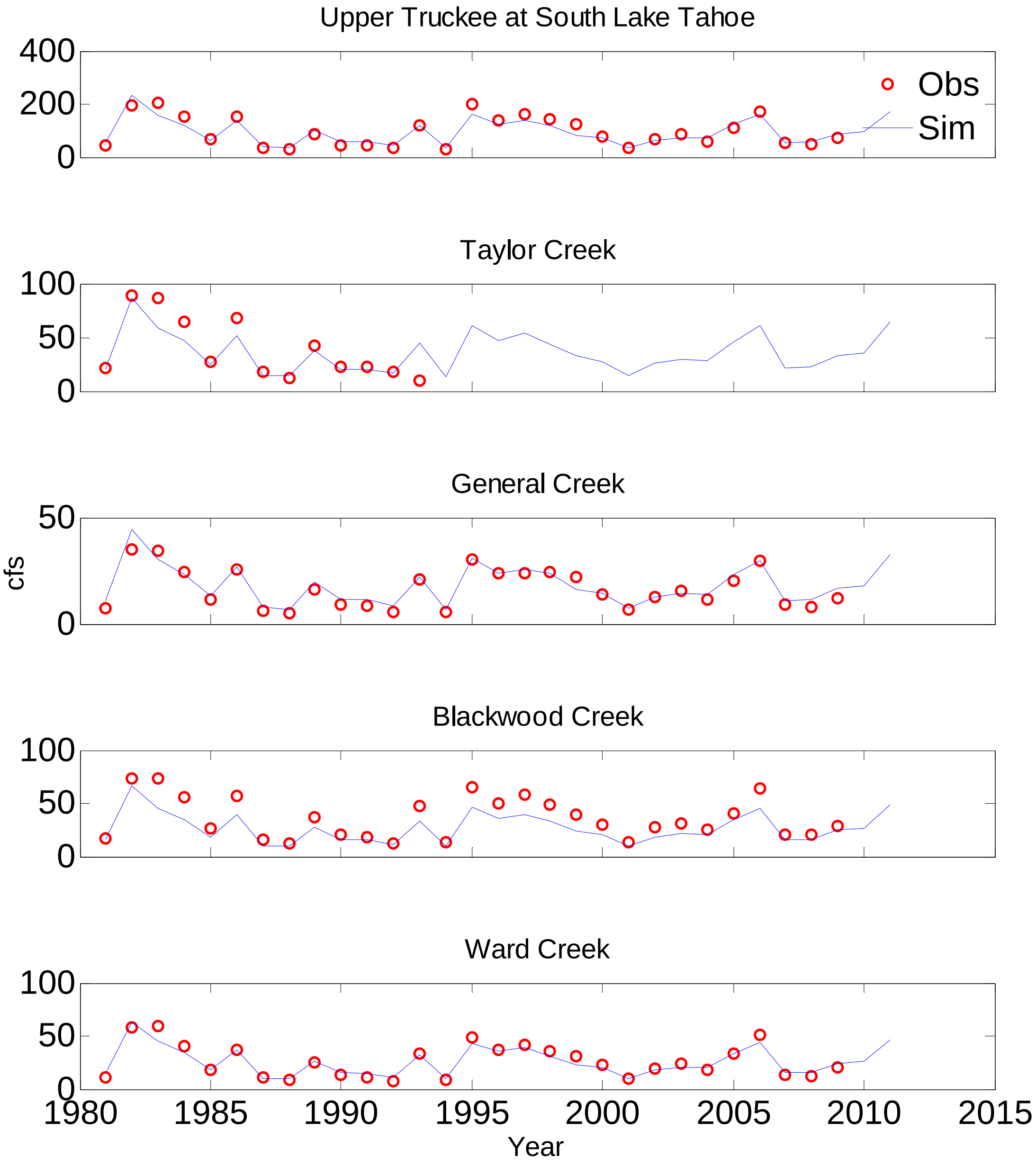


Figure IV-12. Annual streamflow comparison between model simulated and observed values.

Tahoe MODFLOW model development and calibration

a) Lake Tahoe Basin Framework Grid

A hydrogeologic framework model (HFM) that maintains a balance between hydrostratigraphic resolution and grid discretization was developed for the Lake Tahoe Basin MODFLOW model. Construction of this framework grid employed a combination of data-driven automated and manual hydrostratigraphic interpolations conditioned to observe well log lithologies, cross sectional and surficial geologic maps, geophysical surveys, and conceptual understanding of the sub-surface system. Particular emphasis was placed on maintaining continuity between mountain block, alluvial, and basin fill units through layer configuration in order to improve model performance and efficiency.

Initially, geologic surveys and maps were used to designate bedrock and basin fill units at the surface (Burnett, 1971, Sylvester et al., 2007). Spatial hydrogeologic and stratigraphic data, primarily reported by Plume et al. (2009), were used to develop the conceptual hydrogeologic framework model (HFM) and vertical and horizontal model discretization. Once this was implemented onto the grid, hydrogeologic units and layer thicknesses were derived from well log lithologies and geophysical surveys (Markiewicz, 1992, Niblack, 1988, Thodal, 1992). Using the geologic modeling and visualization software Leapfrog, interpolations through data rich areas constrained layer thicknesses. These values were then assigned to the model grid in ArcGIS and manual interpolations were made for layer thicknesses up into data deprived areas. Adjustments were also made to maintain continuity throughout each layer, and maintain smooth transitions between the mountain block – alluvial fill interface (Figure IV-13). These adjustments allowed for rapid model performance by reducing layer discontinuities.

The HFM was divided into five basic geologic units, including top soil, alluvium, weathered bedrock, and less-weathered bedrock. Layer 1 (soil), 2 and 3 (alluvium), and 4 and 5 (mountain block) ranged in thickness from 0-4m, 0-210m, and 60-120m, respectively. Layer 2 represents basin fill sediments characterized by interbedded fluvial sediment deposits and glacial till, layer 3 is representative of alluvial material made up of interbedded clays, silts, sands, and gravels, layer 4 represents weathered bedrock consisting of fractured volcanic and granitic boulders, and layer 5 represents less weathered bedrock made up of consolidated volcanic flows and granite plutons of the Sierra Nevada batholith. Layers 2 and 3 are considered the main water bearing units.

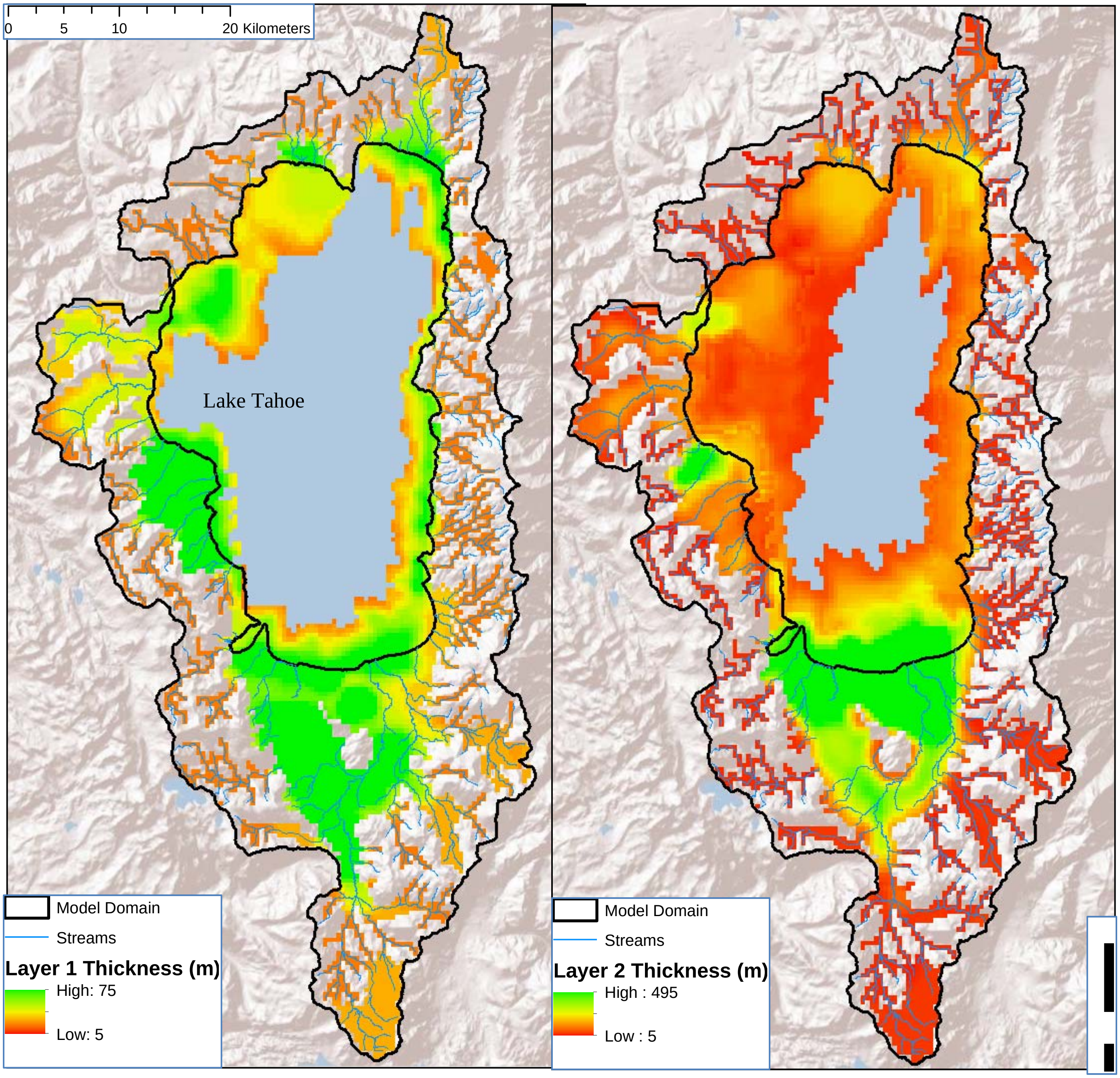


Figure IV-13. Tahoe basin model domain with smoothed layer 1 and 2 thicknesses. Layer thickness values were assigned manually for mountain block streambeds, then gradually smoothed into data driven thicknesses in the lower elevations

b) Lake Tahoe MODFLOW steady state calibration

MODFLOW-NWT (Niswonger et al., 2011) was calibrated independent of PRMS using a steady-state stress period, including representation of stream flow (SFR2), Lakes (LAK7), and unsaturated-zone flow (UZF1). Mean annual PRISM precipitation was scaled to represent the mean annual streamflow (i.e., sum of recharge, interflow, and overland runoff), and utilized as net infiltration for UZF1 and MODFLOW-NWT. Calibration of UZF1 and MODFLOW-NWT was performed by adjusting the precipitation scaling factor and layer specific homogeneous aquifer hydraulic conductivity values until there was a good correspondence between the simulated steady-state flows in streams, lake levels and lake outflows, groundwater heads, and the locations of major discharge and wetland areas. Wetland areas were also used to calibrate the model by comparing surface elevations to simulated head. The calibrated spatial distribution of depth to water (DTW) is very intuitive, where there is shallow DTW near streams, valleys, and meadows, with DTW increasing in mountain block and high elevation areas. Groundwater heads in layer 4 are above land surface in some valley floor mountain transition zones, while heads in layer 2 in these areas are only slightly above land surface and discharging as groundwater ET and stream seepage. Figure IV-14 illustrates the spatial distribution of steady state net flux (recharge – discharge) for Lake Tahoe and tributary watersheds, where significant groundwater discharge is occurring along stream valleys and around the lake rim at major transition areas of changing topography and hydraulic head gradients. Analyses of model results indicate that the preliminary calibration and model results of PRMS and MODFLOW-NWT for Lake Tahoe are fairly robust and accurate. In addition, our preliminary calibrated water budget compares well to precipitation, ET, and recharge percentages derived from recent watershed modeling, chloride mass balance, and Darcian flux estimates of recharge in adjacent watersheds with similar geology, vegetation, and precipitation magnitudes (Maurer and Berger, 1997; Jeton and Maurer, 2007).

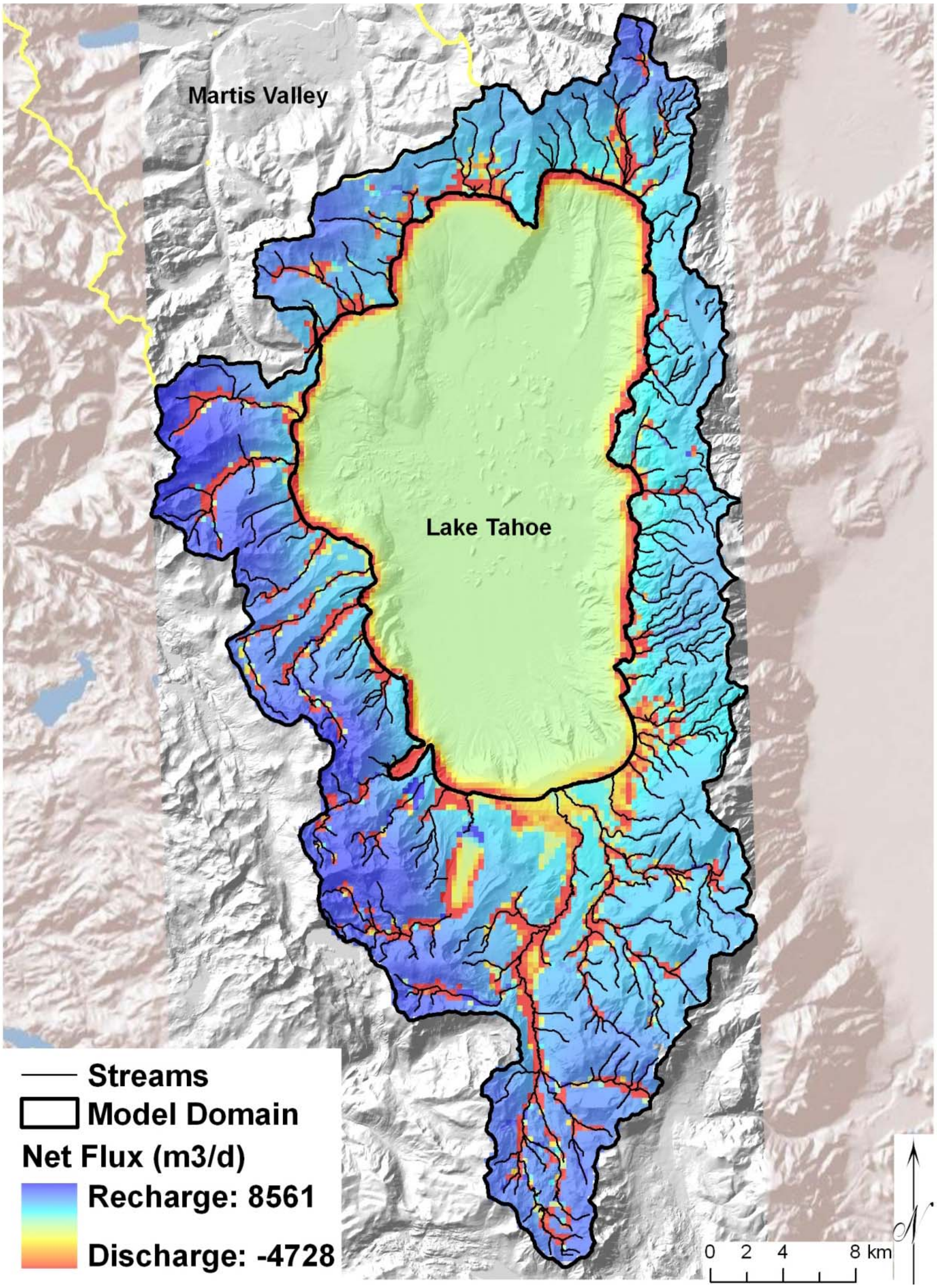


Figure IV-14. Lake Tahoe simulated steady state groundwater net recharge and discharge provided by lakes, streams, evapotranspiration, and diffuse recharge for each model cell. Positive values indicate recharge and negative values indicate discharge.

Tahoe GSFLOW model development and calibration

Compiling GSFLOW

First extract GSFLOW from the tar ball format by typing “tar –xvf gsflow_1_1_4.tar.gz”. Next, goto the src (source code) directory, and individually compile mms, modflow, and prms by typing “make” in the designated directory for each of these respective codes. The codes are supplied by Makefiles from the USGS that utilize GNU gfortran and gcc compilers to compile these codes. Once the individual codes are compiled, back up a directory and use the “global” makefile to compile GSFLOW. The GSFLOW executable is then located under the GSFLOW directory. An example file supplied from the USGS flow from the Sagehen Basin is then used to ensure that the code is compiled and running correctly.

a) GSFLOW transient run to predict Lake Stage in the Tahoe Basin

PRMS and MODFLOW were linked with GSFLOW and calibrated to transient conditions. The primary transient observation used to calibrate was a time series of historical lake stage. This observation of lake stage is a perfect variable to use as an indicator of the basin wide Tahoe model performance, as it integrates the hydrologic response of the entire basin. Simulated lake stage primarily relied on the MODFLOW lake package with specified outflow based from the historical record. Simulated water budget variables of precipitation, ET, and lake evaporation were ‘fine-tuned’ so that the simulated lake stage matched the observed lake stage to within a reasonable level of error. Results indicate that the model can fairly accurately simulate lake stage over a wide range of drought and wet cycles in the historical record (Figure IV-15).

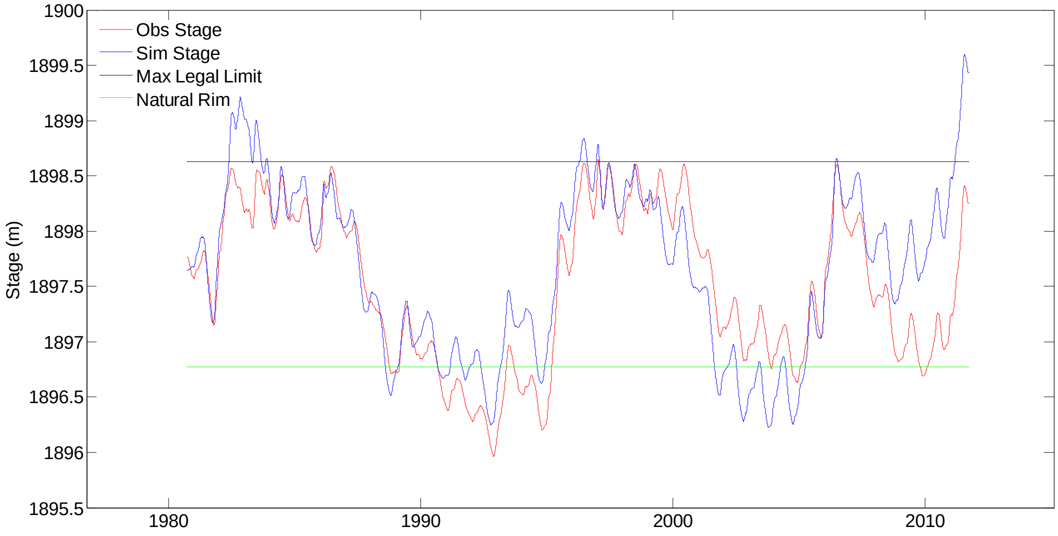


Figure IV-15. Lake Stage simulated by the transient GSFLOW model. Note that the accuracy of the model is two within 0.25m on average.

b) Downscale climate for long term future projections

To assess future hydrologic change, bias-corrected and spatially-disaggregated general circulation model (GCM) projections of daily temperature and precipitation were used as direct input to GSFLOW. The projections came from six different GCMs that contributed to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment (Christensen et al., 2007), considering the Special Report on Emissions Scenarios. We use of data from 5 climate models (Figure IV-16) to consider uncertainty in future hydrologic conditions (Prudhomme et al., 2003; Wilby and Harris, 2006). Four future projections are representative of wet and dry extremes (two each), with one projection representing the ensemble mean of the 36 models evaluated. Downscaled projections of temperature and precipitation from 1950-2100 at 12 km resolution were developed from the bias-corrected spatial disaggregation (BCSD) method (Maurer and Hidalgo, 2008; Cayan et al, 2009) for GCMs presented in table 2, responding to the A2 greenhouse gas scenarios. Specifically, climate model projections were taken from two 12 km grid cell that were coincident with the Mt. Rose and Tahoe City Cross SNOTEL stations, and the Tahoe City NOAA weather station. These projections were further interpolated to the Mt. Rose SNOTEL and Tahoe City NOAA weather stations using a quantile-quantile mapping approach (Panofsky and Brier, 1968) to account for biases in temperature and precipitation due to elevation differences between 12 km GCM projections and weather-station elevations.

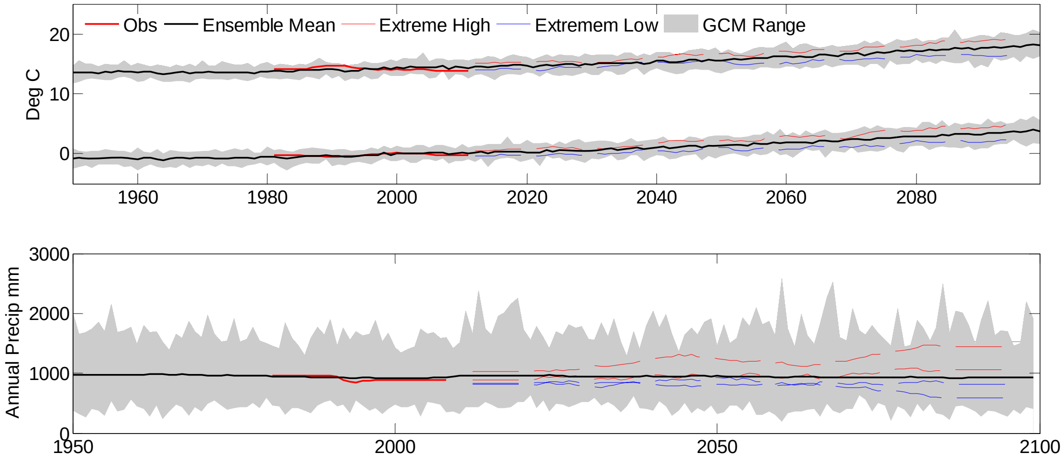


Figure IV-16. Downscaled GCM climate scenarios. The historical observations are in solid red. The GCM ensemble range is shown in grey, and extreme future scenarios are dashed lines.

Table IV-2. The GCM scenarios selected based on analysis of extremes.

	Tmax	Tmin	Precip
Max	UKMO_HADCM_3_1	UKMO_HADCM_3_1	IPSL_CM4_1 and MPI_ECHAM_5_1
Mean	MPI_ECHAM_5_2	MPI_ECHAM_5_3	UKMO_HADCM_3_1
Min	NCAR_PCM_1_4	NCAR_PCM_1_4	GFDL_CM2_1_1 and NCAR_PCM_1_1

c) Lake Tahoe GSFLOW model runs with future climate

Hydrologic simulations were run using daily time steps in GSFLOW, where one full GSFLOW simulation was executed for each GCM forcing, totaling 5 future model runs. GSFLOW results were analyzed for temporal and spatial changes. Specifically, and perhaps most important, is the change of Lake Tahoe stage. Figure IV17 illustrates the simulated projection of stage for Lake Tahoe, where it is evident that the GFDL model forcing results in simulated lake stage dropping below the natural rim of the lake, meaning that there is no outflow from Lake Tahoe into the Truckee River. It should be noted that Lake Tahoe has ceased flowing into the Truckee River 20 times in the last 110 years, so it is not supprizing that this will happen in the future. It is critical that we evaluate the reoccurrence of Lake Tahoe dropping below the natural rim, perhaps permanently, and utilizing multiple GCM projections, as done in this report, is a step in the right direction for making such an evaluation.

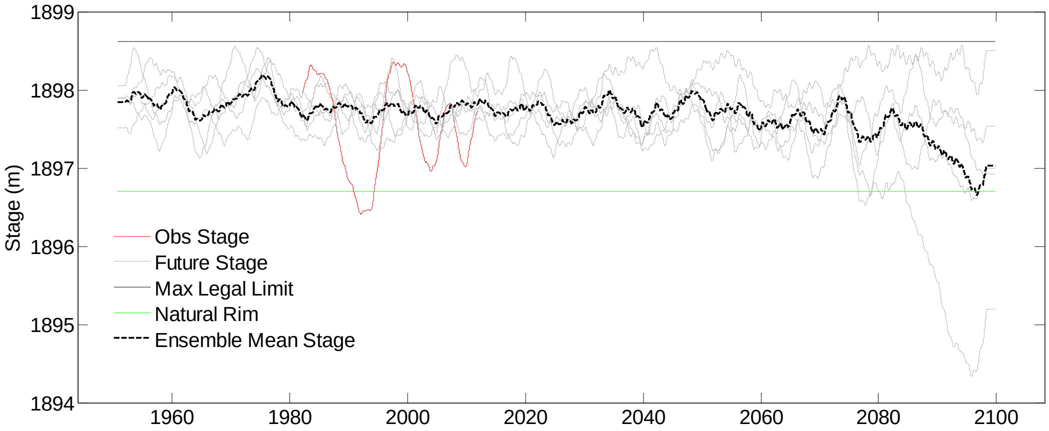


Figure IV-17. Future simulation of lake stage based on forcing the GSFLOW model with future climates. Notice that even though the ensemble mean precipitation does not decrease (figure 16) the ensemble mean stage of the lake decreases.

Development of a Publication that Describes the Integrated Hydrologic Modeling Effort

Appendix B contains an abstract for a publication that details the development and implementation of the integrated hydrologic model for the Truckee River basin. The completed manuscript will be submitted to a peer-review publication.

Conclusions and Future Work

In this report we present historical and future hydrologic projections using an integrated hydrologic model of Lake Tahoe, a basin of complex mountain terrain. Upland catchments represented in this model are very important because the majority of available water in the Truckee River basin emanates from these catchments as snowmelt runoff. Because GSFLOW can simulate the interactions among all the major co-varying hydrologic processes, including snowmelt, runoff, evapotranspiration, and SW-GW interactions, its use is a big step forward in terms of simulation capabilities for assessing the effects of climate on water resources. As described in this report, efficient and accurate representation of hydrogeologic features within the model is paramount for developing a robust model that can be calibrated and ensure objective model performance relative to diverse sets of observation data. Results of future climate and hydrological projections show that even though the ensemble mean precipitation does not go down for the Tahoe Basin, the ensemble mean lake stage for the Tahoe Basin goes down. This is a significant finding and one that should be studied in more detail to understand its management impacts.

While this type of integrated modeling is new and novel, it should be kept in mind that models need to be continuously evaluated and recalibrated to accommodate newer data and information gathered. Currently all the available streamflow records were used to construct the model, but in the future if more flow data becomes available then the model will have to be calibrated again taking into account newer information. This statement holds true for climate data driving the model.

In this report we presented an end member type approach to looking at how climate extremes will affect available water in the Tahoe Basin. Instead of using such an approach, if one were to run all the 112 GCM future scenarios through the integrated model, would the end result be any different? Only a detailed investigation will reveal the answer to this question.

V. VISUALIZATION

Introduction

We have developed the Horizon software package for the purpose of creating an interactive Lake Tahoe application to run in DRIVE6, DRI's virtual reality environment (VRE). Horizon is a planetary terrain renderer written in C++ that runs on the desktop and in a VRE. As a planetary terrain renderer, Horizon allows seamless transition from a global view to a local view and places local data in its global context. Horizon takes advantage of efficient algorithms and hardware to rapidly deliver rendered images. For example, by using the adaptive level-of-detail (ALOD) algorithm (Bernardin et al., 2008), Horizon determines at runtime the resolution of various chunks of terrain to produce an efficient but faithful representation of the world. Horizon also uses the graphics processing unit (GPU) to accelerate raster preprocessing and runtime composition of raster data.

The benefits of developing Horizon to DRI and to the DMV project are threefold. First, DRI owns copyright ownership over the code. This enables partnership with industry and other institutions and allows the selling of the software as a service. Second, in order to run in a VRE, the software must be designed with special considerations. Our software is written to run in a VRE as well as on the desktop to increase utility for various use cases. Third, while Horizon does not replace existing GIS tools, it does supplement them. By custom building visualization software, we can implement features that researchers need that are nonexistent in other visualization tools. For example, Horizon supports the ability to create an animation from any viewpoint from a set of raster files in a directory.

Features

Data Processing

There are numerous features supported by Horizon in the areas of data processing, rendering, data visualization, and interaction. Data processing involves preparing raster data in a format and structure that is efficient for rendering at runtime. Horizon performs this preprocessing step using the GPU to accelerate composition of multiple datasets into a multiresolution raster data structure. Westerteiger, Chen, Gerndt, Hamann, & Hagen (2012) describe a similar approach using CUDA for GPU programming. We employ a similar approach but use GLSL shaders to perform the GPU resampling of raster data. Multiresolution rasters organize data in a quadtree such that the lower levels of the quadtree represent coarse, low resolution data and the higher levels represent fine, high resolution data, as shown in Figure V-1 (Bernardin et al., 2008). By using GPU algorithms to accelerate generation of multiresolution rasters, we reduce the time taken to get data into the visualization.

(Figure, next page)

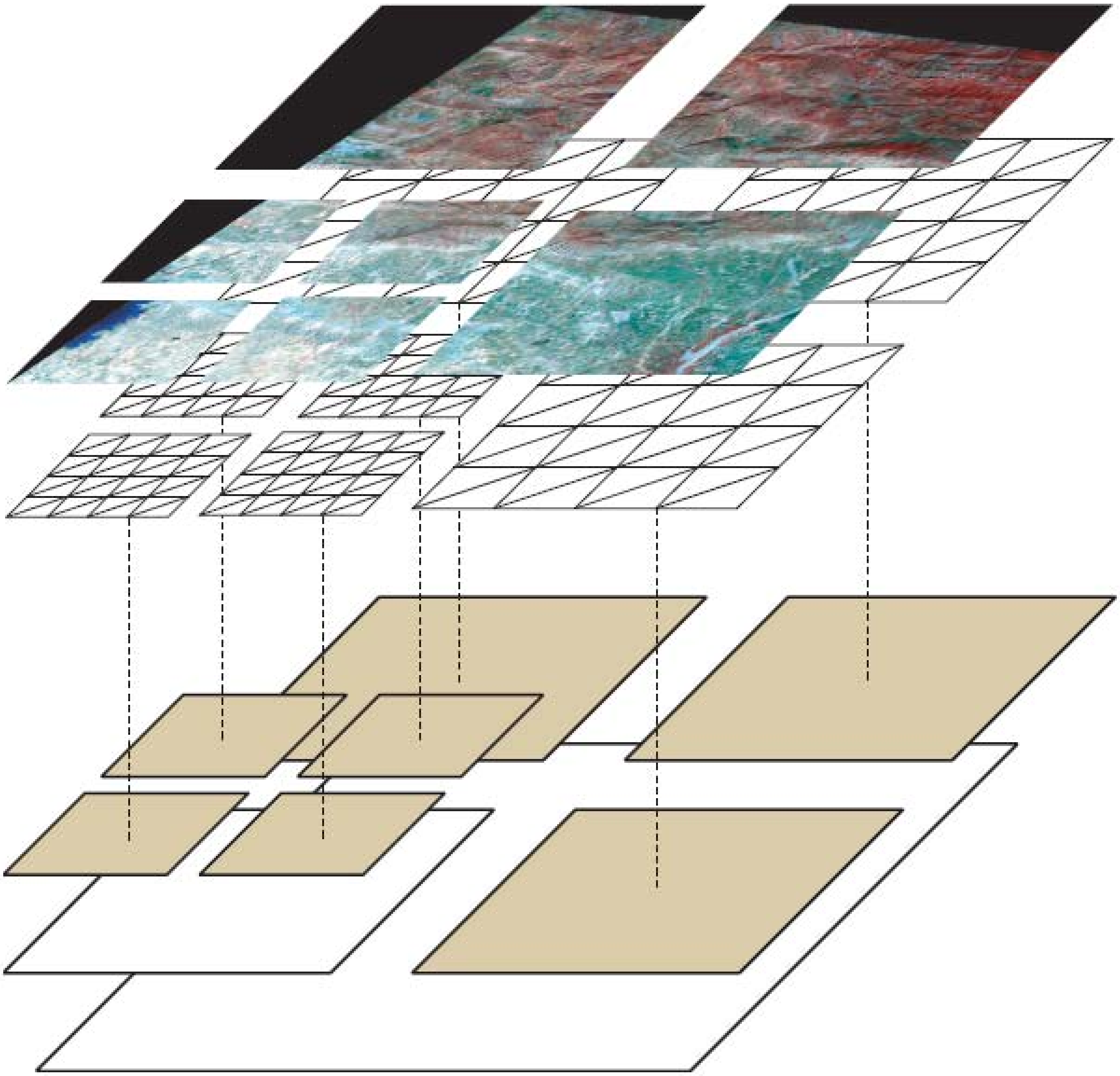


Figure V-1. A multiresolution raster organized as a quadtree. Each higher level of detail is created by subdividing the previous tile into four parts (Bernardin et al., 2008).

As source rasters are processed into multiresolution rasters, they can be optionally reprojected from most map projections into the map projection supported by Horizon. This is performed using GDAL, a standard library for GIS software development. The tiles of the multiresolution rasters are stored individually on disk in a hierarchical database. The ability to access each tile individually from this database facilitates out-of-core streaming of data in a technique similar to that described by White (2011).

Rendering

Rendering is a process that occurs at runtime and is responsible for displaying the planetary terrain efficiently and interactively. Terrain renderers typically generate terrain geometry from raster data offline and stream it to the GPU for rendering. Horizon makes this process more efficient by streaming raster data to the GPU and generating geometry on GPU hardware. This is more efficient since raster data generally takes less memory and therefore less time to stream to the GPU than full CPU-generated geometry. This process is made possible by using the gnomonic map projection to store multiresolution rasters. The gnomonic map projection has simple geometric relationships between planet coordinates and raster coordinates that make a GPU implementation possible, as shown in Figure V-2. The gnomonic map projection works by inscribing a spheroid within a cube and, for each of the six tiles, projecting along the ray from the planet center through the tangent plane (Lambers & Kolb, 2012).

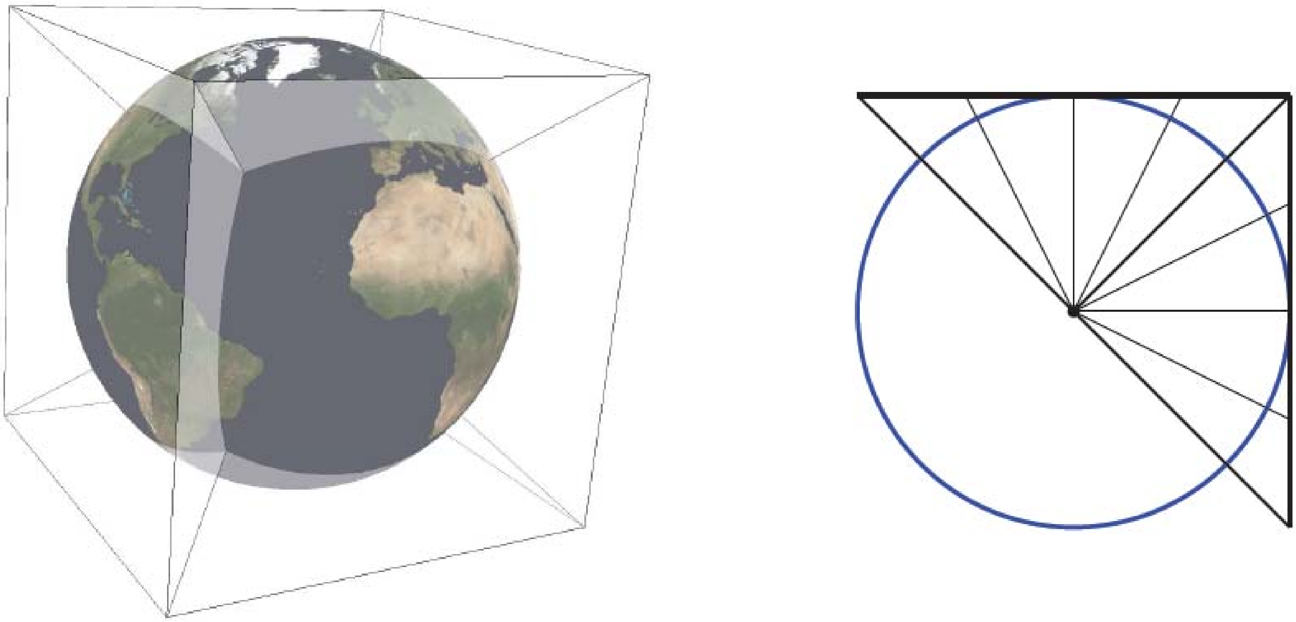


Figure V-2. The gnomonic map projection applied to planetary terrain (Lambers & Kolb, 2012).

In order to create a complete view of the world, color data must be overlaid on top of terrain geometry. Just as multiple rasters can be composited offline during preprocessing into a single multiresolution raster, multiple multiresolution rasters can be composited at runtime using a GPU algorithm called deferred texturing, an algorithm described by Kooima et al. (2009) and Mahsman (2010). This algorithm combines all of the relevant and overlapping color rasters for the current viewpoint and overlays them atop terrain geometry. Deferred texturing works by performing all compositing in screen space, i.e. it uses multiple screen-sized frame buffers in an image processing operation on the GPU. By using yet another GPU algorithm, Horizon expands the capability and efficiency of the rendering process.

During runtime, Horizon selects the tiles from the terrain database on disk and loads them for rendering using the techniques of adaptive level-of-detail (ALOD) and out-of-core streaming. ALOD selects only those terrain tiles that are needed for the current viewpoint, reducing the amount of time taken to generate a frame of the visualization (Bernardin et al., 2008). Without using ALOD, it would not be possible to visualize large terrain databases required by planetary terrain. Out-of-core streaming finds the tiles selected by ALOD and loads them from disk asynchronously with the renderer. This allows the renderer to interactively display low-resolution data while the higher-resolution data is loading, as opposed to pausing the program to wait for data to load (White, 2011).

Data Visualization

The data visualization features expand Horizon's capability to display different types of data in various ways. Horizon can take a folder of raster datasets that represent an animation over a period of time and display these rasters as an animation in the visualization. Figure V-3 demonstrates three frames of an animation that shows the change in water recharge on the northeast shore of Lake Tahoe over a year long period. This data is from the work of Huntington and Niswonger (2012).

(Figure, next page)

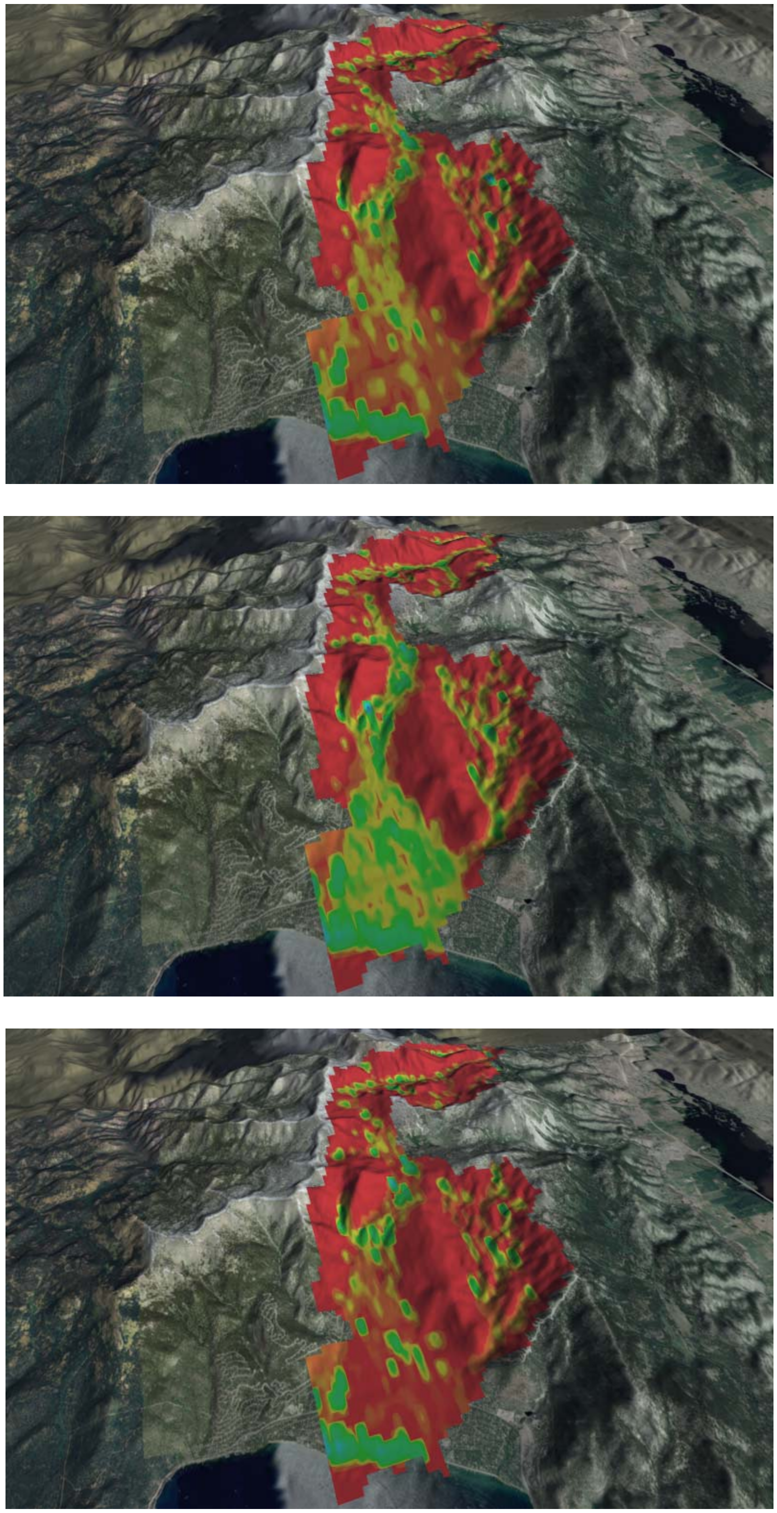


Figure V-3. Three frames of an animation of water recharge over a year on the northeast shore of Lake Tahoe.

Horizon supports the loading and display of hyperspectral and multispectral bands. This is accomplished by making the bands available for rendering and then allowing the user to selectively map any three of the bands to the red, green, and blue components. This process is shown in Figure V-4. The hyperspectral data shown here was collected by SpecTIR and processed at DRI by Tim Minor. By allowing dynamic mapping of bands, different combinations can be explored and investigated at runtime.

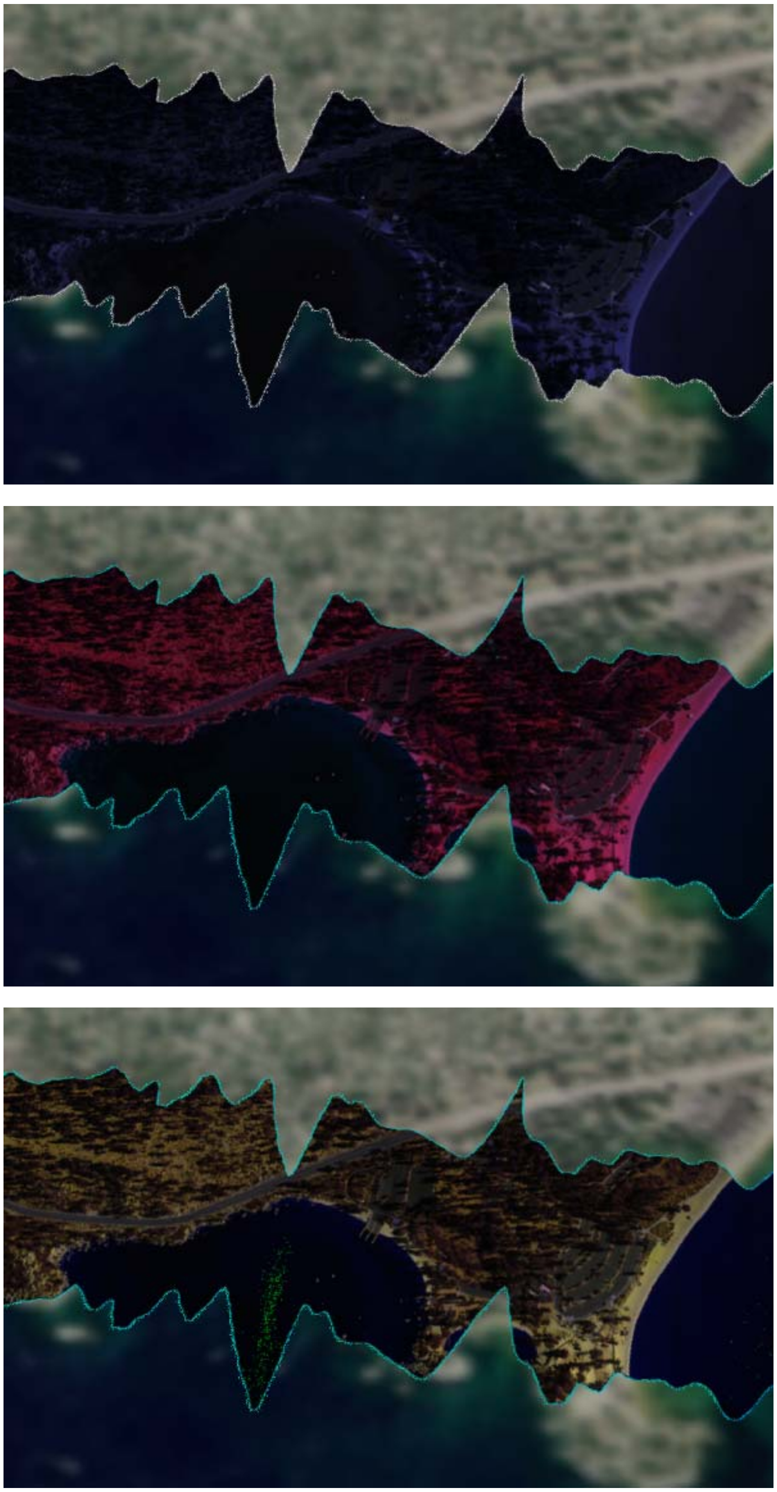


Figure V-4. Dynamic mapping of hyperspectral bands to the red, green, and blue components of a color map.

Horizon also displays layered volume data, as demonstrated by Figure V-5. This data is from the work of Gardner et al. (2013) and Huntington et al. (2013). This dataset shows layer thicknesses of four types of material in the Lake Tahoe basin. These layers are represented by four different digital elevation models (DEMs) in addition to a fifth DEM for the terrain geometry. The visualization allows the user to define and move a clipping plane, which cuts away the terrain to create a dynamic cross section of the volume data.

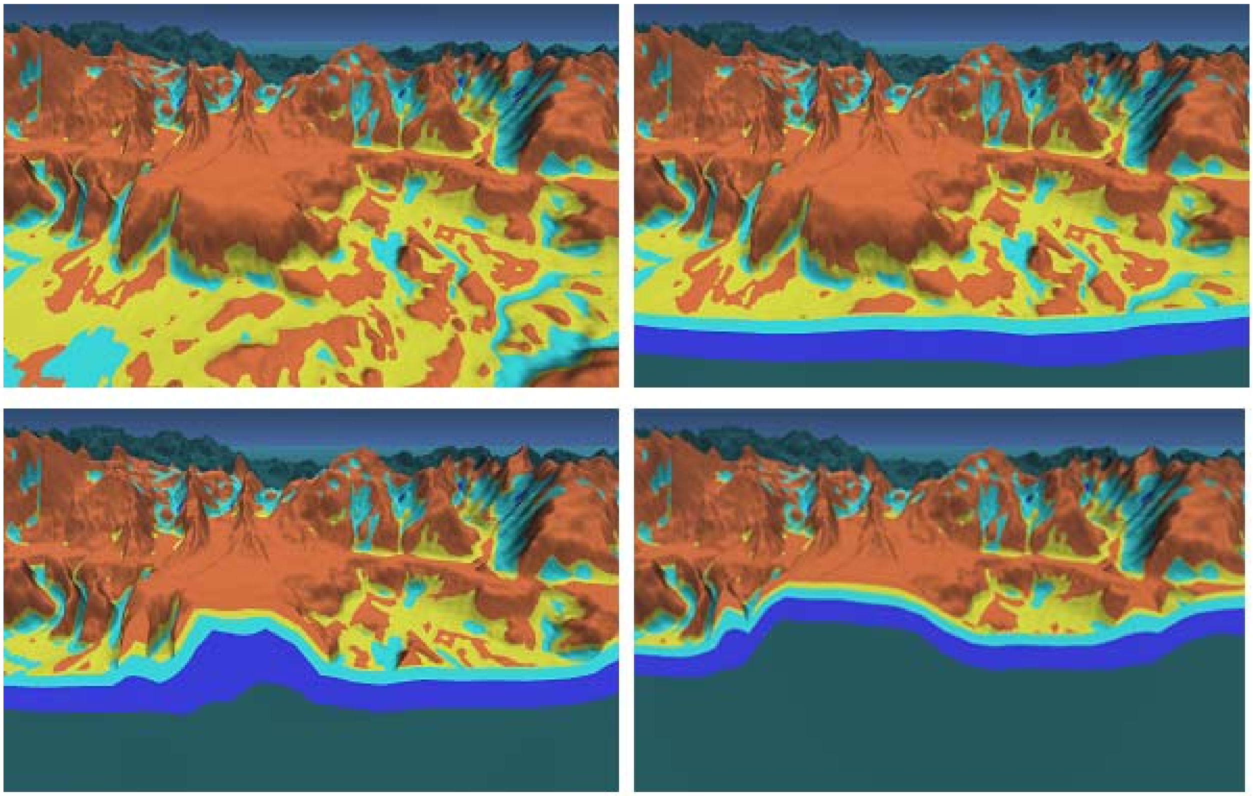


Figure V-5. Thicknesses of four different layers of material in the Lake Tahoe basin with a changing clipping plane that creates various cross sections.

Interaction

The features of interaction, in combination with the previously discussed features, allow the construction of a complete visualization of the Lake Tahoe watershed. Easy-to-use camera and navigational controls allow exploration of the planetary terrain. Intuitive controls are particularly important in a VRE since jittery and sudden movement tends to cause physical discomfort in users. Horizon also implements terrain ray casting, which allows the positioning of objects on the terrain (e.g. trees and buildings).

Software Architecture

The software architecture addresses the needs of GIS for visualization by constructing planetary information from multiresolution rasters, which are a central data structure in Horizon. The primary modules are shown in Figure V-6.

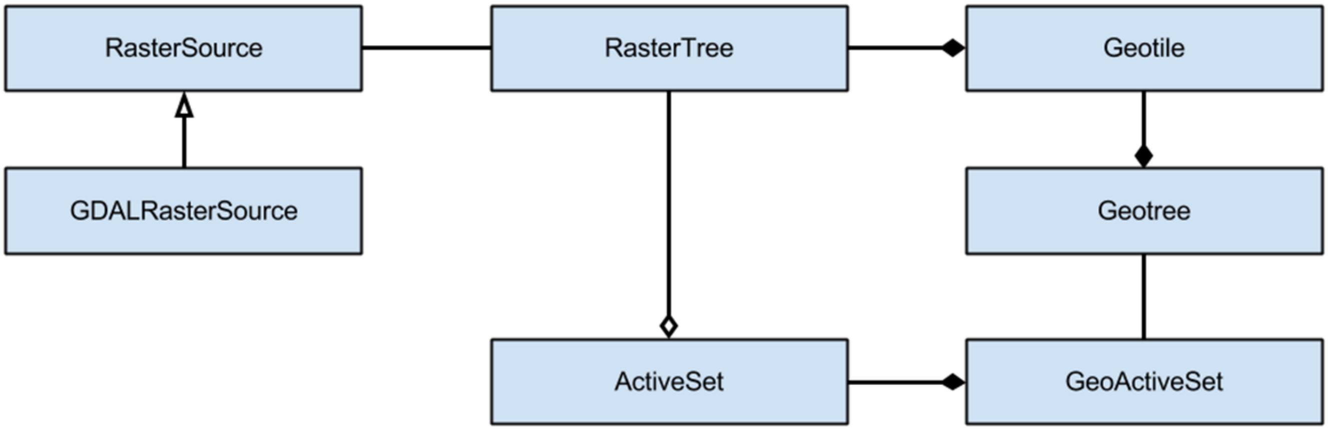


Figure V-6. Class diagram detailing the major components of Horizon.

RasterTree represents a multiresolution raster. It is named as such since it uses a quadtree to organize the raster data in coordinates of the map projection relative to the upper left corner of the raster. During preprocessing, RasterTree takes raster data from a RasterSource object and uses the GPU to composite the data into its quadtree. RasterSource is an abstract interface that allows RasterTree to interact with virtually any source of raster data; we have implemented GDALRasterSource to allow RasterTree to read data from any GIS file format supported by GDAL. GDALRasterSource also performs automatic reprojection of source data into the map projection of the RasterTree. Every RasterTree tracks the raster's datum, map projection, and geotransform for conversion between the various coordinate systems involved in GIS.

A RasterTree using any map projection is sufficient for planar terrain rendering. However, to build a planetary representation, two more classes are used, Geotile and Geotree. Geotile encapsulates a RasterTree that uses a gnomonic map projection. Alongside the features of a RasterTree, Geotile provides information about the gnomonic map projection's tangent plane. The geometric information provided by the gnomonic map projection makes it useful during preprocessing for map reprojection and during runtime for GPU construction of terrain geometry. Geotree comprises six Geotiles which are arranged in a cube to fully cover the datum. Geotree, as the planetary analog of a RasterTree, provides all of the functionality of a RasterTree except applied on a planetary scale. Therefore, Geotree can composite RasterSource data using the GPU and perform pixel lookup in planetary and geographic coordinates.

During runtime, ActiveSet takes a RasterTree and uses geometric information about each tile within the quadtree to determine the set of active tiles for display to the user. GeoActiveSet is an aggregation of six ActiveSet objects to represent an entire planet. This process is called adaptive refinement, and accomplishes the task of ALOD. The algorithm uses a restricted quadtree traversal, which means that neighbors of a tile may be no more than one level coarser or finer than the tile. This results in a gradual transition from high detail to low detail (Bernardin et al., 2008). The raster data for each active tile is uploaded to the GPU in a process that is amortized across multiple frames to maintain interactivity. This means that, for a single frame, only a number of tiles are uploaded to the GPU within a specified time limit. After the time limit, the program moves on to do other rendering and input work. When the raster data has arrived on the GPU, the terrain geometry is constructed from this raster data using a GPU program. Since the gnomonic map projection is used, this process involves for each pixel a ray cast onto the tangent plane of the map projection and a scaling of the resulting position onto the datum.

Impact and Scope of Work

The contribution of this work involves presentations at the 2012 Tahoe Science Conference and the 2013 NWRA Annual Conference. The previous version of the terrain renderer developed under Phase I was used by Steve Squyres in a Mars rover demonstration for local middle school students. The current version has been incorporated into the sequence of applications given for DRIVE6 demos. The visualization in DRIVE6 has been presented to DRI researchers who reviewed the display of their data.

The visualization group collaborated with the modeling and data groups to produce the primary contribution of Horizon, an interactive Lake Tahoe watershed visualization that incorporates all of the data interaction features discussed previously. The modeling group provided the visualization group with various model data: water recharge data over a year period (see Figure IV-3) and layer thickness volume data (see Figure IV-5) for the entire basin. The data group processed base data layers, providing aerial photography from the USDA National Agriculture Imagery Program (NAIP), topographic and bathymetric data from the USGS and hyperspectral data from SpecTIR (see Figure IV-4).

Table IV-1 explains the original scope of work and the features completed. Features in italics were not part of the original scope of work. Horizon was built on top of SMEngine, DRI’s graphics and simulation software. In the process of extending SMEngine, we have produced documentation for SMEngine and added the necessary components to link Horizon into SMEngine’s framework. We were not able to complete Deliverable 3.1 (Display vector data) since we added Deliverable 4.1 (Hyperspectral and multispectral data display) and Deliverable 4.2 (Volume data with clipping plane to create dynamic cross sections) during development. These features were important for creating a Lake Tahoe visualization that uses more data from both the Modeling group and the Data group.

Table V-1. Deliverables from the scope of work.

Deliverable	**Completed**
1. Refine, extend and harden SMEngine, the main DRIVE6 software asset for creating investigative applications	x
1.1 Develop a robust software engineering environment for the asset	x
1.2 Produce documentation	x
1.3 Create greater modularity to allow greater extensibility for other application	x
1.4 Identify and add specific features to the code to support the GIS component	x
1.5 Investigate use of the software for desktop deployment in addition to the CAVE	x
2. Develop a Virtual Globe Rendering system, suitable for supporting terrain rendering in DRIVE6 and integrated into SM-Engine	x
2.1 Display raster data (height and color) on planetary terrain	x
2.2 Incorporate adaptive level of detail (ALOD) based on user position	x
2.3 Composite color and height data at runtime on the GPU	x
2.4 Implement intuitive camera controls for navigating planetary terrain	x
3. Refine the Virtual Globe Rendering system to support custom and configurable applications. Some representative feature to be incorporated include	x
3.1 Display vector data (e.g. roads, rivers, and borders)	Replaced with 4.1,4.2
3.2 Atmospheric lighting	x
3.3 Pre-processing of datasets for performance	x
3.4 Ray-terrain intersection using the database for positioning objects on the terrain	x
4. Develop an interactive Lake Tahoe terrain rendering application using Nevada WRDMV datasets for use in the DRIVE6	x
4.1 Hyperspectral and multispectral data display	x
4.2 Volume data with clipping plane to create dynamic cross sections	x

Conclusions and Future Work

In collaboration with the data and modeling groups, we have developed an interactive visualization of the Lake Tahoe watershed that features various model datasets. The visualizations run on the desktop and in DRI's VRE for an immersive user experience. Within the visualization, users can explore hypserpectral data, animation data of water recharge, and volume data showing layer thicknesses around the basin.

In the future, we would like to use a relational database to store terrain tiles rather than storing them in flat files via the filesystem. This would increase the amount of data able to be visualized due to the compression provided by the database software and due to no longer user the filesystem which places limits on the number of tiles in a single directory. Using a relational database would also allow the implementation of an efficient central data server. The processing and display of hyperspectral data could be improved. Currently only a relatively small number of hyperspectral bands can be loaded and displayed at once. This work would expand the number of bands able to be loaded into the hundreds and implement real-time image processing operations for hyperspectral data in the visualization. We would also like to collaborate with researchers to build geological and hydrological tools for measurement of terrain data, similar to the work of (Bernardin et al., 2011). In this way we could improve dataset exploration and allow virtual field work to be done. Finally, the ability to dynamically modify terrain geometry would open up the terrain renderer for more flexible visualization and simulation, allowing you to modify the terrain for specific situations. It would also allow for modification by vector data, for example carving out smooth roads and accurate river beds, as demonstrated by Bruneton and Neyret (2008).

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VII. APPENDIX A. ABSTRACT FOR PUBLICATION – DATA WEB PORTAL DEVELOPMENT

Development of a Web Portal for Historical Remote Sensing Products Related to Hydrologic and Environmental Monitoring in the Truckee River Basin

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ABSTRACT

The Truckee River supplies water for both agricultural and municipal uses, and as such is as a likely area for potential water supply conflicts. A critical aspect of these potential conflicts is the amount of water consumption by both agricultural crops and natural vegetation. The ability to accurately measure and monitor water consumption on a large scale is extremely important to water managers, irrigation districts, and water users. Recent advances in the use of remote sensing and related modeling techniques that calculate evapotranspiration (ET) and have proved valuable when attempting to quantify water consumption down to the farm scale for large study areas. Many derivative remote sensing products, including surface reflectance, albedo, and vegetation indices, are required for these complex ET models based on the use of remotely sensed data such as Landsat Thematic Mapper (TM) data. This paper highlights the development of a web portal that serves historical remote sensing products for the Truckee River Basin for an 11 year time series (2001 to 2011). Over four thousand derivative image products were successfully loaded as ImageServices on a server systems using commercially available software. A graphical user interface was developed, also using commercially available software, allowing the user to visually display each data product by scene location and date, overlaid on base layers such as topography and/or street maps. Additional data layers such as watershed boundaries are also displayed to help locate areas of interest. Users have a set of tools available for querying cell values and locations. Once users view the data of interest, they can select the data product for downloading and store the data on a local machine or network server. The web portal provides users with direct access to derivative remote sensing products, saving the time required to develop these complex data sets themselves, and providing valuable inputs for ET and other hydrologic models.

VIII. APPENDIX B: ABSTRACT FOR PUBLICATION – INTEGRATED HYDROLOGIC MODELING

Integrated Hydrologic Modeling of Lake Tahoe and Martis Valley Mountain Block and Alluvial Systems, Nevada and California

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ABSTRACT

The U.S. Department of Interior has identified the Truckee River basin as highly likely for potential water supply conflict in the future. A critical water supply to the Truckee River is outflow from Lake Tahoe, and surface and groundwater contributions from the Martis Valley hydrographic area. This paper highlights the development of an integrated surface water and groundwater model, GSFLOW, in the Lake Tahoe and Martis Valley hydrographic areas to ultimately assess the effects of changing climate on surface and groundwater resources, and to identify the hydrologic mechanisms responsible for observed and simulated effects. Maintaining a balance between accurate representation of spatial features (e.g., geology, streams, and topography) and computational efficiency is a key objective for developing a realistic and computationally efficient model that can adequately simulate important hydrologic processes, including groundwater, stream, lake, and wetland flows and storages. Computational efficiency is required in order to calibrate to a diverse set of observation data, including surface water flows, lake levels, and groundwater head observations. Our work highlights how maintaining continuity between mountain block, stream zones, and basin fill units through data driven and conceptual layering is efficient, and results in accurate calibration to both surface water and groundwater observations. Additionally, we treat spring and wetland areas as groundwater head observations equal to land surface elevation, which provides constraints on groundwater heads over a much broader part of the model domain relative to well head observations alone.

IX. APPENDIX C: SAGEHEN DATA COLLECTION

Evapotranspiration Data

Evapotranspiration (ET) and energy balance data was collected at the Sagehen Creek experimental watershed. These variables include solar radiation, temperature, humidity, windspeed, and estimation of ET. Figure VIII-1 illustrates estimated ET for non-water limited vegetation surrounding the weather station tower.

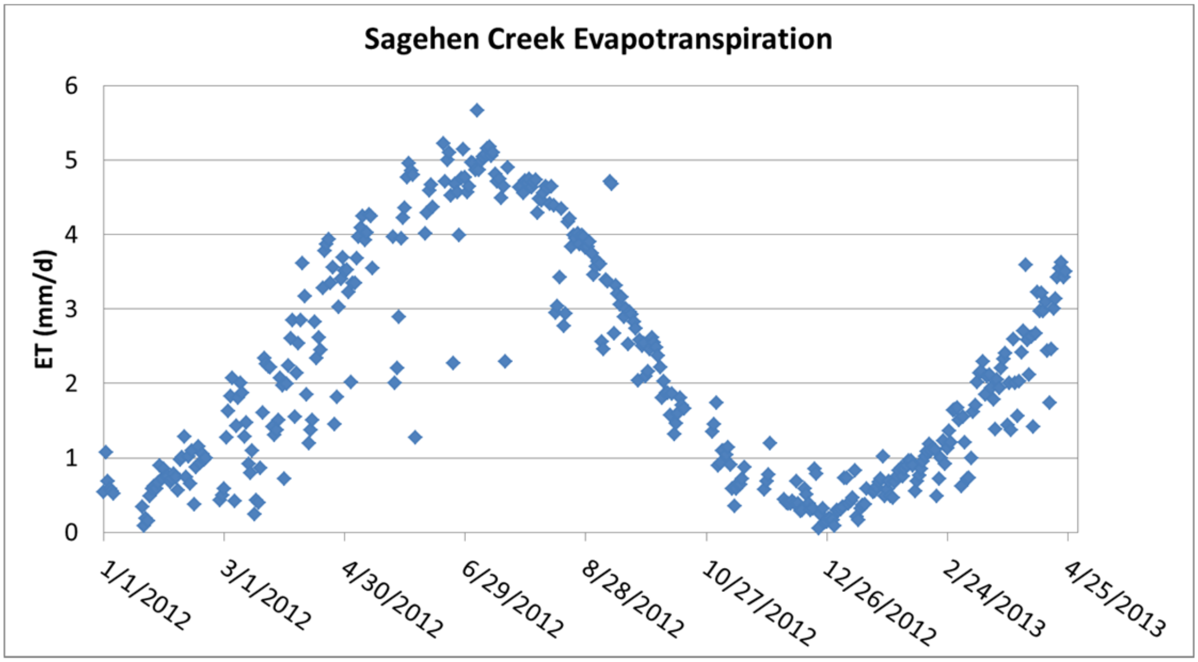

Figure IX-1. Estimated evapotranspiration at Sagehen Creek, CA.

Snow Cover Area

Remotely sensed snow cover area from the satellite MODIS was obtained and averaged to the watershed boundary (figure VIII-2). These fractional snow cover area data (MOD10 products shown in figure VIII-3) based on the normalized snow index are proving to be extremely useful for calibrating and validating hydrologic models in the area.

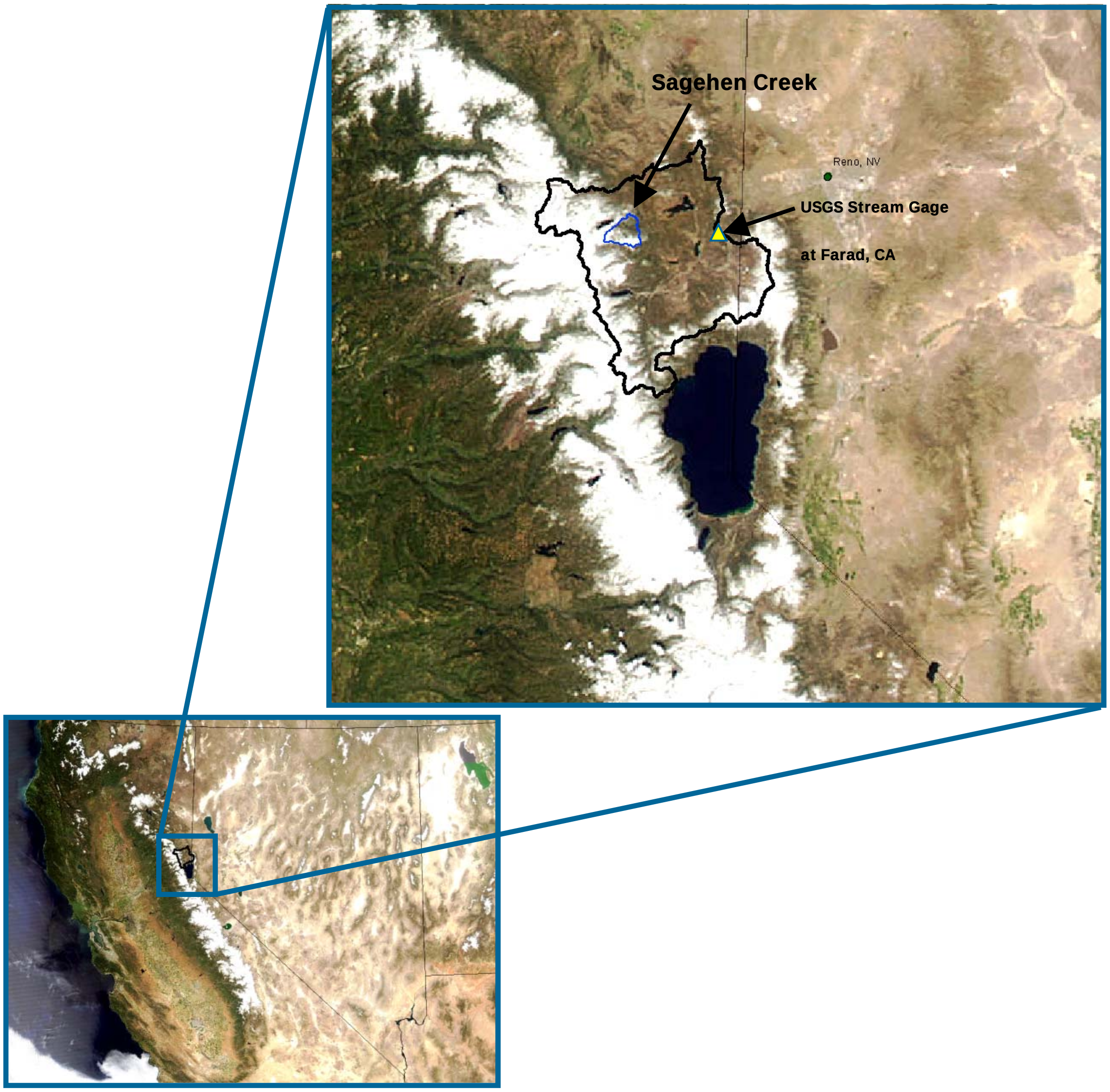

Figure IX-2. Location map showing the Upper Truckee River Basin and Sagehen Creek PRMS model domain.

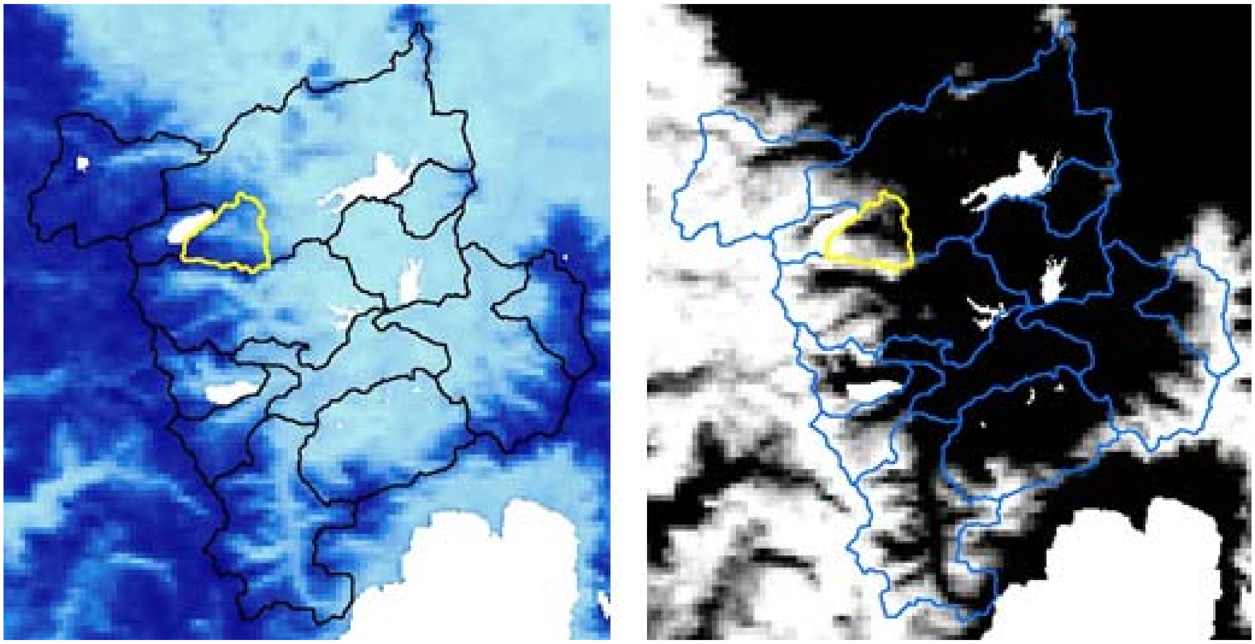

Figure IX-3. An example of the Normalized Snow Index and MOD10 Fractional Snow Covered Area showing Sagehen Creek (yellow) and remaining Truckee River subbasins (blue). Fractional SCA ranges from 0% (black) to 100% (white). Image date is from January 2012.

Using MODIS snow cover is useful to help calibrate runoff models. An example of this is shown in figure VIII-4, where calibrated PRMS simulated snow cover is compared to MODIS snow cover, where it is evident that PRMS, in general, captures the timing of observed melt in the fall and spring periods.

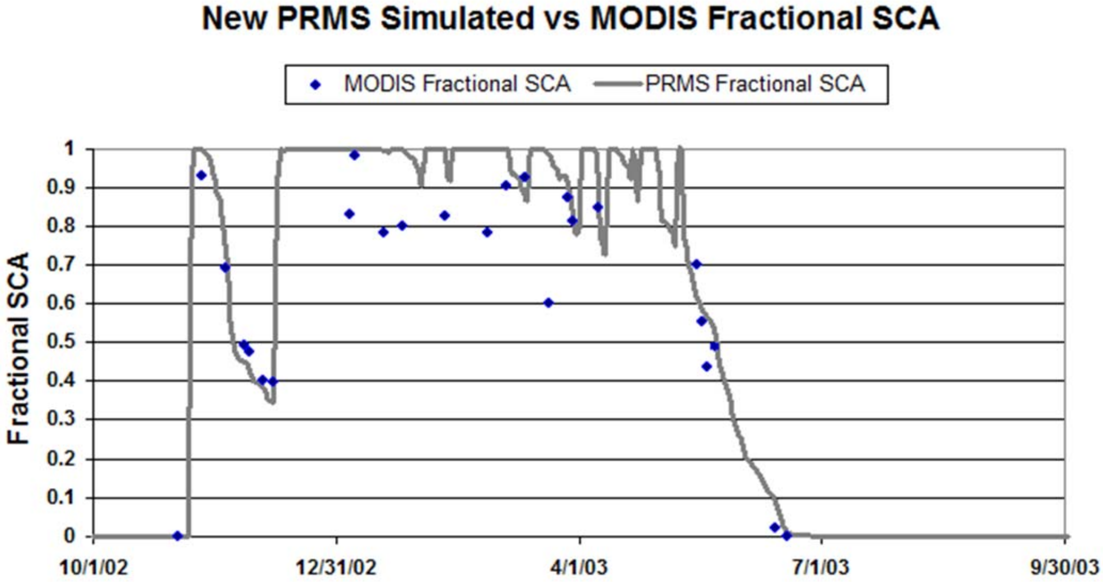

Figure IX-4. PRMS simulated vs MODIS fractional SCA using the PRISM precipitation and temperature lapse rate method. Notice that the simulated depletion of SCA compares well with the observed depletion of SCA, and hence the timing of runoff.

Snow Pillow Data

A snow pillow was installed in the upper portion of the Sagehen Watershed to acquire daily precipitation (as snow). The precipitation data is shown in Figure VIII-5. Annual snowfall ranges between 25 – 28 in over the period 2007 to 2012.

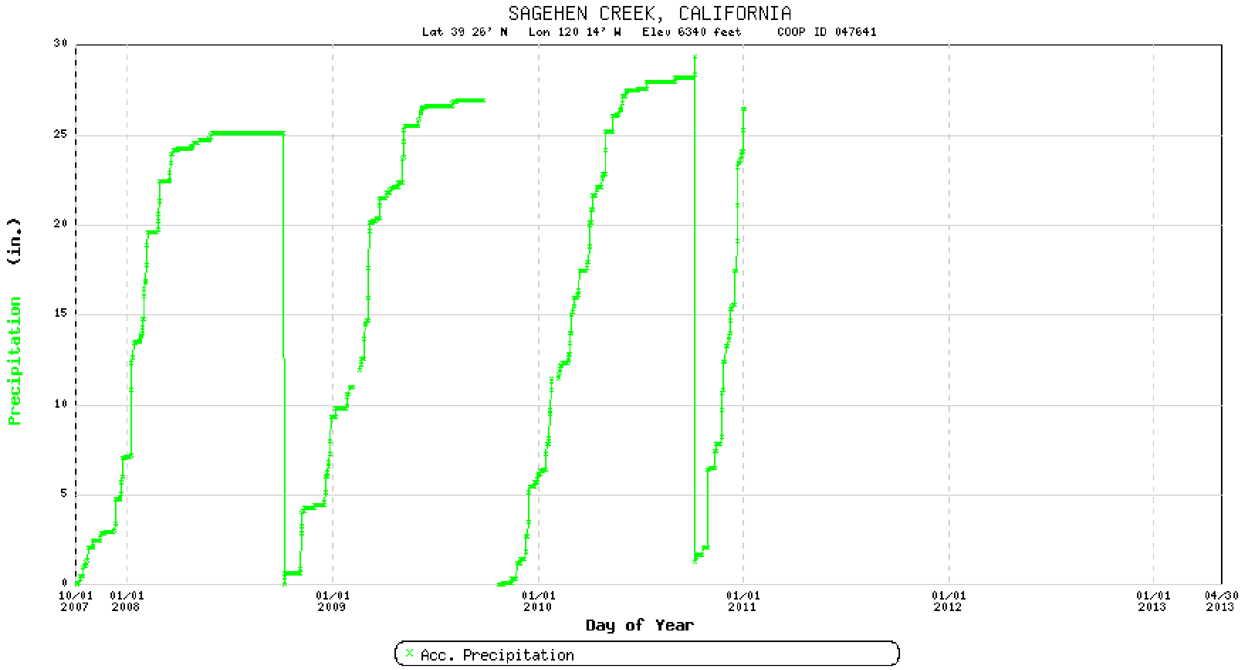

Figure IX-5. Precipitation record (snowfall only) for the Sagehen Creek Experimental Watershed.

Water Level Data

Water level data was acquired adjacent to the Sagehen Creek in the meadow adjacent to the research station facilities. These data are shown in Figure VIII-6. Water levels fluctuate approximately 1.5 ft throughout the season in response to the flows in the creek.

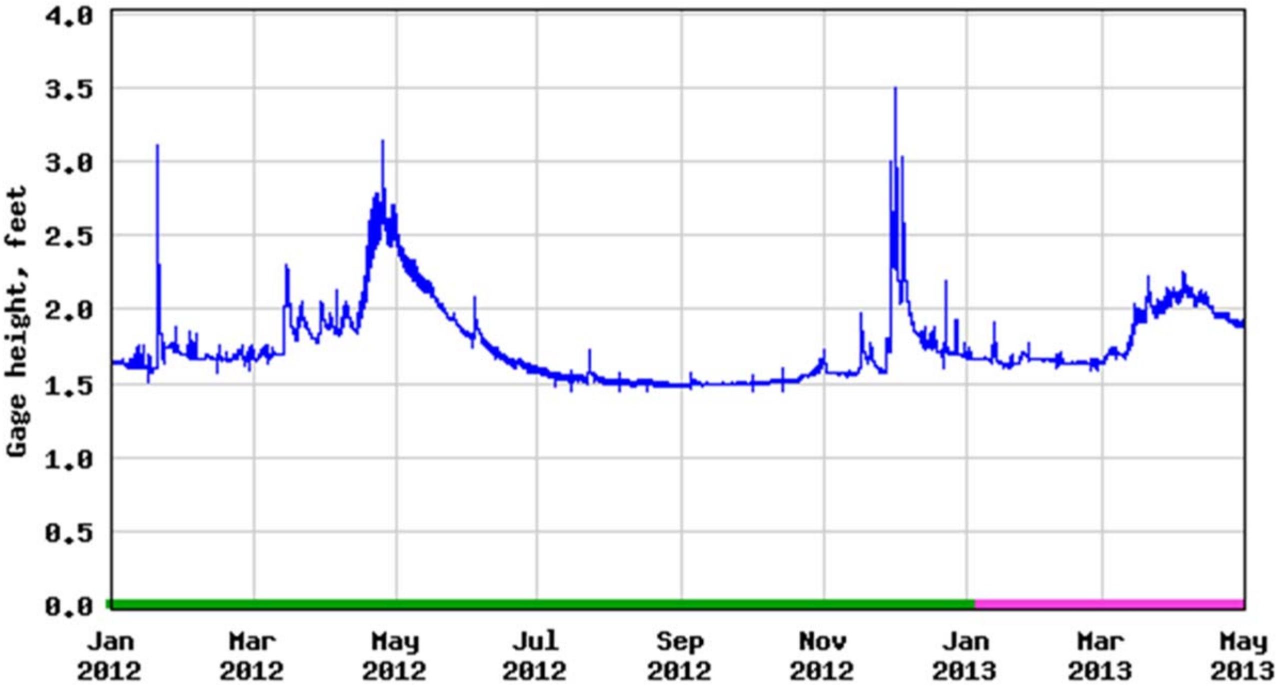

Figure IX-6. Water level data near Sagehen Creek.