SECTION 4.1 BACKGROUND

4.1.1 Consortium Motivation and Rationale. The Western U.S., like many other parts of the Nation and world, faces daunting challenges, including a demand for fresh water that exceeds the available supply. Regional and global climate change and variability are affecting natural resources, disturbance regimes such as fire frequency and magnitude, and the region's economies and citizens. The EPSCoR jurisdictions of Idaho, Nevada, and New Mexico responded to these challenges by establishing the Tri-state Western Consortium in 2008. The objective of the Western Consortium was to identify key areas of overlap and opportunities for leveraging resources and expertise so that the cumulative impact of NSF EPSCoR investments in the three states could exceed the sum of the parts.

Initial steps taken by the Consortium included holding combined annual meetings of all participants and forming a Consortium Cyberinfrastructure (CI) Committee to identify and adopt data, metadata, communication, and web standards and protocols. Subsequently, the Consortium received Track-2 funding (EPS-0919514) for a project entitled "Cyberinfrastructure Development for the Western Consortium of Idaho, Nevada, and New Mexico" that was designed to: increase connectivity and bandwidth, enhance data and model interoperability, and utilize CI to integrate research with education; Track-2 project outcomes are summarized in Section 4.2. Another key Consortium success was the formation of the Consortium Diversity Committee that led to the development and implementation of a Tri-state diversity plan.

State Project Directors and representatives from the Idaho, Nevada, and New Mexico EPSCoR State Committees met annually over the course of the current Track-2 project (2010-2013) to review progress, share ideas and approaches (e.g., characterizing the STEM landscape within each jurisdiction), and plan future collaborations. Consequently, the three State Committees unanimously endorsed continuation and evolution of Consortium activities, and specifically recognized the need to expand Consortium infrastructure improvements in support of watershed science, underlying CI, and workforce development.

4.1.2 New Opportunities to Address Regional and National Needs. Building on the foundation of collaboration and leadership already established, the Consortium is well positioned to address research and education challenges that each state cannot fully address individually. Mechanisms responsible for observed and projected hydrologic change in high-elevation catchments are poorly understood, especially with respect to snowpack dynamics, surface-water/groundwater linkages, and interactions with vegetation. Understanding such mechanisms requires easy access to data and models, as well as the ability to integrate data from different sources and different but complementary models. Major CI improvements are needed to accelerate collaborative, interdisciplinary watershed research and discovery through innovative visualization environments and through streamlined data management, discovery, and access. Furthermore, watershed science is tackling extremely challenging problems that increasingly depend on engaging faculty and graduate students in interdisciplinary team-based watershed research and enhancing graduate and undergraduate student skills in modeling and visualization. *Idaho, Nevada, and New Mexico propose a Western Consortium for Watershed Analysis, Visualization, and Exploration (WC-WAVE) whose overarching goal is to advance watershed science, workforce development, and education with cyberinfrastructure (CI)-enabled discovery and innovation*.

WC-WAVE will enable the Consortium to address key regional and National needs with respect to Watershed and Hydrologic Science. Mountain watersheds provide a large proportion of the water and ecosystem services for communities throughout the western U.S. Climate change threatens these resources through the risks of intensified drought, earlier snowmelt runoff, and increased fire frequency and severity (Westerling et al., 2006; Running, 2006). Management activities aimed at mitigating expected climate change impacts would benefit from a better understanding of the nature of watershed response to climate forcings that impact these complex systems. However, forecasting change under such complexity is beyond the capabilities of conventional approaches (e.g., modeling, observation) performed in isolation of one another (National Research Council, 2012). Thus, integration of creative observation strategies with advanced modeling and visualization approaches is a critical step towards advancing understanding and predicting complex responses to climate and hydrologic change. The integration of data and models in a virtual watershed (VW) framework through digital experiments will guide parsimonious model development and field campaigns to focus on essential processes. The modeling framework will be tested on experimental watersheds in each jurisdiction.

4.1.3 21st Century CI. The concept of a *virtual watershed* is central to the proposed research and development. It denotes a combination of data resources and computing activities and services that

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enable linking scientific modeling, visualization, and data management components for the purpose of enhanced analysis and exploration of real or hypothetical watersheds. The proposed VW platform directly supports several key cyberinfrastructure needs identified in the *Final Report of the National Science Foundation's Advisory Committee for Cyberinfrastructure - Task Force on Grand Challenges* (2011):

- Data Integration and Interoperability – through supporting access to heterogeneous data sources through a single interface.
- Data Provenance and Stewardship – through automated capture and integration of research data products into data management systems for both active use and long-term archival storage.
- Scientific Workflow and Metatools – through integration with the Community Surface Dynamics Modeling System (CSDMS) and development of virtual watershed instance definition capability.
- Active Storage and Online Analysis – through streamlined bi-directional data and metadata exchange between models and the data management system.
- Data Storage and Management – through integration of the data management systems in each state with both the CUAHSI and DataONE networks, and coordinated data replication into institutional repositories in Consortium states.

4.1.4 STEM Workforce Development. Graduate students involved in the project, as well as their faculty advisors, will participate in an educational program that fosters interdisciplinary understanding and collaboration. The program will be modeled in part on the NSF Integrative Graduate Education and Research Traineeship (IGERT) program, which is designed to prepare graduates for a range of career options and the increasingly interdisciplinary nature of the STEM workforce (Abt, 2010). In addition, the virtual watershed environments proposed by the Consortium provide a platform through which to engage undergraduate students and faculty at predominantly undergraduate institutions, many of which are minority-serving institutions, with new technologies and approaches that are likely to contribute to student retention and success in STEM areas. Visualization and modeling are critically important tools in many areas of science, and developing three-dimensional thinking skills is viewed as an important goal for undergraduate science education (Reynolds, et al., 2005).

4.1.5 Impact. WC-WAVE will enable integration of creative observation and analytical strategies using advanced modeling approaches and CI in a virtual watershed platform. The research and CI are critical to understanding and predicting complex responses to climate and hydrologic change and cannot be accomplished by the Consortium members individually. In particular, the VW platform will allow researchers to integrate experimental and observed data, models, and visualization capabilities that can simulate watershed drivers and dynamics and lead to new discoveries. The WC-WAVE Workforce Development and Education program will prepare graduate students to work in collaborative, interdisciplinary teams to effectively address complex scientific issues, promote faculty professional development, and prepare diverse undergraduate students for future STEM education and employment.

SECTION 4.2 RESULTS FROM RELEVANT PRIOR SUPPORT

Prior EPSCoR investments provide the foundation of collaboration, research infrastructure, cyberinfrastructure, and attention to diversity upon which the current proposal builds. Below are the most relevant NSF awards for each PI/Co-PI that have increased our capabilities in modeling, visualization, watershed science, data management, and workforce development.

Dana (NV): EPS-08143720; $15,000,000; 9/1/08-8/31/13. *Nevada Infrastructure for Climate Change Science, Education, and Outreach*. Intellectual Merit: furthered understanding of climate variability and its impact on water, soil, and plants within key vegetation zones from valley to mountaintop through the Nevada Climate-ecohydrological Assessment Network (NevCAN); advanced knowledge and expertise in science data portals with the the Nevada Climate Change Portal (NCCP) and SENSOR system; and advanced regional climate modeling efforts by downscaling general circulation model outputs into resolutions appropriate for hydrological, ecological, and economic impact modeling studies and predictions for impact assessment. Broader Impacts: created teacher summer institutes impacting 800 middle school students annually, and an online game, "Losing the Lake," that focuses on water conservation and provides experiences in using simulations and modeling for a general audience. This project has resulted in 91 peer-reviewed publications and more than 600 million observational measurements available via the NCCP and its six Web services and two search interfaces.

Goodwin, Glenn **(ID): EPS-0814387,** $15,000,000; 9/1/08-8/31/13**.** *Idaho RII: Water Resources in a Changing Climate*. Intellectual Merit: fostered research capacity for understanding of how the quantity, quality, and timing of water supply are changing with climate, and how changes in water supply are affecting ecosystems and the goods and services they provide. Broader Impacts: involved 400 participants at the postsecondary level, and $60.9 million awarded through funded proposals. Idaho added 10 new faculty positions (filled by 60% women and 20% underrepresented minorities) related to this theme. The project has helped train 84 graduate students. A Data Sharing Policy and a Statewide MOU for CI and research data management were developed and resulted in a CI Strategic Action Plan for Idaho Universities. The project created the Idaho Climate Impacts Partnership (ICIP) to promote sustainable agency-university interactions for climate-related science. Idaho has contributed significantly to the Idaho STEM Roadmap, particularly for a state strategy for increasing diversity. A more robust faculty-mentoring program was also established. Results: 87 peer-reviewed manuscripts published as a direct result; creation of the Northwest Knowledge Network and data portal for life cycle management of research data at a regional scale; the Idaho LiDAR Consortium; and HydroDesktop, open-source software that enhances access to hydrologic data.

Michener (NM): EPS-0814449; $15,000,000; 9/1/08-8/31/13. *New Mexico EPSCoR RII3: Climate Change Impacts on New Mexico's Mountain Sources of Water*. Intellectual Merit: connected infrastructure designed to improve long-term, multi-scale monitoring of stream flows in high elevation watersheds to downstream flows that directly affect large populations; filled instrumentation gaps in the NM climate observation network, including the Navajo Nation, and established an extensive array of surface water quality monitoring devices, including the Jemez River in the Valles Caldera National Preserve (VCNP). Broader Impacts: involved more than 350 participants and increased participation of female faculty and students to 42% and underrepresented minorities to 32%; reached over 8,500 K-12 students and 750 teachers with climate change education activities; created climate change Museum exhibit for 200,000 visitors per year; collaborated with traditional and agency water managers to connect research results to policy decisions. Forty-seven publications; 20 graduate students completed; 212,000 datasets are available through the data portal, including over 2,500 datasets generated by NM EPSCoR researchers.

Benedict (Co-Investigator), Daniel, Michener **(NM) EPS-0814449, Harris,** Dana **(NV) EPS-0919123, Glenn, Sheneman (ID): EPS-0919514;** $2,000,000 each; 9/1/09-8/31/13**.** *Track-2 RII: Collaborative Research: Cyberinfrastructure Development in the Western Consortium of Idaho, Nevada, and New Mexico***.** This project formed the Western Consortium upon which the current proposal builds. Intellectual Merit: improved connectivity in each state; developed data portals built upon shared standards and a metadata content model, allowing data sharing across the three jurisdictions and with national data systems (e.g., DataONE, EarthCube, geo.data.gov, CUAHSI HIS, and GEOSS). Broader Impacts: CI-related training for graduate students and faculty, a new staff data manager at UI, and creation and implementation of a Tri-state Diversity Plan. Twenty-nine journal publications completed.

Ahmad (NV): CMMI-0846952; $430,000; 2009-2014. *CAREER: Vulnerability of Water Infrastructure to Climate Variability and Change: Implications for Sustainable Water Management.* Intellectual Merit: developed a new theoretical framework for sustainable management of water resources that provides an improved method to evaluate and choose water supply and infrastructure management projects, and contributes to advancing engineering methods to promote sustainable growth. Broader impacts: 6 graduate students partly funded; 4 MS theses produced; 10 journal publications completed.

Daniel (Co-Investigator), Benedict, Michener **(NM): EPS-1005886;** $1,176,470; 9/1/10-8/31/12. *EPSCoR RII Grant: Inter-Campus and Intra-Campus Cyber Connectivity (RII –C2)*. Intellectual Merit: improved bandwidth and cyber connectivity at three rural, minority-serving NM institutions. Broader Impacts: enhanced campus connectivity increased enrollment of underrepresented minority (URM) and women in STEM courses and related opportunities. The project's outreach activities enhanced K-12 students' quantitative reasoning, data analysis, and modeling skills. Faculty at undergraduate institutions developed course materials that incorporated 3-D visualizations.

Flores (ID): NSF RAPID-1235994; $19,912; 4/15/12-3/31/13. *An unusual opportunity to track snow ablation using stable isotope evolution of the 2011-2012 snowpack near Boise, Idaho.* Intellectual merit: stable isotope samples within the snowpack were collected and analyzed using a Los Gatos Research cavity ringdown liquid water isotope analyzer. Broader Impacts: An early career scientist from an underrepresented group was engaged in research. No publications to date.

Stone (NM): CMMI-1032496; $174,575; 8/2010-7/2013. *BRIGE: Investigating the influence of riparian vegetation on floods.* Intellectual Merit: improved computer models of the influence of riparian vegetation on flood conditions and use of models to study the phenomenon of flood wave attenuation. Broader Impacts: design of stream restoration projects to enhance flood protection allows decision makers to use approaches to flood control that will not adversely impact river and floodplain functions. This project will also broaden participation of underrepresented students in civil engineering. Two publications to date.

Tyler (NV): EAR-0929638; $446,906; 9/15/2009-9/14/2012. *Collaborative Research: Facility Support: Transformation of Distributed Environmental Sensing*. Intellectual Merit: This project represented the initiation of the Centers for Transformative Environmental Monitoring Programs and focused on instrument development and instrument support to the community. Broader Impacts: provided technical support and/instrumentation resulting in 12 published manuscripts between 2010 and 2012.

SECTION 4.3. CONSORTIUM-BASED SCIENCE AND ENGINEERING PROGRAM

4.3.1 Introduction Idaho, Nevada, and New Mexico propose the Western Consortium for Watershed Analysis, Visualization, and Exploration (WC-WAVE) with the overarching goal to advance watershed science, workforce development, and education with cyberinfrastructure (CI)-enabled discovery and innovation. The Consortium will support new science and knowledge relevant to water, environment, and cyberinfrastructure, key elements of each state's Science and Technology Plan. WC-WAVE has three integrated components, each with a corresponding goal:

1. Watershed Science Component. Advance understanding of hydrologic interactions and their impact on ecosystem services using a VW framework.
2. Visualization and Data CI Component. Accelerate collaborative, interdisciplinary watershed research and discovery through innovative visualization environments and through streamlined data management, discovery, and access.
3. Workforce Development and Education Component. Engage university faculty and graduate students in interdisciplinary team-based watershed research, and broaden undergraduate student participation in STEM through modeling and visualization.

WC-WAVE collaborations and impacts will be sustained beyond the award via: (1) multiple collaborative research projects; (2) incorporation of data and models in open-community-based data centers and code repositories; (3) CI adoption by individual state programs; and (4) development of undergraduate and graduate STEM course materials. Each of the three WC-WAVE components, with objectives and outcomes, is discussed in more detail below.

4.3.2 Watershed Science Component

4.3.2.1 Background and Proposed Research

The goal of the watershed sciences component is to advance understanding of hydrologic interactions and their impact on ecosystem services using a VW framework. The proposed project will increase research capacity and establish the framework to make VWs useful for scientific discovery and decision-making. The proposed research will address the following research questions by applying a VW framework to three experimental watersheds:

How do shifts in temperature and precipitation patterns and watershed management impact:

1. Watershed hydrologic services of water storage (snowpack and soil moisture), flow moderation (flood wave attenuation and baseflow augmentation), and water quality changes?
2. Timing and volume of water fluxes between precipitation (especially snow), soil moisture, groundwater, and streamflow?

The proposed research directly aligns with elements in the National Research Council's (NRC) Challenges and Opportunities in the Hydrologic Sciences (National Research Council, 2012), including the causality of subtle shifts and regime changes in streamflow and the environmental impact of these changes as a research opportunity. NRC (2012) also highlights the opportunity of researching hydrologic response to abrupt changes in climate and land cover over short time scales and longer variations in climate. In addition, Tri-state Consortium researchers will contribute to the NSF-funded EarthCube through future community opportunities similar to the 2012 AGU session "Progress and opportunities in Earth System model coupling with emphasis on hydrological model components" and to future EarthCube solicitations aimed at data discovery, access, and mining.

4.3.2.2 State of the Science

Hydrologic modeling in a changing climate: The well-being of humankind has always been intricately tied to the multitude of resources provided by natural ecosystems. This concept is referred to as *ecosystem services* and has received considerable attention from ecologists, resource economists, and others (e.g. Costanza et al., 1997; Daily 1997; Daily et al., 2000). *Hydrologic services* encompass the benefits such as in-stream and extractive water supply, flood damage mitigation, water-related cultural services, and water-related supporting services (Brauman et al., 2007). Each of these services is defined by attributes of quantity, quality, location, and timing of flow (Postel et al., 1996). Watersheds and riparian zones are widely acknowledged to contribute to water storage, flow moderation, and water quality improvement. However, the exact nature of these services is difficult to quantify, even under existing conditions. An even greater challenge is forecasting how interacting changes in watershed conditions and climate will influence these important services and how we might mitigate such changes.

The mechanisms responsible for observed historical and projected hydrologic change in high-elevation catchments are poorly understood, especially those regarding snowpack dynamics, surface-water/groundwater interactions, and interactions with vegetation. In conjunction with information provided by atmospheric models, hydrologic models are useful tools for studying the effects of climate change on water resources. Hydrologic processes such as runoff, recharge, and evapotranspiration (ET) all co-vary in time and space, and are correlated to each other. Determining cause and effect for any one hydrologic process is difficult without an integrated framework to model all the processes simultaneously.

Watershed modeling infrastructure: Because of the complexity and heterogeneity inherent to the hydrologic cycle, modeling of watershed processes has historically been characterized by a broad spectrum in spatial, temporal, and process representations within individual models. The use of an integrated virtual modeling framework to assess the effects of climate and weather on surface and groundwater interactions and the hydrologic mechanisms responsible for changes in groundwater levels, summer baseflows, spring flows, and soil moisture, provides a unique opportunity to thoroughly explore complex interactions. Below is a non-exhaustive summary of modeling approaches and platforms that exemplify this spectrum in spatial and process representation. This discussion is organized around the key processes that give rise to the hydrologic services provided by mountain watersheds and provides the intellectual rationale for the models that we plan to use in the watershed sciences component.

Snow Models: Model classes, from conceptually-based to physically-based, exist to simulate snow accumulation and melt. Spatially lumped conceptual models such as SNOW17, the operational snow model used by the National Weather Service, employ techniques such as temperature index methods. Physically-based models such as iSNOBAL (image SNOw energy and mass BALance) (Marks et al., 1999) simulate the coupled snow mass and energy balance.

Watershed Models: The dynamics of soil moisture is represented in a range from simple conceptual models to complex physics-based simulation models. Rudimentary conceptual models of soil moisture represent the vertical soil column as a “leaky bucket” with some finite capacity (e.g., Manabe et al., 1965). More sophisticated soil moisture models simplify the governing equations through a kinematic approximation, assuming piston-style infiltration of precipitation into the soil (Leavesley et al., 1983, Ivanov 2004 a, b; Qu and Duffy, 2007). The most sophisticated models typically represent the dynamics of soil moisture by numerically solving the nonlinear Richards equation either in one dimension, allowing for subsurface lateral moisture exchange (Downer and Ogden, 2004, Ivanov et al., 2008a, b; Flores et al., 2012) or in three dimensions (Maxwell and Miller, 2005; Kumar et al., 2009; Kollet et al., 2010).

Groundwater Models: In mountain watersheds groundwater frequently plays a critical, albeit complex, role in modulating the movement of water from the soil to streams (McDonnell, 2003). Because the parameters of these models are difficult to constrain and the models are extremely computationally expensive, continuum approaches based on an assumption of Darcian flow remain the most common method of groundwater simulation. For example, the ParFlow model was formulated using a soil water potential-based version of the three-dimensional Richards equation (Maxwell and Miller, 2005; Kollet et al., 2010). Groundwater models also require the spatiotemporal distribution of recharge from the unsaturated zone as a boundary condition. The ParFlow model uses the Common Land Model to describe surface water and energy balance (Maxwell and Miller, 2005).

River Hydrodynamics Models: Hydrodynamic modeling of stream channels and floodplains, especially in complex channels, is an active research area. The underlying methods are based on the solution of the Saint Venant Equations, which are an expression of conservation of mass and momentum for shallow flow (Chaudhry, 1993). Despite recent advancements in hydrodynamic models, predictions remain unreliable due to uncertainty in the underlying modeling frameworks (parameterizations) and input parameters. Uncertainty increases as a function of channel complexity due to the approaches used to parameterize complex phenomena such as energy dissipation and momentum fluxes.

Riparian Vegetation Models: Riparian vegetation recruitment, growth, and removal experience two-way interactions with both hydraulic and geomorphic processes. Efforts to spatially model riparian vegetation dynamics have frequently built on the 'recruitment box' concept to connect seedling establishment to hydrologic parameters (Mahoney and Rood, 1998), and use modeled estimates of shear stress to drive vegetation removal (García-Arias et al., 2012). Established cohorts of vegetation may be resilient to uprooting even in the rarest floods and only susceptible to removal by bank erosion, a process affected by root density (Pollen-Bankhead and Simon, 2010a, b).

4.3.2.3 Watershed Science Research Activities

Team. Faculty: ID: Peter Goodwin, (PI, UI), Nancy Glenn (Lead, ISU), Sarah Godsey (ISU), Lejo Flores (BSU), Jim McNamara (BSU), Mark Seyfried (USDA-ARS); NV: Scott Tyler (Co-Lead, UNR), Sajjad Ahamad (UNLV), Ed Kolodziej (UNR), Lynn Fenstermaker (DRI); NM: Mark Stone (Co-Lead, UNM), Dan Cadol (NMT), Julie Coonrod (UNM), Laura Crossey (UNM), John Wilson (NMT). Graduate students: 6 total (2 each from ID, NV, NM).

The watershed science team will collaborate with the CI team in the process of model development and integration to produce a virtual watershed environment. We will use the resulting modeling tools to answer the proposed research questions and, in the process, establish a lasting and flexible watershed modeling framework to address new research questions that arise. The watershed science team proposes three research activities, education activities, and sustainability-related activities. The research activities are described below, the educational activity is described in Section 4.3.4, and sustainability activities are described in Section 4.5.

We will test the VW framework with data from three well-instrumented watersheds, one in each Consortium member state; each have benefited from past EPSCoR investments. These include the Jemez Watershed, NM; the Nevada Climate-ecohydrological Assessment Network (NevCAN), NV; and Reynolds and Dry Creek, ID. These experimental watersheds and field sites are described in each State's "Facilities, Equipment, and Resources" document. These sites represent environments in which the impacts of climate change on hydrologic processes and hydrologic services will be expressed differently.

This differential hydrologic process response to climate change necessitates an approach and investigator team that is appropriately equipped to address the uniqueness of each study site. As such, the hydrologic sciences aspect of this project is designed to leverage expertise in each state that is unique to the geo-environmental settings of each study site. Therefore, each state is leading one component of the integrated modeling effort.

Despite the necessity of geography- and process-specific assignments outlined below, the overall approach and research questions will be addressed through close collaboration across all Consortium institutions. In close collaboration with the CI Team, the Watershed Science team will integrate the different models based on the Community Surface Dynamics Modeling System (CSDMS) Modeling Tool (CMT; Peckham et al. 2012). CSDMS has a basic model interface (BMI) that the team will use to incorporate into the CMT for linkage. The BMI has been designed to be easy to implement and will be applied by the graduate students in collaboration with the CI team and the CSDMS group.

Research Activity 1. Parameterize and validate watershed models

Four watershed models will be applied in this project as summarized in Table 1, and Figure 1 illustrates the connectivity between the models. Modeling will be coordinated among students located at the following campuses: Boise State University, Idaho State University, University of New Mexico, New Mexico Tech, University of Nevada, Reno, University of Nevada, Las Vegas, and the Desert Research Institute. ParFlow will be used to model soil moisture and surface water-groundwater interactions. In the first year, the student based at BSU will parameterize the Dry Creek watershed for modeling. In the second year, this student will train and assist the UNM student in parameterizing the Valles Caldera watershed. ParFlow will be implemented in Nevada by the UNR and UNLV students. SRH-2D will be used to model channel flow and hydraulics. In the first year, the UNM student will parameterize the Valles Caldera channel for use with the model, and in the second year will train and assist the BSU student in parameterizing Dry Creek. Snow dynamics will be modeled with iSNOBAL. In the first year, the Dry Creek model will be calibrated by the ISU student, building on previous work, and work will begin to make the model CSDMS-compatible. Implementation of iSNOBAL in Nevada by the UNR and UNLV students will be assisted by the ISU student. Riparian vegetation dynamics will be modeled using RIPFLOW or a model to be developed. Model evaluation will take place in the first year, led by the NMT student, and model implementation or model development will begin. Integration with SRH-2D will be tested manually in the second year, and CSDMS compatibility will take place in the third year. CSDMS integration of RIPFLOW will be assisted by the DRI student.

Research Activity 2. Develop CSDMS adapters for models

The watershed science team will collaborate closely with the CI team to develop and integrate the models based on the Community Surface Dynamics Modeling System (CSDMS) Modeling Tool. Two of the proposed models are currently CSDMS compatible (Table 1). Thus, adapters will need to be developed for the remaining three models in order to enable interoperability between each other and other models. The watershed science faculty and graduate students will be introduced to the process for adapter development during the first Summer Institute (see Workforce Development and Education Section 4.3.4). This will involve participation by the CI team along with personnel from the CSDMS group. The processes for developing and validating the adapters will be refined through the Summer Institute. The ISU graduate student will be responsible for the iSOBAL adapter development with support from the UNR and UNLV students. The UNM graduate student will be responsible for developing the SRH-2D adapter with support from the BSU graduate student. The NMT graduate student will lead the development of the RIPFLOW adapter with support from the DRI graduate student. The final adapters will be shared with the general modeling community by loading them onto the CSMDS website.

Table 1. Models to be used in the Watershed Science research activities.

Model, Lead Student Responsible	Package	Already CSDMS compatible?
Snow: ID	iSNOBAL	No
Surface Water/Groundwater & Soil Moisture: ID, NV	ParFlow	Yes
River Hydraulics: NM	SRH-2D	No
Riparian Vegetation: NM	RIPFLOW, or to-be-built	No
Water Quality: NV	HSPF	Yes

Research Activity 3. Model simulations and answer research questions using the VW framework

The models will be used in the VW framework to simulate various future conditions in order to improve understanding of watershed processes. Initial test cases will involve simulations of watershed processes under a limited number of climate change scenarios using simple stepwise adjustments in temperature and precipitation. As the watershed science team (particularly the graduate students) develops experience, climate scenarios produced through downscaled Global Circulation Models (GCMs) will be used to investigate impacts of climate change. Next, the climate change conditions will be combined with potential changes in watershed management conditions. The results from the various simulations will be used to study changes in hydrologic processes within and between the study watersheds with a focus on our research questions as follows.

To answer research question 1, the hydrologic services of water storage, flow moderation, and water quality changes (temperature, nutrients, natural organic matter concentrations, and organic contaminants) will be quantified under each of the simulated conditions. The ParFlow model will be used to investigate water storage in the forms of snowpack and soil moisture under each scenario. Floodwave attenuation will be studied using the SRH-2D simulations, which will also be coupled to the RIPFLOW model to predict changes in riparian vegetation and hence changes in energy loss in the floodplains. Water quality changes in response to hydrological perturbations will be assessed using the CSDMS-compatible Hydrologic Simulation Program Fortran (HSPF) model, which can be used by watershed managers to understand and mitigate the effects of

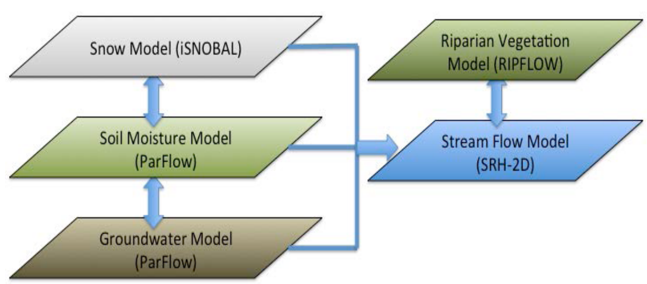

Figure 1. Connectivity between watershed models.

adverse water quality on ecosystem health. Similarly, the results of the various model scenarios will be investigated to quantify changes in water fluxes associated with precipitation, evapotranspiration, infiltration, recharge, and return flows (Question 2).

4.3.3 Visualization and Data Cyberinfrastructure Component The overarching Cyberinfrastructure (CI) goal is to accelerate collaborative, interdisciplinary watershed research and discovery through innovative visualization environments and through streamlined data management, discovery, and access. CI describes research environments that support data acquisition, data storage, data management, data integration, data mining, data visualization, and other computing and information processing services distributed over the Internet (Atkins, et al., 2003). A significant portion of the WC-WAVE project is a multi-institutional CI collaboration that emphasizes a new approach to data and model visualization (CI-Vis described in Section 4.3.3.1) by using technologies similar to those utilized by the gaming industry to provide project users (i.e., watershed science researchers, faculty at undergraduate institutions, graduate, and undergraduate students) with an alternative and enriched approach to understanding watershed science. The relationships between the CI-Vis visualization capabilities, the CI-Data (Section 4.3.3.2) management, discovery and access services, the VW platform, models enabled for integration through CSDMS, and connections to external data networks are illustrated in Figure 2.

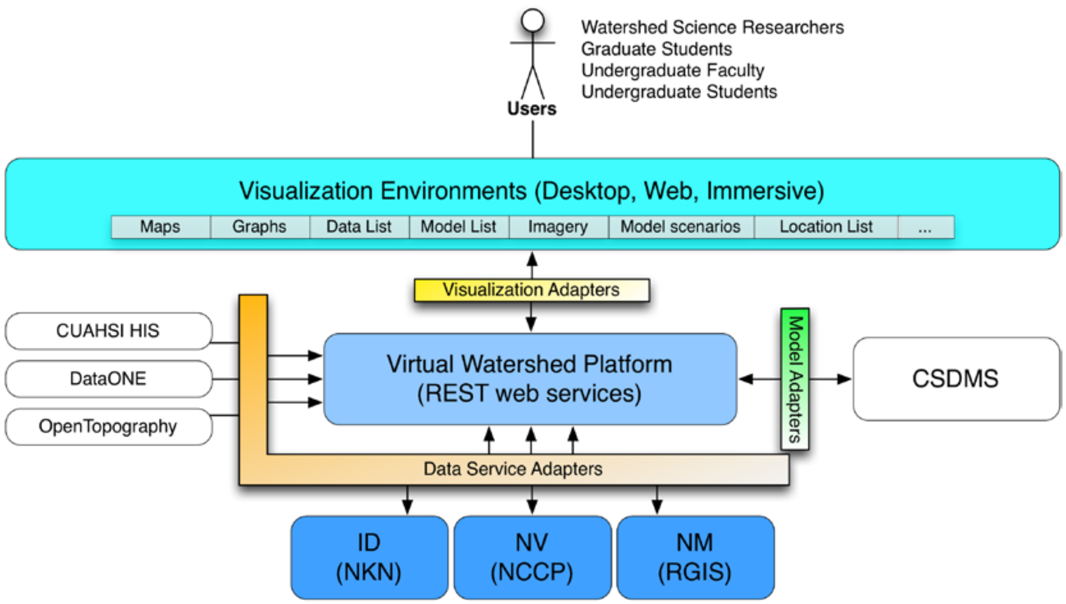

Figure 2. Diagram illustrating the relationships of proposed project components: virtual watershed platform, data management services and portals developed in each of the Tri-state Consortium member states, and visualization environments that will be developed for use by project researchers, faculty, and students, Connections to external data networks (CUAHSI HIS, DataONE, and OpenTopography) and to CSDMS-enabled models are also shown. Linkages between these components are enabled through the three classes of adapters included in the figure: data service adapters, model adapters, and visualization adapters.

While CI-Data leverages previous work accomplished by the Tri-state Consortium, it expands the capabilities of the Consortium through additional integration of data into the national Data Observation Network for Earth (DataONE) and Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) networks and expands the utility of the DataONE, CUAHSI, and OpenTopography data resources by expanding their use into the proposed VW platform. This approach to visualization becomes a device to propel arguably one of the most challenging areas of CI research: data integration. Such integration is a prerequisite for the proposed gaming platform as it will require a common data model and associated services to standardize the multidisciplinary data types that are the focus of the proposed watershed modeling and analysis efforts. The specific CI development activities proposed as part of the CI-Vis and CI-Data components are outlined in the following two sections.

4.3.3.1 CI Visualization (CI-Vis)

Background and Proposed Research

Working in tandem with the CI-Data component of the project, the goal of the CI-Vis component is to accelerate collaborative, interdisciplinary watershed research and discovery by creating innovative visualization environments. CI-Vis will interconnect real and synthetic data obtained through CI-Data from environmental sensing networks, computer-enabled processing and modeling activities pertaining to watershed research, and user-centered visualization techniques to create VWs and facilitate improved understanding of watershed dynamics. Workstation-based visualization software and immersive virtual reality environments provide platforms to foster interdisciplinary exploration, collaborative research, and creative insight for tackling complex scientific questions (Djorgovski et al., 2010; Stricker, 2010). Such software and environments enable innovations that can lead to groundbreaking discoveries, potentially accomplishing for environmental science what has been achieved for the oil and gas industry (Bora et al., 2000; Plaisant et al., 2003; Kurc et al., 2005; Vu, 2012): i.e., to make visualization an invaluable component in scientific investigation, particularly by providing easy-to-use tools for exploratory analysis and decision support involving multiple disciplines. The data and models will be updated in real-time to inform how watershed processes progress over time, including for example erosion and deposition, modifications in surface and/or groundwater flow, and vegetation changes, enabling prediction of runoff, floods, and water storage capacity.

Previous Work and Existing Capabilities

The proposed research builds on the visualization research that has been previously conducted across the Tri-state Consortium, and has resulted in several collaborative visualization facilities in each state (described in more detail in the "Facilities, Equipment, and Other Resources" Section). In Nevada there is a 6-sided immersive environment at DRI, a stereo wall at UNR, and a tiled display wall as well as stereo projection system at UNLV. In Idaho there is a 4-sided CAVE at INL (Idaho National Lab) and several portable stereo projection IQ-stations (IQ-Station 2013) at various campuses across the state. In New Mexico there are stereo projection systems at 28 locations across the state that allow collaboration and interaction in an immersive environment.

The Consortium will leverage and build on the research and science applications in each state. In Nevada this includes the development of open source tools for scientific visualization (Sherman et al., 2007b), visualization of atmospheric data (Dye et al., 2007), dust (Bagby et al., 2005; Smith et al., 2008) and mining data (Murray et al., 2007), immersive forest fire simulation and visualization (Brown et al., 2010; Harris et al., 2005; Hoang et al., 2008; Hoang et al., 2010b; Penick et al., 2007; Sherman et al., 2007a), terrain and GIS visualization (Brandstetter et al., 2011; Su et al., 2006; Stuart et al., 2005; White et al., 2011), visualization and interactive analysis of ground penetrating radar data (Sgambati et al., 2011), development of 3D educational games (Phillips et al., 2008; Vesco et al., 2012), design of immersive software environments for command and control (Buntha et al., 2009; Muhanna et al., 2010), and development of new hardware devices for human-computer interaction in immersive visualization environments (Hoang et al., 2010a; Hegie et al., 2010). In Idaho the collaborative development of the IQ-Station (IQ-Station 2013; Sherman et al., 2010) by faculty in the state has propelled several research projects, including avalanche modeling and visualization (Delparte et al., 2012) and data visualization with PARAview and Maptek 3D. Idaho researchers and developers have also created the Hydro Desktop toolset for searching, visualizing, and analyzing hydrologic and climate data registered with the CUAHSI HIS (Ames et al., 2012; Hydro Desktop, 2013), the construction of the standalone Hydrology Interactive Visualization Environment (HIVE) (Gertman et al., 2012), the development of fire spread visualizations using a game platform, and the creation of a Virtual Hydrology Observatory for immersive visualization of hydrology modeling (Su et al., 2009).

CI-Vis Research Activities

Team. <u>Faculty</u>: ID: Donna Delparte (Co-Lead, ISU) John Anderson (UI), Alark Joshi (BSU); Shannon Kobs-Nawotniak (ISU); NV: Haroon Stephen (UNLV), Fred Harris (Lead, UNR), Tom Jackman (DRI), Sergiu Dascalu (UNR). NM: Karl Benedict (Co-lead, UNM). <u>Technicians:</u> NV (1, DRI), NM (2, UNM). <u>Graduate students</u>: ID (1, BSU; 1 ISU); NV (1, UNR). <u>Undergraduates:</u> ID (4, UI).

Based on the watershed researchers' needs, the current prevalent technologies, and the expertise and resources available in the Consortium, we will develop three types of visualization environments that serve as interactive tools for the users of the proposed VWs: *desktop visualization environments* for use on individual workstations; *web-based visualization environments* for use anywhere and anytime on a variety of devices, including mobile devices; and *immersive visualization environments* (such as stereo-projection or CAVE-based) for more sophisticated exploration and analysis of scientific 3D representations. These visualization environments fall under two major activities: (1) developing and deploying Visualization Environment (VE)–Virtual Watershed (VW) Platform adapters (i.e., *visualization adapters*), and (2) developing and deploying user interfaces (or *front end user interfaces*) for the visualization environments. These activities require tight collaboration and coordination with the project's CI-Data and Watershed Science teams.

Research Activity 1. Develop and deploy Visualization Environment (VE)–Virtual Watershed (VWS) Platform adapters (*visualization adapters*)

The CI-Vis team will create operational *visualization adapters* for interfacing the proposed types of visualization environments with the VW Platform, described in the CI-Data (Section 4.3.3.2). This is necessary for implementing the innovative, layered design of the proposed CI system of the project (Fig. 2) and ensuring effective access for the project's users to a broad, expandable range of computational and data resources. Development of the visualization adapters will begin in year 1, be completed and deployed by the end of year 2, and, based on user feedback (i.e., by the project watershed scientists), revised and refined in year 3. The development of such adapters, shared with the CI-Data component of the project, will be led on the visualization side by Donna Delparte (ISU) and Shannon Kobs-Nawotniak (ISU) and on the VW Platform side by Karl Benedict (UNM).

Research Activity 2. Develop and deploy user interfaces for the Visualization Environments (VEs)

The second major activity focuses on building *front end interfaces* that are visible to the users. This requires more varied technical expertise than for developing adapters (which will rely on the common VW Platform code base), for each of three types of proposed VEs. Taking a user-centered view, we will start in year 1 by eliciting, analyzing, and defining the front end interfaces' functional and non-functional requirements (Sommerville, 2010) through interviews and discussions with the project's watershed scientists and other potential users. Project rapid prototypes (McConnell, 1996) will then be developed for all three types of VEs. In year 2 we will use the rapid prototypes to conduct usability studies with project users to inform further the construction of the visualization software. By the end of year 2 full operational prototypes for the three types of VEs will be developed, deployed, and used by researchers and students for running interactive watershed simulation scenarios. In year 3 these prototypes will be revised and improved in terms of design and implementation.

The tasks of specifying requirements and performing usability studies for creating interactive front end interfaces for the proposed VEs will be led by Fred Harris (UNR), involve at least one other CI researcher from each VE, and watershed scientists and their graduate students in the proposed watershed research. John Anderson (UI) will lead the development of a desktop client using a game engine such as Unity (Unity 2012), and Alark Joshi (BSU) will spearhead the development of a desktop front end in a GUI environment such as Qt (Qt Project, 2012). Tom Jackman (DRI) and his technician and Fred Harris (UNR) will work on creating the immersive version of the VE, which will run on the stereo displays available throughout the Consortium. Fred Harris will also lead the development of the web-based VE, with help from ID and NM collaborators. Given the importance of the visualization front ends for enabling more effective interaction of the project's watershed scientists with the VWs (and thus, accelerate research) further details on the their interaction with the VEs are provided in the next section.

Training, education, and outreach activities for the CI-Vis component of the project include training the project's watershed scientists and students on how to use the VEs; educating graduate students about CI developments needed for scientific research in general and for watershed research; and disseminating results through articles, conferences, presentations, and workshops.

User Interaction with the Visualization Environments

The novelty of our proposed approach resides in the unique combination of extensive data management capabilities provided by the proposed VW Platform: the adapters that will serve as interfaces and communication channels to a broad range of CI facilities; the powerful concept of the VW seen as an aggregate of computational and data resources; and the VEs that will enable more productive user interaction with the VWs. Briefly, there are seven main steps in developing and running a simulation scenario using a VW *instance*. A VW *instance* is a specific embodiment of a virtual watershed, with specific datasets, models, and model configuration options defined.

1. **Initialize**: Querying the VWS Platform for a list of VWs available, as well as for a list of watershed instances that may already be saved locally or remotely.

2. **Select Watershed:** Select a VW or an available VW instance; if an existing (saved) VW instance is selected, then steps 3 and 4 will be skipped.
3. **Obtain Virtual Watershed Resource Information:** The software allows the user to configure a watershed instance.
4. **Select Virtual Watershed Resources**: User will select options such as specific datasets, quality of the terrain, which model(s) to run. Synthetic or real datasets can be selected; the user has the option to save the newly created VW instance.
5. **Obtain Watershed Resources**: resources not on the local machine will be downloaded by the VWS Platform; static data will be visualized; the user will start configuring the simulation/interaction scenario on the VW instance.
6. **Configure Simulation Scenario**: the user either selects a saved scenario or sets the parameters and specifies the execution order and the connections between the processing activities; the user can save the scenario.
7. **Interact with Simulation Scenario**: the user may run, reconfigure, save, store outputs, etc.

The first six steps can be seen as part of the environment's *configuration mode*, while the last step, consisting itself of several sub-steps (or user commands), can be considered the *execution mode* of the environment, in which the actual interactive simulation takes places. Specific details of all steps and sub-steps in the VE will emerge after a complete specification of the requirements has be produced during year 1, based on interviewing and consulting the researchers that will use the VEs. Furthermore, the usability studies that will be performed at the beginning of year 2 of the project, together with feedback received from users throughout the project, will help refine and shape the specific characteristics of the user's interaction with the VEs.

4.3.3.2 Data Management and Services (CI-Data)

Background and Proposed Research

The concept of a *virtual watershed* forms the linking capability that will connect the scientific modeling, visualization, and data management components of this project into a coherent whole. The CI-Data activities will focus on the shared – with the project Watershed Science and CI-Vis teams – specification of the required VW services and capabilities in support of *Accelerated Watershed-Scale Hydrologic Science* (sensu National Science Foundation 2012). These activities will be enabled by:

- Streamlined access to data (both local and remote) required for model initialization and boundary conditions;
- Analytic scenario development through interactive visualization of available data, model configuration options, and storage of those scenarios in specific VW instances;
- Generation of model execution platform configuration files based upon developed VW instances;
- Rapid assimilation of model outputs into the data management system for access and use by subsequent models.

The Virtual Watershed Platform will be developed to meet these requirements. It will consist of an application programming interface (API - resources in a Representational State Transfer [REST] web services context; Fielding, 2000; Granell, et al. 2013; Richardson and Ruby, 2007). The VW will rely on a data model of its own, designed for optimizing access to data, data services, data processes, and computing activities, and mediating between those data and processes, the visualization environments, and models. The uniform communication between the VW Platform and data repositories and data management services, the visualization platforms, and the computational models will be provided by three classes of *adapters*: *data service adapters*, *model adapters*, and *visualization adapters*. Data service adapters will allow the VW to connect to data and metadata services provided by external data providers (OpenTopography, CUAHSI, and DataONE) and the data management platforms within the Tri-state Consortium (NM Resource Geographic Information System [RGIS] and its underlying Geographic Storage, Transformation and Retrieval Engine [Gstore], the Northwest Knowledge Network [NKN], and the Nevada Climate Change Portal [NCCP]). The VW will provide a single interface to the model and visualization adapters, effectively hiding the heterogeneity of the data and metadata resources with which the platform can interact. The developed model and visualization adapters will connect to the VW to access data, metadata, and VW instance management services in support of their respective needs.

The VW data model will primarily consist of pointers to resources (datasets, data services, adapters, data processes, and models), definitions of the VW instances created, and descriptors of related scenarios. This model will be implemented using an XML-based representation. As a set of computational resources the VW Platform will initially be installed on dedicated computing resources at UNM's Earth Data Analysis Center (EDAC). By the end of the project, instances of the virtual watershed will be deployed in all three states for both redundancy and distribution of computational load.

The proposed CI-Data activities complement and build upon current developments in *integrated environmental modeling* (sensu Laniak, et al., 2013). CI-Data activities focus on a hybrid solution between component-based and service-based modeling approaches (Granell, et al., 2013), where the developed VW platform is the core of a *resource oriented architecture* that provides access to heterogeneous data resources and services through a RESTful web service interface. The *adapters* will act as translators between the VW platform and other web services as *service components* (as defined by the CSDMS modeling framework (Peckham, et al., 2012)), or as OpenMI *exchange item* objects (as described in Castronova, et al., 2013). The proposed work is distinct from the other efforts described above in that, while it will contribute to the continued development of improved model integration technologies, it will also have a specific focus on accelerating the delivery and publication of *model products* into a data management system that supports additional modeling. It will also improve the discovery of and access to well-documented data products in support of other research, education, and decision support activities.

CI-Data Research Activities

Team. Faculty: ID: Greg Gollberg (Co-Lead, UI) Luke Sheneman (UI); NV: Sergiu Dascalu (Co-Lead, UNR); NM: Karl Benedict (Lead, UNM). Technicians: ID (3), NM (1). Graduate students: NV (3); NM (1). Undergraduate: NM (1).

The CI-Data component is at the nexus of the proposed hydrologic and related watershed-scale environmental modeling and visualization activities through a set of related tasks. The following sections describe activities that support these tasks, and the capabilities upon which the activities will build.

1. Acquisition, processing, and publication of *data* required for the proposed models.
2. Provision of a suite of *interoperable data services* for those data.
3. Development of a combined data and configuration service suite: the *VW* platform that links models and the visualization tools with the available data services providers.
4. Development of *adapters* that serve as translators between the interoperable data services and the VW platform.
5. Development of *adapters* that enable bi-directional data and configuration exchange between CSDMS-enabled environmental models, visualization tools and the VW platform.

Existing Capabilities

Through the course of the current EPSCoR Track-1 and Track-2 cyberinfrastructure development, all three collaborating states have developed parallel data and metadata services, support for Federal Geographic Data Committee (FGDC) and International Standards Organization (ISO) metadata standards, Open Geospatial Consortium data and visualization services, CUAHSI WaterOneFlow web services, and a variety of other specialized web services. These services are provided through the data portals and associated platforms developed and maintained in each state as described above and with more detail provided in each State's "Facilities, Equipment, and Other Resources" Section.

Data Requirements

Required data for virtual watersheds is determined (1) by the selection of initial models to be incorporated in the VW and CSDMS and (2) by the selection of the visualization requirements for the three target platforms used to render the VWs. Multi-resolution elevation models will be required to create the 3D rendering of the ground topology, location and size of hydrologic features, and vegetation composition and structure. Standard LiDAR pre-processing will be applied to differentiate between "bald earth" and vegetation structure. These data will provide a *virtual watershed visualization* foundation upon which hydrological model results will be displayed while also providing alternative elevation models upon which hydrologic models may be based. Initial data requirements are provided in Table 2.

Table 2. Initial Model Data Requirements and Availability by State

Data Type	Required by Model	ID	NM	NV
• Elevation <1m - 90m resolution	• ParFlow • SRH2D • iSNOBAL	• SRTM (can be obtained) • LiDAR	• SRTM • Photo-based autocorrelation • NED • LiDAR (CZO & OpenTopography)	• SRTM (can be obtained) • NED (can be obtained)
• Vegetation	• ParFlow • SRH2D • iSNOBAL	• RCEW	• MODIS Land Cover	• Deployed SENSOR system
• Soils	• ParFlow • RIPFLOW	• RCEW	• STATSGO • SSURGO	• Deployed SENSOR system
• Geology	• ParFlow	• RCEW	• NM Bureau of Geology and Mineral Resources	• NV State Climate Office
• Groundwater	• ParFlow	• ID Dept. Water Resources	• NM Office of the Engineer	• USGS; TMWA; SNWA
• SPOT and/or Landsat imagery		• RCEW	• Available	• Available
• Aerial Photography			• Statewide 1-m resolution • Localized 6-inch resolution	• Ground photography from SENSOR system

Data Services

The data products to be obtained in support of the proposed modeling and visualization activities and the data products generated by the supported models will be published through a combination of standards-based, community, and project-specific web service interfaces. This section outlines the specific standards and protocols that will be used for both visualization and modeling.

Open Geospatial Consortium (OGC). The data access (Web Feature Service (WFS), Web Coverage Service (WCS), and visualization (Web Map Service (WMS)) standards of the OGC provide a set of services that are supported by the Tri-state collaborators and many external providers (e.g. NOAA's data centers). Implementation of these standards maximizes the number of existing client tools and platforms (primarily GIS) that can use published data. Maintaining these standards as foci for data management and delivery also allows for integration of externally hosted OGC services into the VW Platform.

DataONE. Implementation or expansion of the capabilities of the Tri-state Consortium members to participate in the DataONE network as replicating member nodes will facilitate the discovery by and delivery of data products to members of that network while expanding the data products available to the VW Platform through a planned data access adapter for the DataONE network.

CUAHSI. Existing support for point time-series data through the CUAHSI HIS service model in ID and NM, and planned support in NV provides a foundation for further expansion of support for the integration of new data and model products into this network.

OpenTopography. OpenTopography (OT) is an NSF-funded center for the management and delivery of LiDAR data and derived elevation products. LiDAR products for the project (the Valles Caldera, NM CZO LiDAR products) are already published through OT, or are in the process of being published (e.g., Reynolds Creek, ID). New project-related LiDAR products will be submitted to OT for publication, with the project then making use of the published data through the OT service interfaces and a planned data adapter between the Virtual Watershed Platform and OT.

REST Data Streamers. In instances where OGC, DataONE, or CUAHSI data services cannot meet the needs for data access (e.g. delivering data from multiple datasets in a response to a single request), an expanded data streaming REST model will be used. An API for this access model has been deployed as part of the Gstore platform hosted at EDAC and will provide the foundation for the implementation of authenticated data streaming services in all three states.

Metadata Services. It is anticipated that the OGC Catalogue Services capabilities now supported by all three states will be sufficient for the project's metadata service requirements. These are based upon the FGDC and ISO 19115-2 metadata that all three states are generating to support their data portals.

4.3.4 Workforce Development and Education Component

Team. Faculty/Participants: ID: Sarah Penney (Co-lead, ID EPSCoR), Bill Ebener (CSI), Tim Link (UI), Jim McNamara (BSU); NV: Michele Casella (Co-lead, NV EPSCoR), Laurel Saito (UNR), Scott Tyler (UNR). NM: Mary Jo Daniel (Lead, NM EPSCoR), Sam Fernald (NMSU), Selena Connealy (NM EPSCoR), John Wilson (NMT). Graduate students: those identified in the Watershed Science and CI Components. Undergraduate students: 20. Primarily Undergraduate Institution faculty: 20.

4.3.4.1 Background and Proposed Activities

The goals of the WC-WAVE Workforce Development and Education Component are to engage university faculty and graduate students in interdisciplinary, team research, and to broaden undergraduate student participation in STEM. We propose (1) Graduate Interdisciplinary Training (GIT) opportunities and (2) creation of an Undergraduate Visualization and Modeling Network (UVMN).

Graduate Interdisciplinary Training (GIT)

The Consortium effort uses a closely linked observatory system tied to a computational environment—the virtual watershed—that requires faculty and students to understand the project's watershed and CI research. Therefore, all of the graduate students involved in the project, as well as their faculty advisors, will participate in an educational program that fosters interdisciplinary understanding and collaboration, modeled in part on the NSF Integrative Graduate Education and Research Traineeship (IGERT) program. Students will work in interdisciplinary groups on projects oriented around the WC-WAVE themes in the proposed RII project. GIT begins with a "Kick Off" Snow Camp for watershed science graduate students that will create the collaborative foundation of the watershed student cohort. The snow camp is designed to introduce the student cohort to the Consortium faculty, and to Idaho's Reynold's Creek Experimental Watershed site. Because each experimental watershed is dominated by snow inputs as the primary hydrologic signal, the introductory camp will also focus on snow hydrology and measurement methods for snow. It will provide the opportunity to exchange ideas on research topics, and to develop students' dissertation committees from Consortium faculty.

Snow camp will be followed by the year 1 (winter) Tri-state Consortium meeting, during which faculty will present information about modeling, visualization, and data management to enable all project participants to develop a shared vocabulary and conceptual foundation for on-going collaboration. A series of Summer Institutes for graduate students will support project research and CI activities. Consortia graduate students will participate as a cohort in these Institutes. The Consortium coordination meetings described in the Management and Coordination Plan (Section 4.6) will provide additional interdisciplinary training opportunities for students, faculty, and staff. Each annual Summer Institute will have a different focus as described below.

Year 1: Observatory and Virtual Watershed Design. The year 1 Summer Institute will provide training for students, faculty, and staff from all of the Consortium states in developing CSDMS adapters for the models being used by the Watershed Science Component. Students, faculty, and staff from the CI Group will join the cohort of six watershed science graduate students and their faculty advisors. The Institute training will be hosted in conjunction with the year 1 summer Tri-state meeting and will include hands-on training for CSDMS basic model interface building and CSDMS modeling tool development and implementation. One existing CSDMS-enabled model (ParFlow) will be used as the example, with demonstration of a model used in the watershed science work (e.g. SRH-2D) that is not CSDMS-enabled.

Year 2: Interdisciplinary Modeling Course. We will build on a three-credit graduate interdisciplinary modeling course that was designed with prior NSF funding (EAR-0509599) to introduce students to models in different disciplines and give them experience working in interdisciplinary teams (Saito et al., 2007). This year 2 Summer Institute course will address: (1) advantages and limitations of using models; (2) different spatial and temporal scales; (3) differences in degrees of uncertainty of data and models; (4) interdisciplinary modeling options; (5) communication between disciplines; (6) education and training of scientists and practitioners in applying interdisciplinary approaches to address complex problems; and (7) interaction with stakeholders and the public. In consultation with researchers from the project's Watershed and CI Components, Saito (UNR), Link (UI), and Fernald (NMSU) will develop content to offer the course in a 2.5-week format in June 2015. The first week of the course will be held online with students and faculty participating from their respective institutions. Over one weekend, participants will travel to the UNR for a two-day mini-conference, followed by one week of instruction and collaboration in interdisciplinary project teams.

Year 3: Capstone and Leadership Development. The year 3 Summer Institute will consist of cyber-seminars, followed by an in-person workshop held in conjunction with the summer Tri-state Consortium meeting. The cyber-seminars will be presented by students and faculty, and will focus on dissertation work by the students. The cyber-seminars will identify advances and gaps in the watershed science research as preparation for our in-person meeting, during which participants will develop synthesis paper(s) that can serve as the foundation for subsequent proposals. The Summer Institute will provide professional development in leadership, communicating research, and proposal writing.

Undergraduate Visualization and Modeling Network (UVMN)

Visualization and modeling are critically important tools in many areas of science, and developing three-dimensional thinking skills is often seen as an important goal for undergraduate science education (Reynolds et al., 2005). The VW environments proposed by the Consortium provide a platform through which to include new technologies and research to undergraduates and faculty at predominantly undergraduate institutions (PUIs). STEM courses related to on-going research will increase student engagement and retention in STEM programs. Professional development for community college faculty, combined with improved STEM curriculum and resources, will improve science education in our states (Kincaid et al., 2012). Building relationships between PUI instructors and research university faculty will increase collaboration and support for transfer between the types of institutions.

Nearly half of Americans with a STEM bachelor's degree attended a community college, as did about 40 percent of U.S. teachers (National Research Council and National Academy of Engineering, 2012). Each of the Consortium states has primarily undergraduate institutions (PUI) that serve underrepresented minorities, first generation college students, veterans, students with disabilities and women; they are a key component of the states' STEM education systems. Idaho's, Nevada's, and New Mexico's community colleges have 24%, 46%, and 63% URM enrollment, respectively (U.S. Dept. of Education, 2009; Nevada Higher Education, 2011).

To improve undergraduate STEM coursework at PUIs, we will provide professional development for two cohorts of PUI instructors and students through a series of workshops and on-going virtual and face-to-face mentoring. In spring of year 1, 10 teams from across the Consortium, consisting of 1 PUI instructor and 1 student from the same institution, will participate in the UVMN. Participation begins with a three-day summer workshop on modeling, visualization, and other CI tools. Following the workshop, and with the assistance of a faculty mentor, the instructors and students will work collaboratively to develop and implement an educational module that uses appropriate modeling and/or visualization for existing undergraduate STEM courses. The faculty and students will discuss progress, opportunities, and challenges through a *virtual community* and will be included in research updates by the Watershed Science and CI Components. By the spring semester of year 2, the PUI instructor will implement the module(s) in their STEM classes, with the student participants acting as technical assistants.

Each state will have a mentor from the CI or Watershed Science Component who will provide guidance on course module development. The PUI teams—instructors, students, and mentors—will attend the spring (year 2) Tri-state Consortium meeting to participate in a modeling/visualization workshop and to present their work to the broader community. This will be repeated in years 2 and 3 for a second cohort of 10 faculty and 10 students. Cohort 1 faculty will be able to participate in Cohort 2 as "coaches". In year 3 (summer) there will be a workshop for both cohorts to prepare materials to share with other faculty and to identify opportunities for additional course development. Coursework innovations will be available through a web portal to be easily adapted by instructors at other institutions within and beyond the Consortium.

Faculty (Stephen (UNLV), Glenn (ISU), Harris (UNR)) from the CI and Watershed Science Components will collaborate with the Workforce Development and Education Team to design the initial workshop based on connections to the science and CI focus of the project. The workshop will be grounded in effective pedagogy in undergraduate courses and will involve representatives from relevant industries to explore applications of the modeling and visualization capabilities. Undergraduates will also be interacting regularly with graduate students, and will be assisted in exploring opportunities to continue their undergraduate or graduate education at universities within the Consortium. Student team members will be encouraged to apply for undergraduate research opportunities offered by each Consortium state's RII Track-1 projects and will be included in other Track-1 outreach opportunities.

4.3.4.2 Broader Impacts: Immersive virtual reality environments provide platforms foster interdisciplinary discussion and creative insight into complex scientific questions and enable innovations and discovery. Further, they help develop three-dimensional thinking skills, an important goal for science education. Using this platform for professional development of college instructors will improve the undergraduate

STEM experience at community colleges and other primarily undergraduate institutions. We anticipate that each of the 20 PUI instructors will teach students in 4 classes per year. If each class averages 15 students, more than 1,200 undergraduates will benefit directly from the UMVM course during the RII award alone. Retaining more undergraduate students in STEM at PUIs will enhance the diversity of those involved in all levels of STEM research, education, and industry. Creation of virtual communities for mentoring will leverage expertise across numerous colleges and universities and help with overall sustainability of program. In addition, implementing an IGERT-like program will prepare graduate students to work in collaborative, interdisciplinary teams to effectively address complex scientific issues. Combined, these activities will lead to a workforce that is prepared to tackle STEM challenges requiring interdisciplinary collaboration and computational thinking skills.

SECTION 4.4 EVALUATION AND ASSESSMENT PLAN

4.4.1 External Evaluation Team. Evaluation and assessment will be conducted by two different external groups, which include an external evaluation team and a technical external advisory board (see Section 4.6.1.3). Evaluation and assessment will be conducted by a team of independent, external experts from SmartStart Educational Consulting Services, which is led by Dr. Lisa Kohne. SmartStart will conduct three types of evaluation: (a) front-end evaluation to assess needs, (b) ongoing formative evaluation to monitor the quality of project components and implementation while providing feedback to the leadership team, and (c) summative evaluation to assess achievement of stated goals and broader impacts. The evaluation will use a mixed methods approach using qualitative and quantitative indicators. Evaluators will work closely with the leadership team to establish baseline data and measureable targets, and to collect evidence to determine annual progress towards achieving long-term impacts. The project's evaluation and assessment process is based on a comprehensive project logic model and benchmark/milestone tables developed by each of the components.

Front-end evaluation organizes the project and assesses needs. The evaluator will work with the leadership team to finalize the project logic model, benchmarks, milestones, timelines, as well as develop data collection procedures and evaluation instruments.

Formative evaluation monitors the effectiveness of project implementation and provides ongoing feedback to the leadership team to strengthen implementation during the course of the project. The formative evaluation plan provides evaluation data and metrics for activities conducted by each component. Results will be presented in quarterly evaluation reports and used by component and activity leads to improve program implementation and increase impacts. New programs and activities added as the project progresses will be incorporated into the evaluation plan.

Summative evaluation assesses achievement of project goals and broader impacts on project participants, universities, institutions, and the STEM community. Guiding evaluation questions are aligned with the goals of the NSF EPSCoR program and based on the overarching goal to advance watershed science, workforce development, and education with cyberinfrastructure-enabled discovery and innovation and the three following subgoals of this Track-2 EPSCoR project:

1. <u>Watershed Science Component</u> Advance understanding of hydrologic interactions and their impact on ecosystem services using a virtual watershed (VW) framework.
2. <u>Visualization and Data CI Component</u> Accelerate collaborative, interdisciplinary watershed research and discovery through innovative visualization environments and through streamlined data management, discovery, and access.
3. <u>Workforce Development and Education Component</u> Engage university faculty and graduate students in interdisciplinary team-based watershed research, and broaden undergraduate student participation in STEM through modeling and visualization.

Summative evaluation, supported by longitudinal analysis of annual metrics within all project components, will be used to demonstrate progress made at the end of each project year and at project completion. Impacts will be assessed throughout the project using baseline/annual post-surveys, evaluation forms, interviews, discussion groups, and tracking of progress made on identified metrics (Table 3).

Project evaluation will be consistent with methodological strategies described in NSF's *The 2010 User-Friendly Handbook for Project Evaluation*. Evaluators will meet individually with component leads at the beginning of each project year to discuss annual findings and plan the upcoming year. Evaluators will assist with completion of institutional review board protocols, prepare quarterly reports, and meet with the leadership team and advisory board to discuss progress, outcomes, and recommendations for improvement. Findings will be used to improve project implementation and increase impacts.

Table 3. Summative evaluation data and metrics. Summative results will be compared to expected milestones as stated in detailed benchmark/milestone tables (available upon request).

Strategies by Component	Output Metrics	Year 1	Year 2	Year 3	Goals and [Metrics]
Watershed Science					Progress made on annual milestones [80% met], Baseline/annual post survey to assess perceived gains in knowledge and research progress [.25 increase per year]
Paramaterize and validate watershed models	# models				
Develop CSDMS adapters for models	# adapters				
Coordinate model runs with students	# models and students				
Disseminate findings and products	# theses, publications, data				
Snow Camp for students and faculty	# participants				
CI Visualization and Data					Progress made on annual milestones [80% met], Baseline/annual post survey to assess perceived gains in knowledge and research progress [.25 increase per year], Participants report use and value-added impact of CI visualization and data [impact interviews and surveys]
Tri-state coordination	# monthly/quarterly mtgs.				
VW user requirements gathering and prototyping	# users engaged				
Develop and deploy VW visualization adapters	# adapters				
Design VW immersive env. and desktop frontends	% design completed				
VW interface frontend rapid prototyping	prototype completed				
VW interface frontend deployment	deployment				
Data and model requirements gathering (faculty/students)	# faculty/students engaged				
Develop and deploy VW data and service platform	platform deployed				
Develop and deploy VW platform adapters	# adapters				
Develop and deploy VW model adapters	# adapters				
Integration with CUAHSI and WaterOneFlow services	integration completed				
Integration of state data centers as DataONE Nodes	# Nodes deployed				
Data management workshops for faculty and students	# participants				
Workforce Development					Progress made on annual milestones [80% met], Baseline/annual post survey to assess perceived gains in workforce development [.25 increase per year], More qualified graduate, undergaduate students and undergraduate faculty (e.g., retention in STEM, jobs)
Graduate Interdisciplinary Training	# participants				
Summer institutes for graduate students	# participants				
UVMN cohort 1 (10 undergrads/10 faculty)	# participants				
UVMN cohort 2 (10 undergrads/10 faculty)	# participants				
UVMN capstone event	# participants				
Undergraduate modules	# modules				
Project Management and Coordination					Ongoing communication, synergy, and growth as indicated by annual post-surveys and interviews.
Tri-State Annual Meetings (in-person)	# participants				
Virtual Tri-state and State (in-person) Meetings	# participants				
Monthly MT and CT meetings	# participants				
Assessment and Evaluation					Project leaders use assessment and evaluation results to improve project.
External Advisory Board (1 evaluation/yr)	#, report				
External A&E (all programs evaluated)	% completed				
Sustainabilty					Faculty more competitive for R&D funds (10%/yr) [(awards, $)/yr]; models and code added to community repositories; integration of CI with state repositories
Proposals (avg. of 4/yr; 20% success rate)	#, % success				
Incorporation of models into CSDMS	#/yr				
Incorporation of "adapters" code into community repository	#/yr				
"Adoption"/integration of CI by ID, NV, and NM	% success				
Adoption of undergraduate modules	% success				

SECTION 4.5 SUSTAINABILITY PLAN

To sustain the impacts and achievements of this Track-2 project beyond the award our strategy is to: (1) design activities that maximize interdisciplinary, inter-institutional, and inter-state participation, (2) support the mission of existing institutional programs and priorities, (3) actively promote and disseminate the results within and beyond the Consortium, and (4) position interdisciplinary teams to compete for new research proposals that utilize and further develop the improvements. This strategy is reflected in each component of the project.

4.5.1 Watershed Science. Our plan is based on maximizing the interdisciplinary, inter-institutional aspects of the project to build lasting capacity. Sustainability will be fostered through integrated research teams and projects; sharing of data, computing capacity, and expertise; frequent coordination and collaboration; and workshops and training (e.g., summer institutes) for faculty and graduate students. Investigators will co-author a synthesis article focusing on integrated watershed modeling advances and gaps. An integrated modeling session at the fall AGU meeting will also be proposed. Development of online curricula for the Interdisciplinary Modeling Course will support continued collaboration.

The VW platform will be usable and expandable through subsequent research proposals, which are anticipated to focus on (1) full modeling system deployment, (2) incorporation of new components (e.g. upland vegetation, bank erosion), (3) investigation of newly revealed feedbacks/interactions/thresholds, (4) application to resource management and decision-making, (5) watershed science instruction, and (6) use in additional watersheds to answer specific management or science questions.

Engagement with stakeholders and existing research centers will also enhance sustainability. Long-term research commitments in Valles Caldera NP include the Valles Caldera Trust, an NSF-funded CZO, and the USDA Forest Service Southwest Jemez Mountains Landscape Restoration Project. Research groups in Reynolds and Dry Creek watersheds include the Great Basin Landscape Conservation Cooperative, USDA ARS Northwest Watershed Research Center, and Boise Front Ecosystem Management Group (BLM, USDA ARS, USGS). Nevada stakeholders include regional directors of USFS, USFWS, NPS, and water utilities.

4.5.2 Cyberinfrastructure. Software and human capacity resulting from the training and expertise of the individuals involved will last well beyond the award. Software will be open source, typically released under the BSD 3-clause license. The source, user manuals, and developer design documentation will be placed in an open shared repository (e.g.,Github) so that users will be able to enhance and modify it. The visualization tools will promoted and utilized by university RII and UMVN participants following the award. Proposals will be submitted that build on and use the new visualization capabilities. Developed products will be hosted and maintained by each State as resources accessible to and shared among Consortium members. State-specific plans for maintaining continuity leverage existing institutional programs, such as Idaho's Northwest Knowledge Network and New Mexico's Environmental Data Analysis Center (EDAC). This Track-2 project will complement and add capabilities to the Nevada Climate Change Portal (NCCP) and the SENSOR system established with previous Track-1 RII funding. These programs are described in the Facilities, Equipment, and Resources documents for each State and in the Data Management Plan.

CI investments will facilitate growing collaborations with researchers and integration with other national NSF-funded projects such as DataONE and NEON, which will provide greater national and global visibility while enhancing global data stores. Use of CSDMS platforms will lead to integration at the national level for software modules for environmental research. Integration and strategic alliances with these entities are expected to create new opportunities for innovative, large-scale research projects. A relationship with the NSF-sponsored CUAHSI will serve to help facilitate long-term use and advancement of the system.

4.5.3 Workforce Development and Education. The project's Workforce Development and Education activities explicitly support collaboration between Primarily Undergraduate Institutions (PUI) and Research Universities with the intent of enhancing the educational experience for students and faculty at all institutions. A *Western Tri-state Consortium Two-Year and Four-Year College Engagement Plan* has been drafted by the Workforce Development and Education team, which provides a conceptual foundation and over-arching structure for long-term engagement of and collaboration with PUI faculty and students. This Plan will be refined and revised each year and will be an explicit focus at Consortium-wide meetings. Ultimately, the interactions between PUI and University faculty and students will contribute to long-term collaborations between individuals and institutions that will lead to more effective STEM education, and improved student retention, degree completion, and advancement in STEM. Our plan also involves producing adaptable, high quality materials; broad availability and dissemination, particularly through web portals; and adoption of resources by PUIs. These will be accomplished by connecting materials with users, initially via the Track-2 teams and partnerships, and subsequently by continued use and adaptation by other organizations. All of the Consortium institutions have Education, Outreach, and Diversity coordinators who will dedicate time to project sustainability.

The UVMN will position participating college instructors and collaborating faculty from four-year universities to pursue funding through programs such as the NSF TUES (Transforming Undergraduate Education in STEM) program for development of additional modules and/or integration of modules through a sequence of courses or across institutions, and. to NSF WIDER (Widening Implementation and Demonstration of Evidence-based Reforms).

4.5.4 Milestones. The following key milestones, in addition to others articulated in the Evaluation and Assessment Plan, will be met during this RII Track-2 award.

- Proposals (average of 4/yr, 20% success rate)
- Incorporation of models into CSDMS

- Incorporation of ‘adapters’ code into community repository
- Adoption and integration of CI by ID, NV, and NM.

SECTION 4.6 CONSORTIUM MANAGEMENT AND COORDINATION PLAN

The Consortium’s Management and Coordination Plan draws on the strengths of each state’s EPSCoR program structure. There are four primary elements of the Consortium’s management structure: (1) State EPSCoR Committees, (2) State EPSCoR Office leads and Project Management Team, (3) Assessment and Evaluation, and (4) Component CI Data Management and Services, CI Visualization, Watershed Science, and Workforce Development and Education Teams (Figure 3).

4.6.1 Project Management Structure and Functional Roles of Components

4.6.1.1 State EPSCoR Committees. A State Committee that includes members from community, government, private, and academic sectors oversees each State’s EPSCoR program. State Committees are a key catalyst for integrating academic research capacity with state S&T plans and priorities. Each State Committee has endorsed this Track-2 proposal and is committed to overseeing project progress.

Idaho’s 16-member State Committee establishes policies, criteria, and procedures necessary to ensure that EPSCoR goals and objectives are met including (1) guiding and coordinating the state effort under federal-wide EPSCoR; (2) exercising quality control through the use of external reviewers; and (3) ensuring that research supported under EPSCoR is consistent with state economic, human resource development, and S&T strategies. It also oversees the business of the Idaho EPSCoR office and monitors the selection, progress, and implementation of the EPSCoR-like programs in the State.

Nevada’s 15-member EPSCoR Advisory Committee advises the State EPSCoR Director on strategic directions for sustained health and growth of Nevada’s EPSCoR programs; connects science and technology advancements to an educated workforce, and ensures economic development and diversification; supports and assists in the development of science and technology in the State of Nevada, including education, research, and technology transfer; and informs legislators, businesses, committees, associations, and other interested parties about the importance of EPSCoR in Nevada and the critical role science and technology play in economic development.

New Mexico’s 20-member State Committee is the primary governing body for NM EPSCoR. It identifies the focus areas for NM EPSCoR; assists EPSCoR in enhancing the state’s research infrastructure through partnerships with universities, national laboratories, and industry; promotes research and collaboration among the NM universities; increases opportunities for K-graduate education and training; helps develop the science and engineering workforce; and promotes economic development.

4.6.1.2 State EPSCoR Offices and Project Management Team. A strong basis for effective management of the Consortium is rooted in the collaboration created in 2008 by ID, NV, and NM as part of their RII Track-1 climate change programs as well as the ongoing Track-2 project that concludes in 2013 (see Section 4.2). The Track-2 Project Management Team consists of the state Project Directors (Dr. Gayle Dana (NV), Dr. Peter Goodwin (ID), and Dr. William Michener (NM)); Deputy Director Dr. Mary Jo Daniel (NM); the three Project Administrators (Tracy Hart (NM), Marcie Jackson (NV), and Rick Schumaker (ID)); and the Component Team Leads (CTLs: Dr. Karl Benedict and Dr. Mary Jo Daniel (NM), Dr. Fred Harris (NV), and Dr. Nancy Glenn (ID)). Administrative coordination support and outreach assistance are provided by each state’s EPSCoR office staff. Because Nevada is the lead organization, Dr. Dana will be the Lead PI and primary Consortium liaison with NSF. The PDs and PAs will be responsible for overall project management, budgetary and reporting oversight, and ensuring evaluation and assessment requirements are met. One PI/Co-PI will Chair the Project Management Team, with the Chair rotating annually. The Chair will ensure that inter-jurisdictional meetings and activities are scheduled and implemented, and will draft the annual and final reports. EPSCoR office staff of each State will provide web, editing, and communications support for the project.

4.6.1.3 Evaluation and Assessment. The Project Management team will work with the External Evaluator (Dr. Lisa Kohne), an External Advisory Board (EAB), and the Internal Evaluation and Reporting Team to monitor progress towards project goals (see Section 4.4). The EAB and External Evaluator will interact with researchers and with the Project Management Team by attending the annual meeting held in rotating state locations. The EAB will (1) review progress toward achieving outcomes of the projects; (2) make constructive suggestions for improving and/or changing the direction of the work underway; and (3) advise the Project Management Team. EAB members have been selected to ensure that internationally and nationally recognized experts review the subject areas: Suzie Allard (University of Tennessee;

workforce development); Robert Cook (Oak Ridge National Laboratory; Data Management and Services CI); Kelly Gaither (University of Texas, visualization CI); Scott Lathrop (Natl. Center for Supercomputing Applications, visualization and workforce development); David Tarboton (Utah State Univ., CI and hydrological modeling); and Claire Welty (University of Maryland Baltimore County, watershed science).

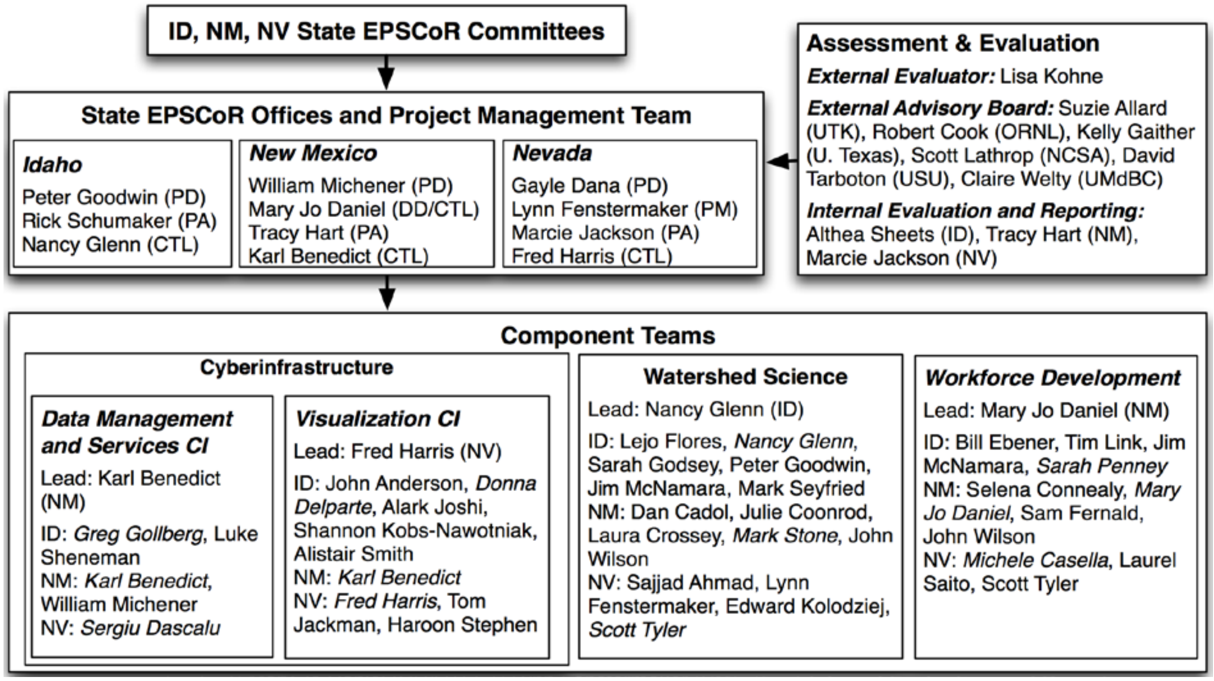

Figure 3: WC-WAVE Project Organizational Chart; state Component Team leads *italicized*.

Component Teams. Each project component has a faculty lead who will oversee a team comprised of faculty from the three states and ensure that component goals and objectives are met: Dr. Nancy Glenn (ID) for Watershed Science; Dr. Karl Benedict (NM) for Data Center CI and Dr. Mary Jo Daniel (NM) for Workforce Development; and Dr. Fred Harris (NV) for Virtual Watershed CI. State faculty leads (in *italics* in Figure 3) are also identified for each component to oversee state-specific component activities. Other members of Component Teams are listed in Figure 3.

4.6.2 Coordination Plan Integration of cross-jurisdictional and cross-disciplinary science will be coordinated via collaboration enabled by two annual Tri-state All Hands' Meetings (2nd and 4th quarters). The two tri-state meetings each year will also focus on collaboration and coordination across components as well as highlighting project accomplishments. Two intervening video teleconferencing (VTC) meetings of all participants will be held in the 1st and 3rd quarters. The VTC meetings will include a 1-hour plenary session that includes all Component Teams plus three concurrent 3-hour sessions that focus on CI (a combination of the CI Data and CI Visualization Teams), Watershed Science, and Workforce Development and Education. The VTC meetings will be preceded by individual half-day state meetings. The Project Management Team will review progress monthly via VTC calls. With the advice of the EAB, the Project Management Team will take corrective actions as necessary to ensure successful attainment of the project's goals. PDs, PAs, and some of the Co-PIs will also meet several times a year at the NSF EPSCoR Project Director and National meetings. Other coordination mechanisms include: a shared knowledge management platform (Atlassian Confluence and Jira) that will be hosted at the Earth Data Analysis Center; source code management using Github; and available web conference facilities. The training workshops described in 4.3.4 provide an additional venue for coordination and communication of all graduate students and faculty.

Project Management and Coordination mechanisms appear in the budget as travel costs for participants to attend in-person meetings, and material and supply costs for the state hosting the annual Tri-state meetings; travel and honoraria for External Advisory Board annual site visits; and Go-To-Meeting annual service licenses. Travel costs for the PDs and PAs to attend NSF EPSCoR PD/PA and National EPSCoR meetings are covered in each state's Track-1 budget.