**NASA EARTH SCIENCE ENTERPRISE**
**APPLICATIONS DIVISION**

***Earth Science for Water Management***

# *Applying NASA Satellite and Modeling Products to USBR Water Supply Forecasts in the Yakima River Basin*

This report documents the benchmarking of Earth science products, from satellites and land surface models, and their ability to add value to decision support systems, like RiverWare, of the U.S. Bureau of Reclamation, in making improved water supply estimates and predictions.

**Benchmark Report**

3 April 2009

*Earth Science for Society*

*Accelerating the realization of economic and societal benefits from Earth science, information, and technology …*

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## 1. Executive Summary

This report describes work completed in partnership between NASA, the U.S. Bureau of Reclamation (USBR or Reclamation), and the U.S. Geological Survey (USGS) to validate and benchmark inputs into the USGS Modular Modeling System (MMS), which has been set up to work with the decision support tool (DST), RiverWare, used by Reclamation. RiverWare is dually supported by Reclamation and the Tennessee Valley Authority (TVA) and mainly developed by the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado at Boulder. RiverWare is a river modeling and water accounting system used by several of the regional Reclamation offices, including the Upper Columbia Area Office (UCAO) and Yakima Field Office (Yakima, WA).

The overarching objective of the project was to demonstrate and measure the value added by information from satellite data, especially from the MODerate Resolution Imaging Spectroradiometer (MODIS) sensor, the Land Surface Data Assimilation System (LDAS) and its high resolution version, the Land Information Systems (LIS), to help improve Reclamation flood and drought risk analyses and water supply forecasts. The main goals are to determine if modeling and assimilating spatial snow data could help improve the initialization of the MMS hydrological model to improve streamflow forecasts used in the RiverWare DST. Efforts have been made to test and demonstrate whether MODIS and LIS integrated snow products add improvement to USGS's and USBR's operational MMS streamflow forecasts and thus RiverWare. The MODIS Snow Cover Area (SCA) product was validated and used to guide the Community Land Model, version 2 (CLM2), land surface model (LSM) in LIS. The Yakima River Basin, a tributary of the Columbia River system, was selected as the pilot study area because it has the most complete set of Watershed and River Systems Management Program (WaRSMP) research products that link the RiverWare modeling and decision support framework to other modeling components or DSTs, like AWARDS ET Toolbox.

Different time periods were identified for this study to investigate the change in snow initialization on MMS daily forecasts, focusing on unregulated sub-basin areas in the Yakima River Basin. These time periods include: (1) 2004 – a normal snow year for the basin; (2) 2005 – major drought and very low-flow year; and (3) 2006 – a water year which involved major snowmelt events. When compared with baseline MMS runs (with no adjustment) and stream gage measurements in three unregulated basins, the MMS baseline runs performed better in the more "normal" water year of 2004 than the two special runs adjusted with the LIS-CLM2 and SNODAS variables. However in the drought year case of WY2005, both the LIS-CLM2 and SNODAS initialized MMS runs performed better overall when compared to the baseline MMS runs. It is important to note here that improving streamflow prediction during low-flow periods is of major interest to water resource managers and engineers, like those at the Bureau of Reclamation.

With the approach demonstrated in this study showing such promising results for a low-flow period, we hope ongoing and future development of such NASA Earth science products will further contribute to enhancing streamflow predictions that will go to benefitting not only water resource managers but the broader public as well.

## 2. The Benchmark Process

The USBR (or Reclamation), a component of the Department of Interior, manages the largest quantity of wholesale water in the U.S. and is responsible for many aspects of water management, including flood baseline, irrigation, maintaining sufficient water levels for healthy wildlife and endangered species habitat, hydroelectric power, and other public- and industrial-related uses. They rely heavily on in-situ observation networks, but these networks do not cover completely all areas that contribute to the river systems for which Reclamation must monitor, predict, and make decisions. Also, due to a lack of spatial information needed, they must calibrate models with just these point measurements, making many assumptions to do so. In response to this need for more spatially and temporally complete information, Reclamation has partnered with NASA and other government agencies to explore the use of remote sensing products and to employ different models and techniques to work further with the remote sensing products.

NASA has defined a benchmarking strategy which involves evaluation, validation and verification of NASA ESE satellite and model products with a systems engineering type approach. The benchmarking process is applied to quantify any improvements made to a partner agency decision support system (DSS) using NASA research results. NASA ESE products are first evaluated for their appropriateness and feasibility to be used in an agency's DSS and then validated against independent observations to determine the potential value-added by the product(s). The validation and benchmark activities described in this report support Reclamation's ongoing mission to serve better its water managers, engineers, and end-users to improve water resources management in the mountainous Western U.S. In addition to providing more spatially based datasets to Reclamation, a goal of this benchmarking stage is to demonstrate the value added by inclusion of the daily to semi-weekly MODIS products that provide more up-to-date spatial information than climatological station information used normally in some current Reclamation models. Three of those MODIS products utilized in part of the project and benchmarking include: 1) snow cover area (SCA), 2) land cover classification, and 3) leaf area index (LAI). These products are employed by most of the LSMs in the LIS modeling framework and are tested within the CLM2 LSM for this project.

## 3. Descriptions of the USBR Decision Support Tools and Datasets

### 3.1 The USGS Modular Modeling System (MMS)

The USGS Precipitation Runoff Modeling System (PRMS) (Leavesley et al., 1983), within the MMS (Leavesley et al., 1996), has been applied throughout the Yakima, Upper Rio Grande and the Truckee-Carson basins as an alternative approach to real-time hydrograph generation for input to RiverWare. MMS-PRMS is used to generate streamflow forecasts by estimating important hydrologic state variables (e.g., soil moisture storage, snow water equivalent, etc.) at the time of the forecast and running the model forward in time with estimates of future daily precipitation and temperature from a variety of different approaches.

PRMS is a modular-design, distributed parameter, physical-process watershed model that was developed to evaluate the effects of various combinations of precipitation, climate and land use on watershed response. A water balance and an energy balance are computed daily for each hydrological response unit (HRU). The sum of the responses of all HRUs, weighted on a unit-area basis, produces the daily watershed response. The Yakima Basin MMS-PRMS modeling

units were set-up and calibrated by Mark Mastin at the USGS Office in Tacoma, WA, for the Yakima Field Office (YFO). The MMS can generate time series of snowmelt and the snowmelt runoff contributions to streamflow.

### 3.2 RiverWare

Reclamation's river management decision support tool, RiverWare, is dually supported by Reclamation and the Tennessee Valley Authority (TVA), and it is mainly developed by the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado at Boulder (http://cadswes.colorado.edu). RiverWare is a river modeling and water accounting system used by several of the regional Reclamation offices, including the YFO. It also provides a flexible framework for developing and running site specific models that incorporate the "law of the river," other policy constraints, and physical processes including hydrology, structural and natural operating constraints imposed by: dams, hydropower generating turbines, spillways, diversions and conveyance structures (canals), river channels and bank storage (Zagona et al., 2001). Within each river system, RiverWare requires streamflow hydrograph estimates as input at many locations throughout the system. For the Yakima area, MMS-PRMS hydrological modeling system is used to estimate the daily runoff hydrographs and as inputs to the various points with the basins. For this study, the MMS streamflow cases are benchmarked against in-situ and baseline simulations as potential inputs to future RiverWare benchmarks.

### 3.3 SNODAS Products

In connection with another project, Reclamation has tailored the output from a modeling system known as the SNOw Data Assimilation System (SNODAS), developed at the National Weather Service's National Operational Hydrologic Remote Sensing Center (NOHRSC), to fit the basin units used in the Yakima River Basin. For the state of Washington, Reclamation has been acquiring and displaying data from SNODAS to a website for the YFO engineers and water resource managers to access. SNODAS is a spatially distributed energy and mass balance model of the snowpack, forced by gridded solar radiation and meteorological variables, physically scaled to 1 km resolution using multiple atmospheric layers and a digital elevation model. The SNODAS modeling system blends data operationally from all available SWE, snow depth, and snow cover information, including snow cover from NOAA AVHRR (Advanced Very High Resolution Radiometer) data. Reclamation archived almost 5 years of SNODAS data for comparison with the NASA LIS 1km snow products developed for this project.

## 4. NASA's ESE Products

### 4.1 Land Information System (LIS)

The Land Information System (LIS) teams of the Hydrological Sciences Branch at NASA GSFC and affiliated with UMBC GEST Center are developing a system that runs multiple land surface models, assimilating and using as forcing the latest in surface observations and remotely-sensed data both operationally and retrospectively. The main hydrometeorological variables that LIS focuses on are soil moisture, evaporation, snow cover, runoff, precipitation, and also

radiation and energy budget variables. All of these, to some capacity, can serve water resource managers in helping to assess and predict flood and drought conditions (Peters-Lidard et al., 2004; Mitchell et al., 2003).

## 4.2 The Community Land Model

The Community Land Model, version 2 (CLM2; Dai et al., 2003) has been incorporated within LIS and is used for the project. CLM2 is designed to run on vegetation tiles or patches and uses leaf area index as a major vegetation parameter. CLM2 was developed originally to be coupled with large-scale atmospheric circulation models, but it contains a wide variety of hydrological, energy, and vegetation modeling components. The LSM also consists of a five-layer snow model. CLM2 was chosen for this project also because it captured most realistically seasonal snowpack changes versus the other LSMs in LIS at higher scales and over the domain selected for the project (refer to the V&V Report: *http://wmp.gsfc.nasa.gov/reports/V&V_RiverWare-091707.pdf* ). CLM2 has been enhanced with corrections to model physics and parameters to allow for additional improvement to the snowpack changes, especially during the snowmelt season.

## 4.3 MODIS Products

### 4.3.1 Vegetation Classification and Leaf Area Index

NASA's Earth Observing System (EOS) satellites, Terra and Aqua, involve international and multi-disciplinary partnerships that focus on collecting a variety of observations of Earth's water cycle, precipitation, land and ocean states, radiative fluxes and vegetation indices. The Terra MODIS land cover product (MOD12, version 4), developed at Boston University (Friedl et al., 2002), was used as the base vegetation parameter map for the LIS model runs. Several different vegetation classification maps are provided with the MOD12 product, including the University of Maryland (UMD) classification which was used in this project.

The Terra MODIS LAI product (MOD15, version 4) is used to parameterize the CLM2 model. This product is developed at Boston University and uses the MODIS land cover classification map in its production algorithm (Yang et al, 2006). Six years (2001-2006) of the MODIS LAI product are used to generate monthly LAI climatologies for the region. The MODIS LAI quality control flags are used to screen out any considerably anomalous LAI values from the 6-year monthly climatologies.

### 4.3.2 Snow Cover Area

The 500m Terra MODIS snow cover area (SCA) product (MOD10A1, version 4) was used (Hall et al., 2003). This MODIS SCA product is provided to the community with a snow albedo product, quality assurance (QA) information and now snow cover fraction, and it is based on the snow mapping algorithm that uses the normalized difference snow index (NDSI) and other correction factors. The Aqua MODIS snow product (MYD10A1) was not used due to difference in bands used in the NDSI calculation, which caused a fluctuating difference in snow cover area values between the two sensors. For consistency purposes, the Terra MODIS data was only used for this project.

### 4.4 Integrating MODIS Products with CLM2 in LIS

The CLM2 LSM in LIS has been enhanced with corrections to model physics and parameters, resulting in improved SWE fields. The MODIS SCA product is used to update the CLM2 model in a way that helps to "guide" the model. Since CLM2 was found to overestimate SWE in the later spring months, an artificial energy component is added to the modeled snowpack when a MODIS pixel has detected no-snow conditions but the model indicates a snowpack presence. To include this additional energy input, the modeled snow temperature variable is set to the downscaled and adjusted 2m air temperature to help promote melt within the persistent modeled snowpack in the spring months. This adjustment to the model improved the timing of the snow melt. The integrated MODIS SCA and LIS modeled products were set up and run for the Yakima River Basin. A four-year spin-up was performed for CLM2 at the 0.01 degree resolution, using the NLDAS meteorological forcing dataset. Six years worth of simulations have been completed so far.

## 5. Verification and Validation of LIS and MODIS Products

### 5.1 Area of Interest: Yakima River Basin in Washington

The Yakima River Basin, a tributary of the Columbia River system, was selected as the region or area of interest for this project because it has the most complete set of Watershed and River Systems Management Program (WaRSMP) research products that link the RiverWare modeling and decision support framework to other modeling components or DSTs, like AWARDS ET Toolbox. In the Yakima Basin, Reclamation is conducting research to improve the operation of the river system to provide a more sustainable environment to meet complex demands. These demands include hydropower generation, irrigation, and municipal and industrial deliveries of water for beneficial use, which must be met while maintaining water quality standards to protect ecosystems and fisheries. The Yakima River Valley area is highlighted in Figure 1 below.

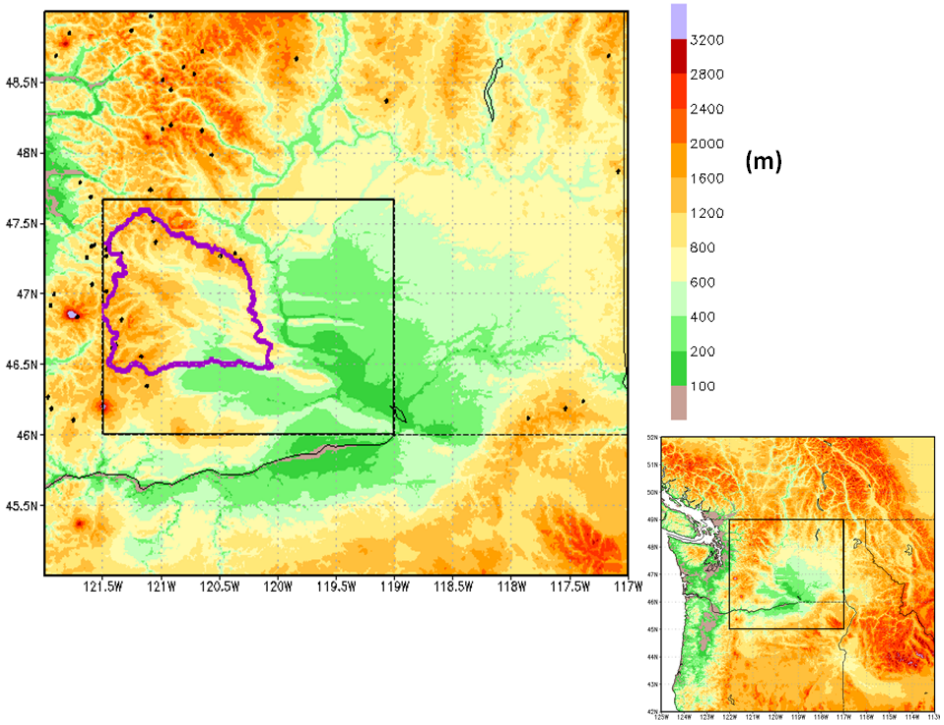



**Figure 1.** This plot shows elevation (in meters) for the Washington area domain with the Yakima River Basin area highlighted (basin boundary outlined in purple) at 1km resolution. The black dots in the main plot indicate the SNOTEL sites used in the study. The smaller plot in the lower right corner shows a larger Pacific Northwest area, which includes an outline of the Washington domain. The dataset source is the National Elevation Dataset (NED).

## 5.2 Assessment of Earth Science Products

### 5.2.1 Validation of MODIS Datasets

For the Terra MODIS land cover dataset (MOD12) for the Washington region, accurate registration of the MOD12 and even other MODIS products is difficult to accomplish due to reprojection and resampling errors. These errors were encountered in this project, since the MODIS products used are converted to the LIS 0.01 degree (~1 km) geographic coordinate system which the LSMs are run on. Overall though, main water bodies and other major land and vegetation features (e.g., extensive crop areas) are captured well by MOD12. For MODIS LAI product (MOD15), the monthly climatologies validated better than previous AVHRR or MODIS LAI datasets and compared well other observed LAI studies, especially for evergreen needle-leaf forest cover areas (e.g., Scurlock et al, 2001) which make up most of the area where snow cover is found.

### 5.2.2 Snow Cover Area (SCA)

For SCA, the Terra MODIS product was found to have a higher rate of snow detection over Aqua, since an error in the Aqua MODIS sensor lends to a slight degradation in the SCA product. Performing a probability of detection (POD) analysis on the Terra MODIS SCA

product revealed an underestimation of SCA pixels being identified as "snow" due to change in snow properties in the springtime and the thick forest cover in the mountainous areas where the snowpack resides. The underestimation in the snowpack detection was most severe in the spring months, when the main snowmelt period occurs. These validation results are shown in the Verification and Validation (V&V) report (http://wmp.gsfc.nasa.gov/reports/V&V_RiverWare-091707.pdf). The impact of this underestimation on the assimilation of MODIS SCA in to LIS is addressed in subsequent sections (i.e., refer to Section 5.3) and also in the V&V Report.

### 5.2.3 Validation of the NLDAS Forcing Dataset

The 1/8 degree North American LDAS (NLDAS) forcing dataset (Cosgrove et al., 2003) was used for the LIS LSM runs. These fields are all downscaled to the 0.01 degree resolution in LIS. Using the ~1 km elevation parameter field, the LDAS meteorological forcing variables (e.g., temperature, humidity) are further downscaled to account for higher resolution elevation adjustments to the local temperature lapse rate. Overall, the downscaled NLDAS temperature fields compared well with in-situ measurements (e.g., SNOTEL temperature data), though biases occur for various geographic locations (e.g., leeward vs. windward side of the Cascade Mountains) and different elevations. Also, the NLDAS precipitation field compared well with in-situ observations, obtaining realistic total amounts per month. However, the precipitation amounts were too great on the lee-ward side of the Cascades and less on the wind-ward side due to the original interpolation scheme used on the CPC precipitation gage product which is used in the NLDAS precipitation product (e.g., Cosgrove et al, 2003). To see results for the forcing validation, refer to the V&V report (http://wmp.gsfc.nasa.gov/reports/V&V_RiverWare-091707.pdf)

## 5.3 Addressing Error Estimates in the Earth Science Data and Models

An important stage of the validation process is estimating the errors associated with the relevant model and satellite products used in this project. Initial validation and error assessments were provided in the companion V&V report; however, we address further here the error estimates related to the use of the satellite data within the chosen LIS land model. Our preliminary evaluation of the LIS land surface models indicated that CLM2 modeled a more realistic snowpack during the snow accumulation period, but it reveals a delay in the onset of springtime snowmelt. This delay was also found to persist into the late summer months. To try to correct for this overestimation in springtime snowpack conditions, a simple direct insertion (DI) assimilation method was first employed and tested in LIS, based on the original study by Rodell and Houser (2004). The 500m Terra MODIS SCA product was aggregated to the 0.01 degree LIS projection and used in this simple assimilation approach in CLM2. Due to the earlier reported underestimation of MODIS snow cover area for this region in the spring months, these biased observations acted to cancel out the overestimation in CLM2's springtime snowpack. However, directly inserting the MODIS SCA into CLM2 mainly resulted in a major under-prediction of its springtime snowpack (see Figure 2 below).

To improve the assimilation process, knowledge of the model and observation biases was used to enhance the assimilation procedure by adjusting the heat energy into the CLM2 snow-soil layer column, which can help with melting the modeled snowpack sooner. Since the

NLDAS air temperature field compared well with in-situ observations, like SNOTEL data, this information was used to adjust the colder temperature conditions of CLM2 by "warming" the snow-layers and inducing more melt on days that warmed up greater than the freezing point. The MODIS SCA product was still used, but it was utilized as more of a "guide" to CLM2 when MODIS detected "snow" or "no-snow" conditions. This adjustment to the DI assimilation procedure allowed MODIS SCA to guide CLM2 as to when possible snow cover removal was occurring on a spatial basis, and the persistent cold-bias in CLM2 was reduced, resulting in an earlier onset of snowmelt in the model. This enhanced DI assimilation run is referred to as the MODIS-SCA model temperature adjusted or "corrected" run. The timing of this melt was improved and matched SNOTEL observations more closely for the overall Washington state domain, as shown in Figure 2a. Finally, in the snow accumulation phase, MODIS SCA was also able to enhance the amount of snow accumulation in CLM2, leading to more realistic seasonal amplitude to the modeled snowpack conditions. This improvement is also shown in Figure 2b for WY2005, the anomalously low snow year, where this temperature-adjusted or "corrected" CLM2 data assimilation run performed better over the baseline (default) CLM2 and MODIS-SCA only assimilated runs.

To estimate the errors associated with these runs in both the "normal" and "low" flow years, the statistical measure, root mean squared error (RMSE), was used to quantify the how the runs differed from the "truth", as represented by the in-situ SNOTEL SWE measurements. RMSE values are calculated daily and then plotted for October 1 to July 31, reflecting the main snow season period. Figures 3a and 3b show the estimated errors for each water year, 2004 and 2005, respectively. The MODIS-SCA model temperature-adjusted DI run reveals lower errors for most of each water year with mainly a reduction in error magnitude during the winter and spring months. In the late spring and early summer months however, the MODIS-SCA only DI method had the lowest and quickest decrease in RMSE values, especially in WY2005. These rapid springtime error reductions indicate that complete removal of the model snowpack due to the direct assimilation of MODIS SCA binary-type data is value-added by the snow information provided by this MODIS product. However, for this study, we are mainly interested in April 1$^{st}$ modeled snowpack conditions as a test to see if they can improve estimated springtime runoff and streamflow in the MMS-PRMS modeling system. Since the enhanced DI method of adjusting the model snowpack temperature and heat energy flux, guided by the MODIS SCA product, produces a lower error estimate on that date, it is thus used in the MMS experiments and evaluated against streamflow data and the MMS simulations initiated with the SNODAS snow states.

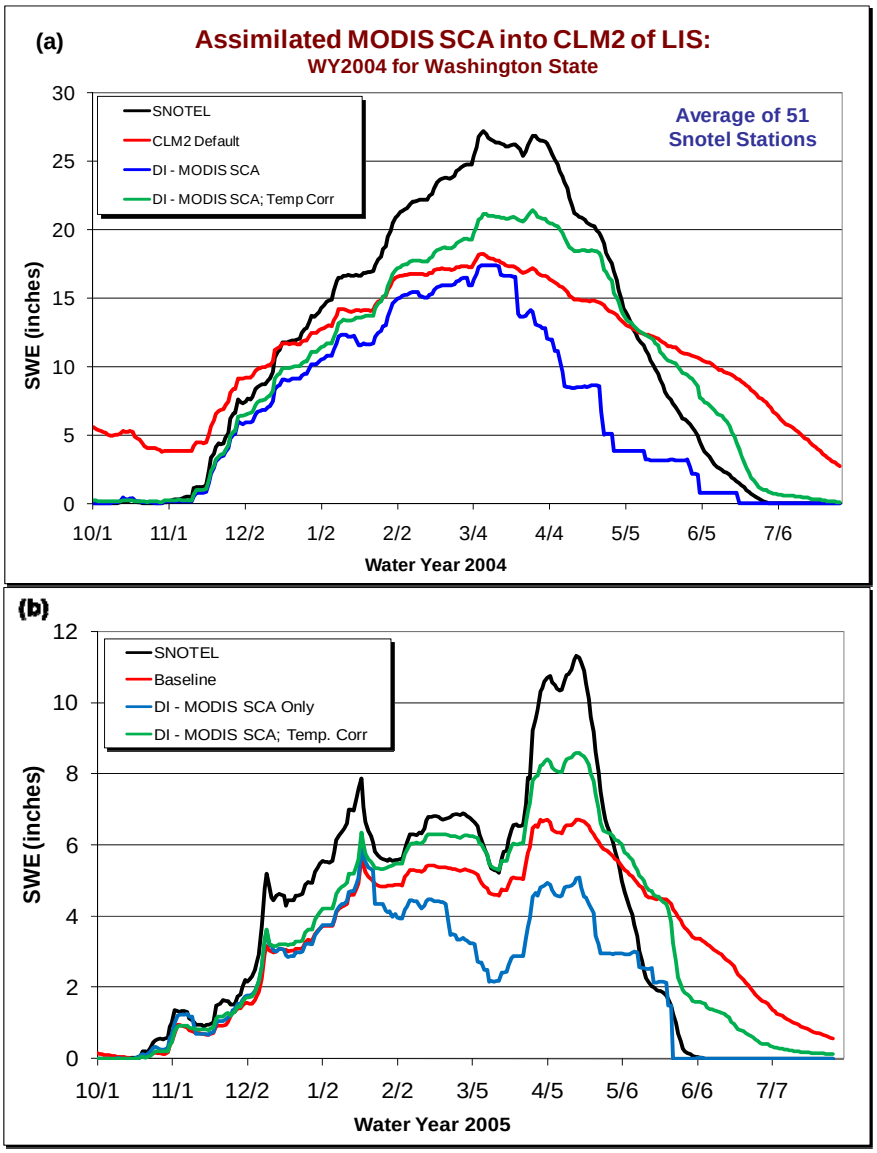



**Figure 2.** a) Time series for WY2004 of averaged SWE for SNOTEL (black line) and equivalent points of the LIS CLM2 baseline run (red line), MODIS SCA DI run (blue line) and the improved temperature-adjusted CLM2 run with MODIS SCA (green line). b) Same description except the plot is for WY2005.

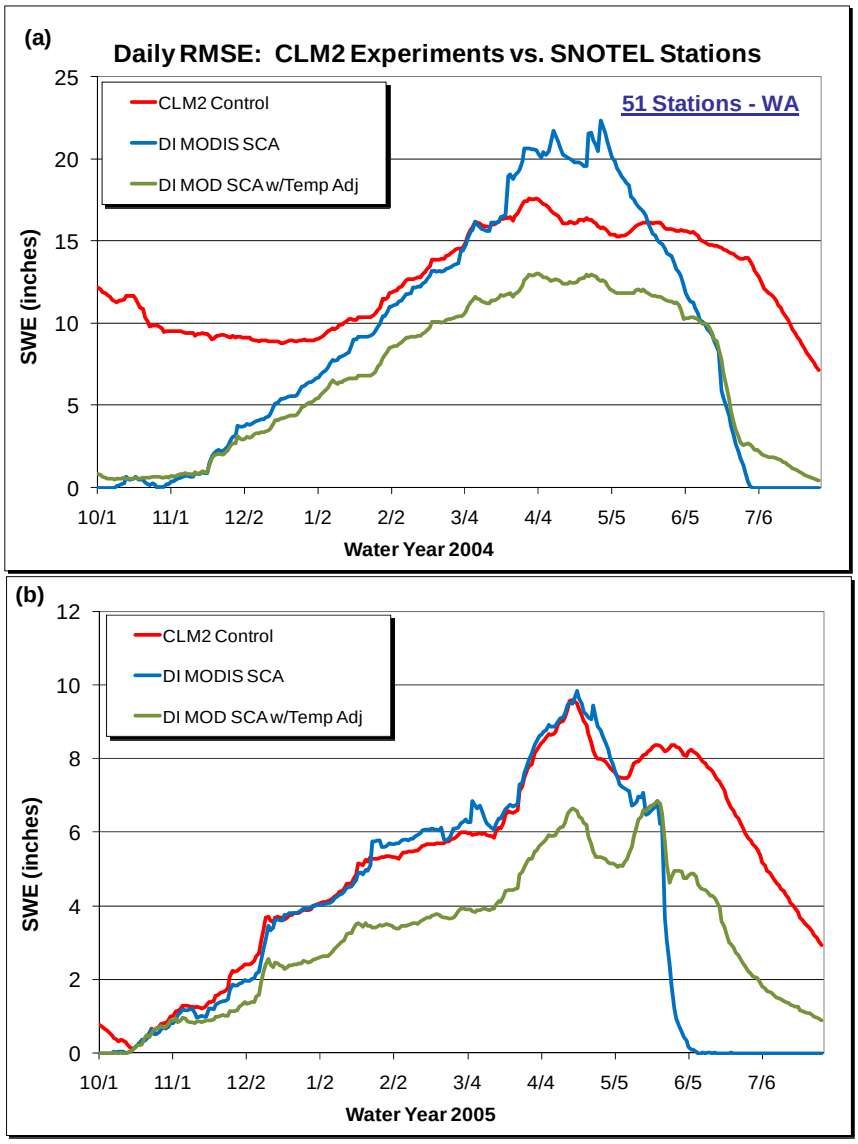



**Figure 3.** a) RMSE time series for WY2004 of averaged SWE for SNOTEL (black line) and equivalent points of the LIS CLM2 baseline run (red line), MODIS SCA DI run (blue line) and the improved temperature-adjusted CLM2 run with MODIS SCA (green line). b) Same description except the plot is for WY2005.

## 6. Steps to Integrate and Utilize NASA Products in MMS

### 6.1 Migrating LIS and SNODAS Grids to the MMS Watershed Polygon System

At the Denver TSC Office, Reclamation project members processed and reformatted both the ~1km NASA LIS-CLM2 and SNODAS snow fields to fit the hydrological modeling response unit (MRU) areas, which are used in MMS. More than four years (2003-2007) worth of both the NASA and NOHRSC datasets were processed to fit the MRUs for use in MMS-PRMS.

The MRUs are separated into four different hydrological regions for the Yakima region, which are treated as major modeling units. These modeling regions are shown in Figure 4 and include: 1) the Naches, 2) Upper Yakima, 3) Toppenish/Satus, and 4) Yakima Canyon modeling units (Mastin and Vaccaro, 2002b).

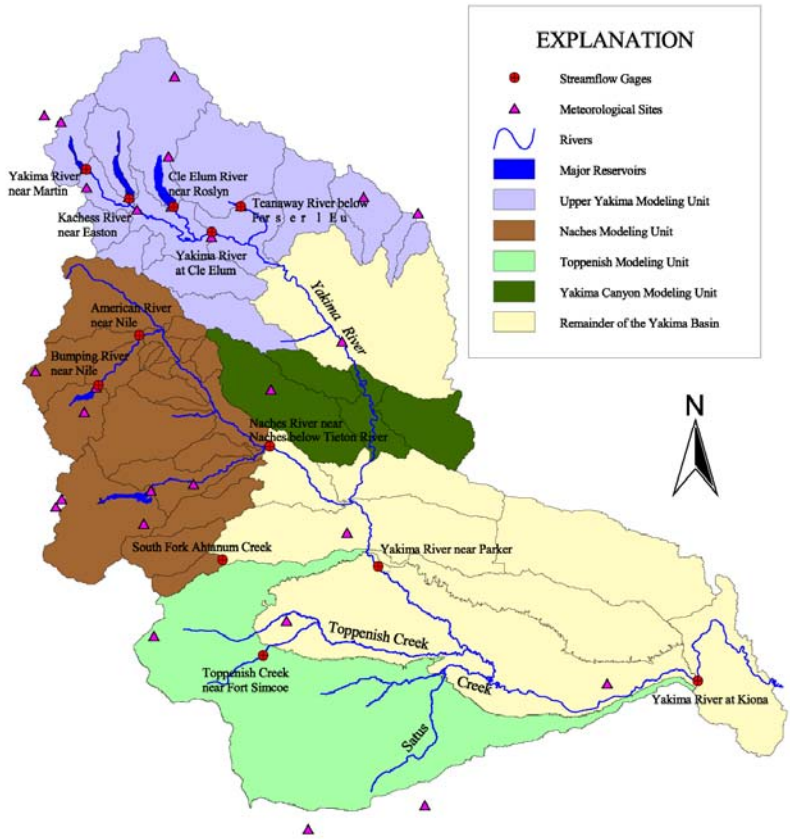
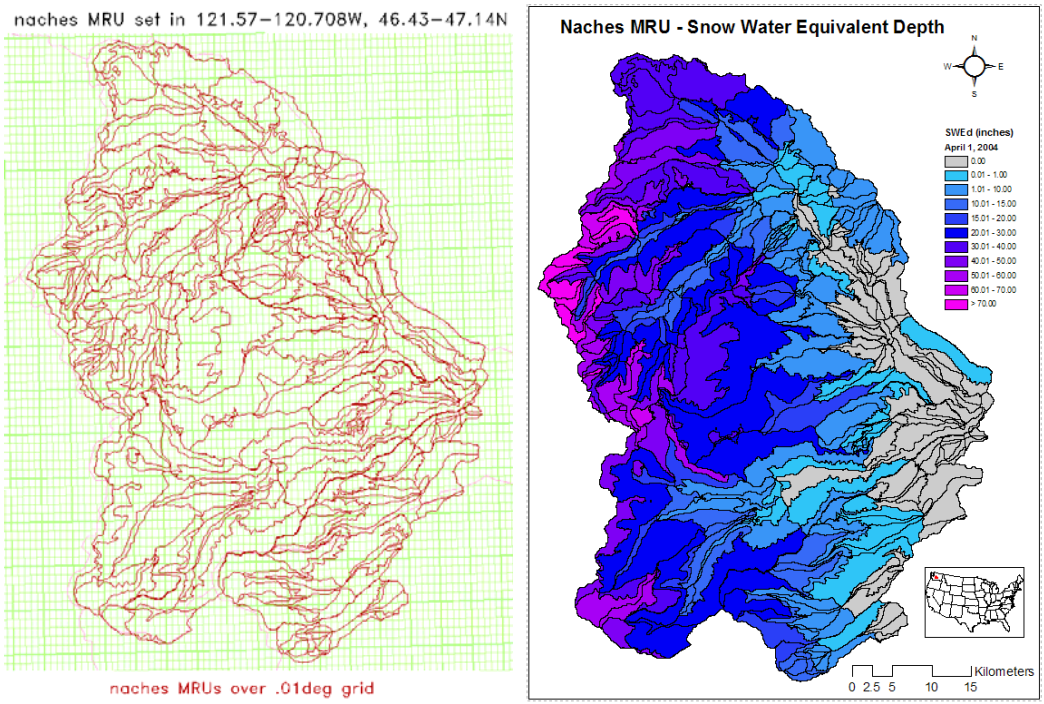



**Figure 4.** The Yakima River Basin's four watershed modeling regions and hydrometeorological in-situ measurement networks are shown in this map. (*Courtesy of Mark Mastin of the USGS*).

USGS provided the MRU map of the four watershed models. To migrate both the daily 0.01 degree LIS and SNODAS gridded snow-related variables to the MRU areas, the grid cell areas were determined and grouped by MRU. The snow variables associated with those grouped cells were then summed or averaged by weight of the fractional area over the MRU. The following variables were processed for use with the MMS simulations:

- Snow Depth (inches)
- SWE (inches) and SWE volume (acre feet)
- Snow Melt (inches; daily sum)
- Snow Temperature (deg C)

An example of the LIS-CLM2 gridded output processed onto the MRUs is shown in Figure 5 below. The enhanced LIS-CLM2 simulated SWE output (as described in Section 5.3) is placed on the MRUs for the MMS Naches Modeling Unit for April 1, 2004.




a) b)

**Figure 5.** a) The LIS 0.01 degree grid system (1 degree/100 pixels) imposed on the MRU set for the Naches modeling unit for the Yakima River Basin area. b) SWE output (in inches) from the enhanced LIS-CLM2 system migrated to the Naches MRUs for April 1, 2004.

## 6.2 Experimental Design for Initializing MMS Runs with LIS and SNODAS

To initialize MMS with daily LIS and SNODAS snow values, a certain day is selected to initialize and then run the model up to that day, update the snow variables, and then run the model from that day onward. Initializing MMS more than just one day at a time would require being entered as a time-series, which the model is currently not set up to handle and would require some effort to do so. For benchmarking a MMS streamflow forecast for a full runoff season, MMS is stopped on April 1, its variable file is updated with either the SNODAS or LIS data, and then the model is run from April 1 to July 31 (or a later summer date). The experiment output is then compared with the baseline MMS model runs. Different storm events could be simulated in this fashion as well.

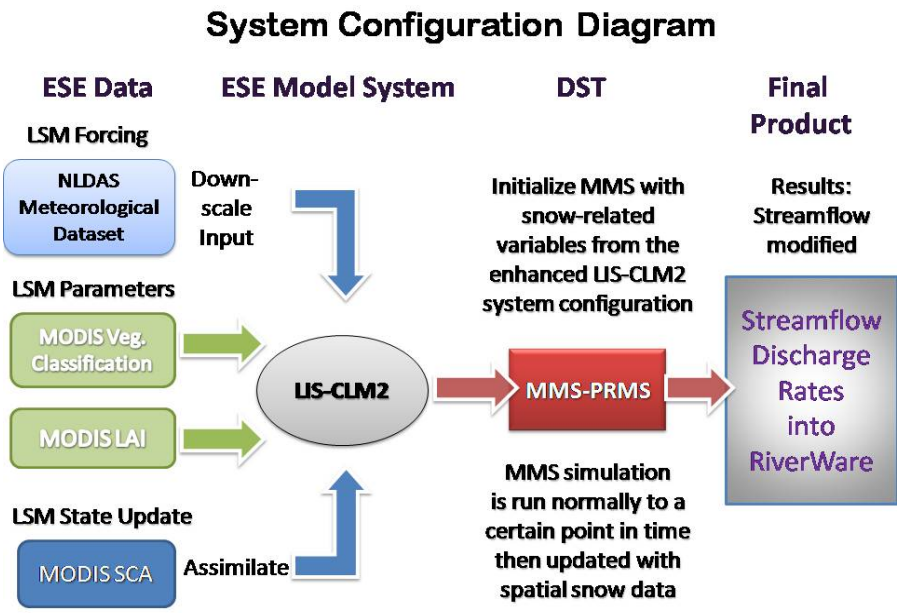



**Figure 6.** This diagram depicts the configuration of which ESE datasets are used and the flow of how they get ingested into the ESE model system, LIS. The CLM2 snow-related variables are then placed in to MRU polygons and used to initialize the MMS DST at a certain time.

### 6.3 Integration and Interoperability Issues

A problem arose with mapping the 0.01 degree grid cells to the MRUs, since some of the MRU polygons were too small to include in the aggregation or assigning process or a MRU polygon may have had an issue with the way it was originally delineated. The former problem caused some issues with providing exact matching with the MMS modeling unit setup. Two MRUs in the Upper Yakima modeling unit were removed from the mapping process of going from the 0.01 degree to the polygon-based MRUs. The main reason they were not included is due to their area being quite small, so no 0.01 degree cell was either resampled or assigned to those small MRU polygons. Since the modeling units were completed about seven years ago, a great deal of effort would need to be made to insure that the MRU polygons were updated in several different places. USGS staff at the time did not have resources to complete such work. So going from an equal-spaced grid cell system to a polygon unit system introduced some small differences in which led to a slight reduction in some grid cell-mapped MRUs. Thus, this would lead to not having the exact number of MRUs and information contained in all the MRUs that would eventually be used in the special MMS runs.

The way that the MMS-PRMS modeling units were set up at USGS for the Yakima Basin they could only be updated at certain points in time with having to run the MMS model to a point, make the update, and then run forward again in time. To do this step more than once would become tedious for the USGS staff member. However to do this updating more frequently with the spatial snow variables in MMS in a more automated way would require several changes to the MMS model setup and for all four units.

In the duration of this project, the Reclamation YFO lost and had to restore the Hydrologic Data Base (HDB) input to MMS after a major system failure in 2005. This non-use of the HDB led to the MMS runs from the USGS to not be updated into 2006 and beyond which led to not using MMS hydrograph information in the RiverWare DSS at the Reclamation YFO. Therefore, the normal case (WY2004) and severe drought case (WY2005) were selected to be tested and benchmarked within the MMS.

## 7. Benchmarking MMS with LIS-Assimilated MODIS Snow Cover Area and SNODAS

### 7.1 MMS Case Studies

Two case study years were selected to perform benchmarking simulations of the NASA products and NOAA SNODAS in MMS. The severe drought of 2005 for Washington was selected along with extreme melt events of 2006. However as mentioned earlier, a loss of the Hydrologic Data Base system in late 2005 led to no more MMS simulated output being incorporated into RiverWare since then, and no updating of the meteorological and other information needed for the MMS runs was maintained beyond 2005. Therefore, two years were selected for a normal case (WY2004) and severe drought case (WY2005) to benchmark the MMS simulations.

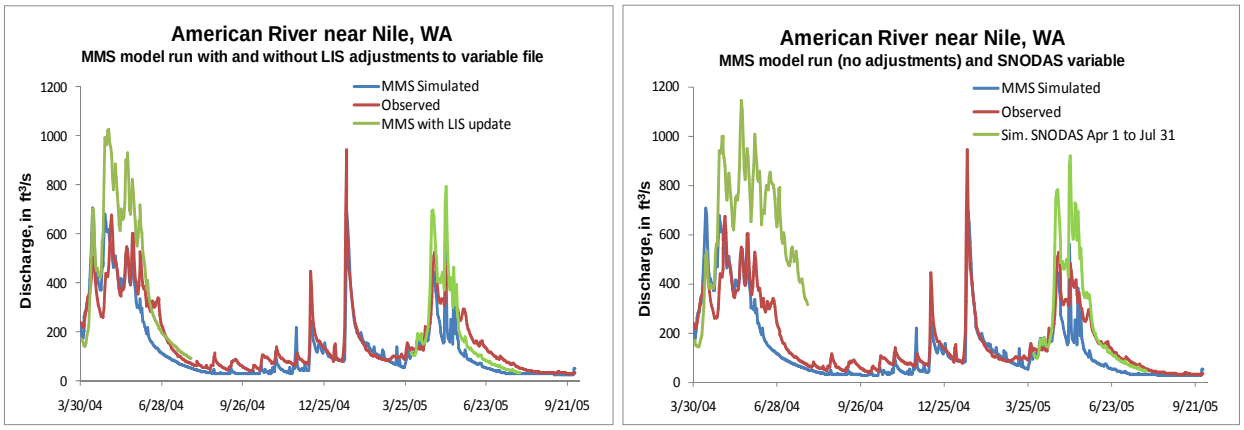
To perform these case studies, MMS is initialized one time at the beginning of the spring snowmelt season, April 1$^{st}$, with the enhanced LIS SWE in place of the calibrated snow curve-derived SWE that is currently implemented in MMS. The case studies are also performed with SNODAS fields for further comparison against the LIS product. The output and hydrographs from these MMS runs are compared against a baseline MMS simulation and local stream gage hydrographs. The comparisons are made for three unregulated sub-basin river test bed areas: 1) American River, 2) Little Naches River, and 3) Teanaway River.

The Yakima MMS model runs include 1) simulations with no adjustments, 2) adjusted with LIS snow data, and 3) adjusted with SNODAS snow data for April 1, 2004 and April 1, 2005. The USGS performed the final benchmark runs. The models were updated on April 1 with the different snow product data and run until July 31, producing runoff volumes for four-month periods of WY2004 and WY2005.

### 7.2 Analysis of DSS Performance with NASA Results Compared with Baseline MMS Simulations and SNODAS Experiments

The results of the baseline MMS runs are compared to the April 1$^{st}$ experiments and streamflow gages for the three unregulated catchments. For the American River (near Nile, WA) in the Naches modeling unit, the MMS baseline run performed better in WY2004 than the two MMS experiments, initialized on April 1$^{st}$ with SNODAS and LIS snow fields. Figure 7a shows the closer agreement of the WY2004 baseline MMS simulations with the streamflow observations, which have the lowest root means square error (RMSE) of 111.1 and a total percent difference with observations of -8.18 (refer to Table 1). Between the two special case runs, the MMS-LIS case performed better in WY2004 (Figure 7a), and the anomalously high MMS-SNODAS discharge rates tend to persist too long into the spring months (Figure 7b). For the severe drought case (WY2005), MMS-initialized with the LIS snow fields performed the best

overall as shown in Figure 7a. Table 1 indicates an RSME of 86.8 and percent difference of 0.22% for the MMS-LIS case, which are the lowest of the compared simulations.




a) b)

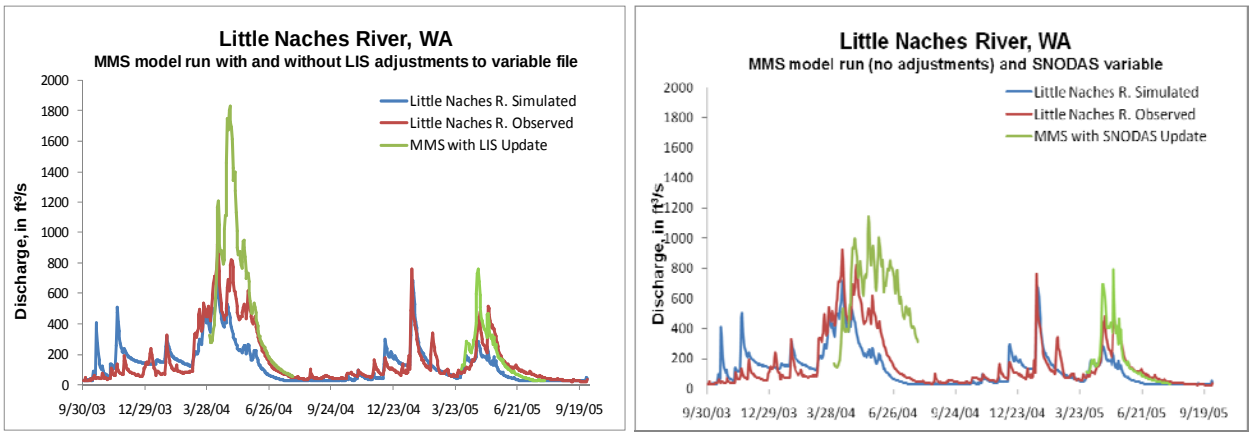
**Figure 7.** Baseline MMS runs (blue) compared with gage observations (red) and MMS-adjusted runs (green) initialized on April 1st with a) LIS and b) with SNODAS snow variables in the American River near Nile, WA. Simulations and observations span a period of two Water Years, 2004 and 2005.

***American River near Nile, WA***

| WY04 | Mean | Std. Dev. | Total | RMSE | % Diff From Obs |
|---|---|---|---|---|---|
| MMS Baseline | 289.9 | 185.5 | 35,368 | ***111.1*** | ***-8.18*** |
| MMS-LIS | 443.7 | 288.3 | 54,132 | 217.4 | **40.54** |
| MMS – SNODAS | 634.5 | 239.1 | 77,405 | 370.4 | **100.96** |
| WY05 | Mean | Std. Dev. | Total | RMSE | % Diff From Obs |
| MMS Baseline | 130.4 | 111.0 | 15,909 | 99.5 | **-34.50** |
| MMS-LIS | 199.2 | 179.0 | 24,342 | ***86.8*** | ***0.22*** |
| MMS – SNODAS | 258.7 | 223.9 | 31,567 | 129.6 | **29.97** |

**Table 1**. This table presents the statistics for the total runoff estimates (in cfs-days) at the American River near Nile, Washington, for the baseline MMS simulation, MMS-initialized with LIS, and MMS-initialized with SNODAS. The period for each Water Year and comparison is from April 1 to July 31.

For the Little Naches River Basin in the Naches modeling unit, again the MMS baseline run performed the best when compared with observations, and the MMS-LIS initialized runs performed second best for the normal snow year (WY2004) as shown in Figures 8a and 8b. However, the MMS-LIS case greatly over simulated the discharge in the spring months, especially in May, 2004, reaching a maximum value greater than 1800 cfs (refer to Table 2). The MMS-SNODAS case again persisted late into spring at too high of a rate (Fig. 8b). In the drought year, both MMS runs initialized with SNODAS and LIS performed better than the baseline simulation. The MMS-SNODAS case performed best overall with an RSME of 78.5 and a percent difference from observations of 2.65.




a) b)

**Figure 8.** Baseline MMS runs (blue) compared with gage observations (red) and MMS-adjusted runs (green) initialized on April 1st with a) LIS and b) with SNODAS snow variables in the Little Naches River, WA. Simulations and observations span a period of two Water Years, 2004 and 2005.

### *Little Naches River, WA*

| WY04 | Mean | Std. Dev. | Total | RMSE | % Diff From Obs |
|---|---|---|---|---|---|
| MMS Baseline | 375.0 | 238.7 | 27,680 | ***182.4*** | ***-39.50*** |
| MMS-LIS | 574.6 | 487.6 | 70,108 | 376.9 | **53.23** |
| MMS – SNODAS | 780.1 | 544.8 | 95,173 | 579.1 | **108.01** |
| WY05 | Mean | Std. Dev. | Total | RMSE | % Diff From Obs |
| MMS Baseline | 169.7 | 119.6 | 11,952 | 106.7 | **-42.27** |
| MMS-LIS | 187.8 | 171.4 | 22,915 | 98.7 | **10.68** |
| MMS – SNODAS | 174.2 | 154.5 | 21,251 | ***78.5*** | ***2.65*** |

**Table 2.** This table presents the statistics for the total runoff estimates (in cfs-days) at the Little Naches River in Washington for the baseline MMS simulation, MMS-initialized with LIS, and MMS-initialized with SNODAS. The period for each Water Year and comparison is from April 1 to July 31.

The final comparisons made at Teanaway River near Cle Elum, WA, in the Upper Yakima modeling unit have a slight difference in the way the MRUs were applied compared to the other two gage sites. Two of the MRUs in the Upper Yakima modeling unit are less than 10 acres in area which posed a small problem with trying to map them to a 0.01 degree grid cell due to their small size. To account for these two small MRU values, they were estimated by applying nearby MRU values. The final results are plotted in Figures 9a and 9b, and the final summary statistics are presented in Table 3 below.

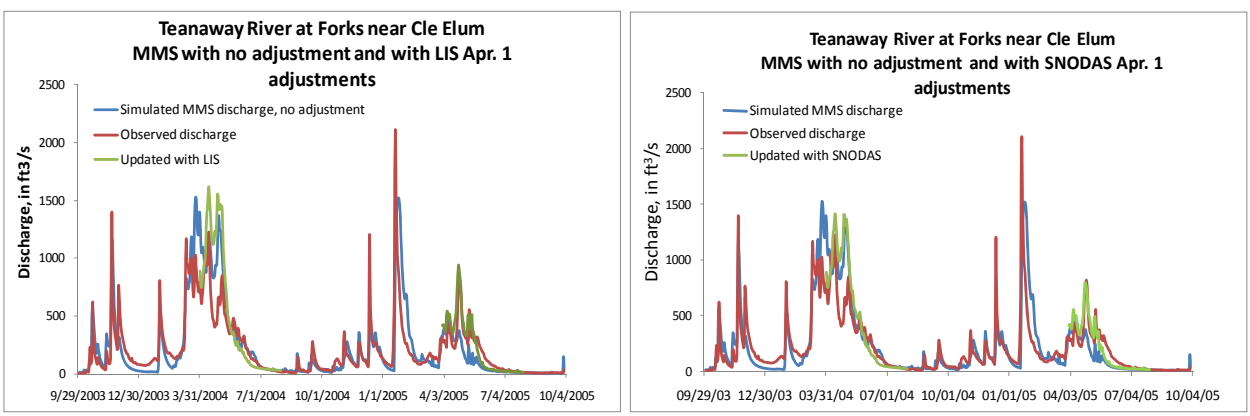
For the "normal" year, WY2004, Table 3 indicates better results for the baseline MMS simulation over the other two special initialized cases, showing the lowest RMSE and percent difference from observed rates. For the drought year, WY2005, the MMS-SNODAS case indicates the best performance. The MMS-LIS initialized case also did well, performing slightly better than the baseline simulation, though it had the lowest RMSE for this given water year.

These initial comparisons suggest some value may be added by initializing MMS with improved spatial snow fields, and in this comparison the greatest value added was shown during the severe drought case year. If the LIS-CLM2 and SNODAS models were better calibrated for these areas and more frequent MMS updates were initialized with these model snow variables, MMS streamflow forecasts could be further improved for different drought and flood potential periods. These comparison results also indicate some of the errors related to the LIS-CLM2 and SNODAS models; however, they could be used to help further improve these model snow products to be used in the future by such models as MMS and RiverWare. The April 1 update showed considerable potential for more frequent daily or weekly nudging of the MMS simulations, which may be feasible in future efforts with larger human and funding resources.

***Teanaway River at Forks near Cle Elum, WA***

| WY04 | Mean | Std. Dev. | Total | RMSE | % Diff From Obs |
|---|---|---|---|---|---|
| MMS Baseline | 435.5 | 412.8 | 51,908 | ***210.9*** | ***23.21*** |
| MMS-LIS | 532.7 | 558.8 | 64,990 | 359.7 | **54.26** |
| MMS – SNODAS | 498.3 | 511.7 | 60,797 | 312.1 | **44.31** |
| WY05 | Mean | Std. Dev. | Total | RMSE | % Diff From Obs |
| MMS Baseline | 125.0 | 139.2 | 15,842 | 146.9 | **-36.32** |
| MMS-LIS | 227.2 | 241.4 | 27,719 | ***78.5*** | **11.42** |
| MMS – SNODAS | 208.2 | 239.4 | 25,402 | 94.7 | ***2.11*** |

**Table 3.** This table presents the statistics for the total runoff estimates (in cfs-days) at the Teanaway River at Forks near Cle Elum, Washington, for the baseline MMS simulation, MMS initialized with LIS, and MMS initialized with SNODAS. The period for each Water Year and comparison is from April 1 to July 31.




a) b)

**Figure 9.** Baseline MMS runs (blue) compared with gage observations (red) and MMS-adjusted runs (green) initialized on April 1st with a) LIS and b) with SNODAS snow variables in the Teanaway River at Forks near Cle Elum, WA. Simulations and observations span a period of two Water Years, 2004 and 2005.

# 8. Future Use of NASA Products and Related Issues

## 8.1 Issues Related to Transfer and Adoption by Partner Agency

Since Reclamation relies upon having accurate and reliable information to use in their volume estimates and forecasts both at the river and watershed levels, several steps may be required before the NASA ESE products tested in this project could be transferred and adopted for routine use. First, despite the enhancements made to the LIS-CLM2 modeling system and checks made on the MODIS products, more case studies will need to be conducted with the MMS and the RiverWare DST, in both unregulated and regulated basin locations, following the Yakima Basin water accounting system that the water resource managers employ at the YFO. Also, the enhanced LIS-CLM2 snow fields with MODIS SCA did validate well against in-situ snow measurements, like the NRCS SNOTEL network, but that involved a comparison of averages. On a station by station comparison, a few more issues and problems in capturing more realistic high resolution snowpack variables remain and could not all be addressed within this project. Further demonstrations of reducing RMSEs between the point measurements and ESE-based snow products may be needed.

In addition, future experiments could also be required that involve the calibration of the MMS-PRMS system with either the LIS modeled output or even with SNODAS output. Calibration could provide better estimates but also cause potential issues when longer term forecasts are made, since they would be calibrated and constrained to certain modeled and/or satellite-based biases. Finally and most importantly, the engineers and managers at the YFO would need to test out the new MMS simulations, generated with the ESE products, in RiverWare for a few different case study years in a retrospective mode and in an operational setting, if possible. This would help test the overall impact on the use of the updated MMS streamflow information in the RiverWare DST and to determine what value is being added. This value could be measured in terms of RiverWare estimates of changes in hydropower generation, increased storage for irrigation, and changes in flood control space within reservoirs.

## 8.2 Recommendations and Remaining Issues Facing Sustained Use of these NASA Products

In the duration of this project, the Reclamation YFO lost and had to restore their Hydrologic Data Base (HDB) input to MMS after a major system failure in 2005. This loss of the HDB prevented MMS runs from the USGS to be updated into 2006, thus MMS hydrograph information was not used in the RiverWare DSS at the YFO after 2006. Once the MMS runs and meteorological datasets have been updated, it is recommended that additional case years be considered, especially a year like WY2006 where major melt periods and flood-type events may have occurred.

Another issue to be addressed is the need for continued support and funding to maintain products and equipment for operational use required by an agency like Reclamation. Reclamation is migrating to mainly a Windows OS environment and away from Linux systems. This includes having the USGS team migrate their MMS-PRMS system to the Windows OS. This could involve some changes to the code or datasets used by MMS, which could require some modifications by the NASA and UMBC teams. If Reclamation wanted to run the LIS system or at least the executable files and use the necessary forcing and MODIS datasets, the LIS

code would need to be compiled on a Windows OS platform and the processing scripts for the MODIS datasets would also need to be migrated to run on Windows, since RiverWare is currently run on Windows operating systems.

One other major issue facing the sustained use of the NASA ESE products by Reclamation is that MODIS is not deemed as an "operational" satellite sensor, and the future duration of its operation is uncertain (e.g., sensor could malfunction, run out of money, etc.). However, similar future satellite missions are planned with other partner agencies, like NOAA and Department of Defense (DoD), such as the Visible/Infrared Imager Radiometer Suite (VIIRS). VIIRS is designed to provide operational, enhanced radiometric products, like SCA, at somewhat high resolutions aboard the National Polar-orbiting Operational Environmental Satellite System (NPOESS).

### 8.3 Resource Estimate for the User Organizations' Adoption of the NASA Products

Reclamation would need to provide some funds and manpower resources to help with the migrating of the LIS modeling system on to a Windows environment, if that is one of the goals in order to use the system locally. It is unknown at this time how much in the way of human resources and funds would be needed to carry out this transfer. To generate the products needed by Reclamation but done at NASA (or an affiliated research institution), funds and manpower would also be needed to support an operational system to meet Reclamation's needs. In addition, some support should be provided to allow the NASA-related researcher to be able to reasonably modify any scripts or data and information in order to respond to any of Reclamation's changing needs. A long-term partnership among NASA, Reclamation, and USGS would be the best solution for a sustainable, highly productive application of these ESE research products and operational decision support systems.

## 9. Lessons Learned

NASA ESE products, like MODIS SCA, provide some information as to the area covered by snow for such moderate resolutions (i.e., 1km), but it is SWE and water volume amounts that end-users, like Reclamation, are most interested. As with this project, just as much attention should be placed on the modeling aspects of making the MODIS SCA product more useful for different water resource purposes. Further studies are needed to test different assimilation techniques, model physics enhancements and different MODIS products, such as the latest MODIS snow cover fraction product that was released with Collection 5. Future satellite missions may provide improved SWE and soil moisture information for integration into LIS and MMs. Projects like WaterNet (Matthews et al., 2008) show how water managers may better integrate LIS and also Global LDAS (GLDAS; Rodell et al., 2004) products into decision-making tools for management of the Danube and American River Basins.

## 10. Potential Socioeconomic Benefits

Improving streamflow estimates and forecasts could result in several potential socioeconomic benefits that can help mangers and planners with providing water supplies for irrigation, hydropower generation, augmented municipal and industrial (M&I) uses, riparian preservation, and recreational uses. Some different ways to measure the value added by these improvements in estimates and forecasts could relate to annual summaries of value added to water operations decision-making in terms of additional "liberated" water for beneficial uses, additional power generated, and other quantitative measures.

Though for this project, the focus was more on how ESE products and models could both be used more effectively in a region like the Yakima Basin and used in modeled streamflow estimates and forecasts. Some value was shown that by introducing more accurate spatial maps of snow-related variables to a hydrological model could improve streamflow forecasts. The results provide a demonstration that with more testing, improvements made to the ESE data products and modeling systems, and better techniques on assimilating and integrating the data into the LSM and hydrological model, respectively, improved streamflow forecasts could result and benefit the end-uses as listed above.

## 11. Summary and Conclusions

The main purpose of this benchmark report was to evaluate and show what value is added by NASA ESE products, including MODIS SCA, LDAS forcing and land modeling capabilities of LIS, to improving the streamflow forecasts generated by the MMS hydrological model and used in the RiverWare DST. Normal and extreme low and high snow season cases were selected to investigate the change in snow initialization on MMS daily forecasts, focusing on unregulated sub-basin areas in the Yakima River Basin. Since some data were not available beyond 2005, the time periods chosen included: (1) 2004 – a normal snow year for the basin, and (2) 2005 – major drought and very low-flow year. MMS was initialized on April 1$^{st}$ for both WY2004 (a "normal" year) and 2005 (a drought year) with LIS-CLM2 and SNODAS snow variables and then run forward through the spring months.

When compared with baseline MMS runs (with no adjustment) and stream gage measurements in three unregulated basins, the MMS baseline runs performed better in the more "normal" water year of 2004 than the two special runs adjusted with the LIS-CLM2 and SNODAS variables. However in the drought year case of WY2005, both the LIS-CLM2 and SNODAS initialized MMS runs performed better overall when compared to the baseline MMS runs. It is important to note here that improving streamflow prediction during low-flow periods is of major interest to water resource managers and engineers, like those at the Bureau of Reclamation.

With the approach demonstrated in this study showing such promising results for a low-flow period, we hope ongoing and future development of such NASA ESE products will further contribute to enhancing streamflow predictions that will go to benefitting not only water resource managers but the broader public as well. Other recently NASA-funded projects being completed include the work by Doug Boyle at the Desert Research Institute (DRI) in Reno, NV (see *http://wmp.gsfc.nasa.gov/reports/Summary_of_Research_Final_Report_Boyle_2008(3).pdf*), University of Washington researchers (e.g., *http://wmp.gsfc.nasa.gov/projects/project_WesternUS.php)*, and

collaborators at NASA Goddard Space Flight Center and the National Weather Service (http://wmp.gsfc.nasa.gov/projects/project_RiverForecast.php) are also demonstrating the value added by NASA ESE products in improving streamflow prediction.

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## 13. Authorship

The main Reclamation partners that were part of this collaborative work are located at Reclamation's Technical Service Center (TSC) in Denver and with their water operations clients in the Reclamation Yakima Field Office.

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## 14. Abbreviations and Acronyms

| | |
|---|---|
| ACE | U.S. Army Corps of Engineers |
| AMSR-E | Advanced Microwave Scanning Radiometer-EOS |
| ASTER | Advanced Spaceborne Thermal Emission and Reflection Radiometer |
| AWARDS | Agricultural Water Resources Decision Support system |
| BATS | Biosphere-Atmosphere Transfer Scheme |
| CADSWES | Center for Advanced Decision Support for Water and Environmental Systems |
| cfs | cubic feet per second |
| CLM2 | Community Land Model, Version 2 |
| CPC | Climate Prediction Center |
| DEM | Digital Elevation Model |
| DMI | Data Management Interface |
| DST | Decision Support Tool |
| EOS | NASA's Earth Observing System |
| ESE | NASA's Earth Science Enterprise |
| ESP | NWS Extended Streamflow Prediction |
| ET | Evapotranspiration |
| ETM+ | Landsat 7 Enhanced Thematic Mapper Plus |
| FSL | NOAA's Forecast Systems Laboratory |
| GIS | Geographic Information System |
| GMAO | NASA's Global Modeling and Assimilation Office |
| GSFC | NASA's Goddard Space Flight Center |
| GUI | Graphical User Interface |
| HDB | Hydrologic Database |
| HRU | Hydrologic Response Unit |
| IAP | Institute of Atmospheric Physics (Chinese Academy of Sciences) |
| LAI | Leaf Area Index |
| LIS | NASA's Land Information System |
| LSMs | Land Surface Models |
| LST | Land Surface Temperature |
| MMS | Modular Modeling System |
| MODIS | Moderate Resolution Imaging Spectroradiometer |
| MOU | Memorandum of Understanding |
| MRU | Modeling Response Unit |
| NASA | National Aeronautics and Space Administration |
| NCEP | National Centers for Environmental Prediction |
| NED | National Elevation Dataset |
| NLCD | National Land Cover Data |
| NLDAS | North American Land Data Assimilation System |
| NOAA | National Oceanic and Atmospheric Administration |
| NRCS | Natural Resources Conservation Service |
| NWS | National Weather Service |
| PRMS | Precipitation-Runoff Modeling System |
| QPE | Quantitative Precipitation Estimates |

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| Reclamation | U.S. Bureau of Reclamation |
| RMSE | Root Mean Squared Error |
| RSS | Rapid Response System |
| RUC | Rapid Update Cycle model |
| SNOTEL | SNOwpack TELemetry |
| SRTM | NASA's Shuttle Radar Topography Mission |
| SWE | Snow Water Equivalent |
| TM | Landsat Thematic Mapper |
| TRMM | Tropical Rainfall Measuring Mission |
| TVA | Tennessee Valley Authority |
| URGWOM | Upper Rio Grande Water Operations Model |
| USBR | U.S. Bureau of Reclamation |
| USDA | U.S. Department of Agriculture |
| USGS | U.S. Geological Survey |
| V&V | Verification and Validation |
| WaRSMP | Watershed and River Systems Management Program |
| WMA | NASA's Water Management Applications Team |
| WSR-88D | Weather Surveillance Radar-1988 Doppler |