North American Water Program (NAWP)

Solutions for North America's freshwater sustainability challenges

September 2012

Motivation: We lack the water storage and flux knowledge, prediction skill and science-informed water management methods to adequately address North America's freshwater sustainability challenges. Atmospheric processes, terrestrial rivers and hydroclimactic processes transcend eco-regions and political boundaries requiring a continental-to-global scale hydroclimate synthesis.

Vision: Establish the scientific basis, observation, modeling and decision approaches needed to manage water security and sustainability through climate, population and environmental change uncertainties.

Objective: An interdisciplinary integration of North American hydroclimate observation and prediction resources that transcends scales and enables procedures and analytic tools to adapt to change.

Science Question: How does climate, environmental and population change affect the water cycle across scales, to what extent is it predictable, and can we adapt to achieve freshwater sustainability?

Challenges:

- ***Adaptation:*** Develop the scientific basis and tools to adapt to climate, population and environmental changes in the water cycle.
- ***Benchmarking:*** Assess water storage and quality dynamics, understand the sensitivity of the water cycle to change, and evaluate model skill for improved hydrologic predictions
- ***Science informing decisions:*** Develop the capacity for science-informed sustainable water management practices in the face of climate, population and environmental change.

Implementation:

- *Quantify*: Systematically quantify North American water storages and fluxes; develop records of atmosphere, water, land and energy-related quantities, including uncertainty estimates.
- Understand: Analyze variations, trends and extremes in the water cycle, and determine the impacts of the specific adaptation measures on water resource and related sectors.
- *Predict*: Improve continental precipitation, cloud and hydrology prediction through accelerated development of coupled atmospheric and land models; Develop advanced hydroclimate models that seamlessly ingest observations to monitor and forecast water availability and change.
- *Solutions:* Develop and transition new observations, models, diagnostic tools and methods, and data management tools to national operational applications.

Overview & Motivation

The water cycle describes the circulation of water, a vital and dynamic substance, in its liquid, solid and vapor phases as it moves through the atmosphere, oceans and land. Water is an integrating component of the climate-energy-geochemical cycles, regulating biological and ecological activities at all spatial and temporal scales. There is an important nexus between water and energy, this being the relationship between how much water is evaporated to generate and transmit energy, and how much energy it takes to collect, clean, move, store and dispose of water. Life in its many forms exists because of water, and modern civilization must continuously learn how to live within the constraints and extremes imposed by the availability of water.

North America is amongst the greatest consumers of water worldwide; "*Americans use water even more wastefully than oil. The U.S relies on non-renewable groundwater for 50 percent of its daily use, and 36 states now face serious water shortages, some verging on crisis*" (Barlow, 2008). Looming climate change complicates the North America's water crisis, but projected increases in water demand from increasing population, industrial, energy and agriculture needs may have four times more impact on the water supply-demand imbalance than climate change (Kummu, 2010).

Problems that are directly associated with water can be simply classified as too much water, too little water and/or poor water quality. This seemingly simplistic classification is key for resolving current water related issues and challenges. The fact is, we don't even know how much water is stored in North America's lakes, reservoirs, streams, groundwater systems or snow packs (Famiglietti 2012) which is fundamental knowledge needed to manage any resource.

Reliable prediction of hydrologic change and extremes is of critical importance for policy and decision makers to adapt to future water challenges. However, the models that we use to understand and forecast water availability, flooding and drought are not up to the task of addressing our most pressing societal issues of food, energy, water and national security. State-of-the-art, comprehensive computer models are not able to seamlessly ingest satellite observations and measurements to help monitor and forecast snowpack, river flows, soil water and groundwater levels (Famiglietti, 2012).

There are important gaps in knowledge of where water is stored, where it is going and how fast it is moving. Our skill in predicting the water cycle is woefully inadequate to reliably inform critical societal decision making. Figure 1 shows our low precipitation forecast skill in comparison to temperature. We clearly need a decisive and coordinated effort to systematically quantify water storages and fluxes, improve water cycle prediction skill, and develop reliable methodologies to translate those predictions into enlightened water resource management – this is the motivation for the North American Water Program (NAWP).

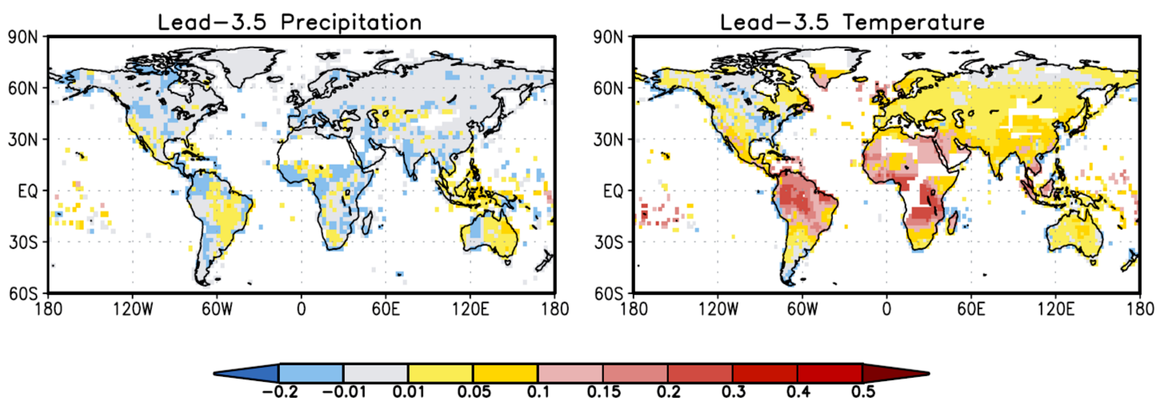

Figure 1: Distribution of ranked probability skill score (RPSS) averaged over all seasons for (left) precipitation and (right) temperature with a 3.5-month lead time (Barnston et al., 2010). The RPSS is used to assess the overall forecast performance of the probabilistic forecasts.

The Challenges

Water is an integrating component of the climate water-energy-geochemical cycles, regulating biological and ecological activities at all spatial and temporal scales. It is well recognized that human demands from a growing population for food, energy, shelter and fiber has impacted the landscape (Foley et al., 2005) and threatens biodiversity and water security (Vörösmarty et al., 2010). Anthropogenic climate change can exacerbate these impacts and threats (Karl et al., 2009).

In order to deal with climate, population and environmental change and its uncertainty, we must extend the current scientific basis with modern observations, models and decision tools, to provide guidance to water planners and engineers. A decisive and coordinated effort to systematically quantify water storages and fluxes, improve water cycle prediction skill, and develop reliable methodologies to translate those predictions into enlightened informed water resource management is needed.

To address the North American water crisis, the North American Water Program (NAWP) must be established to coalesce an interdisciplinary, international and interagency effort to make significant contributions for continental to decision scale hydroclimate science and solutions. By entraining, integrating and coordinating the vast array of interdisciplinary observational and prediction resources available, NAWP will significantly advance skill in assessing, predicting and managing variability and changes in North American water resources to meet ever increasing demands and climate change complexities. NAWP builds on previous North American water research efforts while including the broader climate, carbon, ecology and decision communities, and will provide an integrative framework for continental, basin and field scale projects.

NAWP will be organized around three challenges. The first deals with developing a scientific basis and tools for ***adapting*** to changes in the water supply-demand balance. Adaptation refers to our ability to anticipate and adjust to changes in water supply and demand, to take advantage of opportunities, and to cope with the consequences. The second challenge is ***benchmarking***; to use incomplete and uncertain observations to assess water storage and quality dynamics, and to characterize the information content of water cycle predictions in a way that allows for model improvement. The third challenge is to establish clear pathways to ***inform*** water managers, practitioners and decision makers about newly developed tools, observations and research results.

North American Water Program (NAWP)

NAWP will establish the scientific basis, observations and modeling approaches required to manage water security and sustainability through climate and environmental change uncertainties. This will require an interdisciplinary integration of North American hydroclimate observation and prediction resources that transcends scales and enables procedures and analytic tools to adapt to change.

NAWP CHALLENGES:

1. ***Adaptation:*** Develop the scientific basis and tools to adapt to climate, population and environmental changes in the water cycle.
2. ***Benchmarking:*** Assess water storage and quality dynamics, understand the sensitivity of the water cycle to change, and assess model skill for improved hydrologic predictions
3. ***Science informing decisions:*** Develop the capacity for science-informed decisions related to climate, population and environmental change.

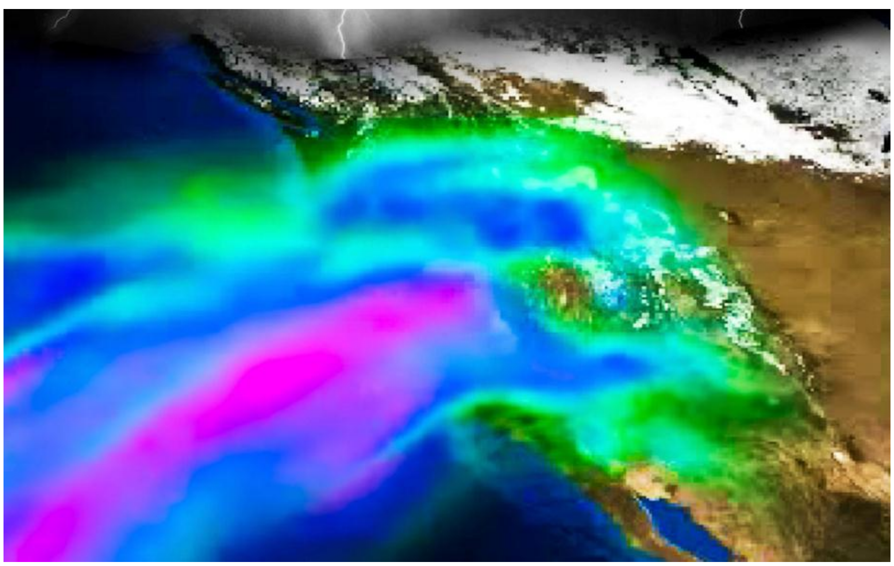

Figure 2: NAWP will provide the scientific basis required to manage water security and sustainability transcending global atmospheric rivers to local water

Challenge 1: *Adaptation*

It is clear that human activities are modifying Earth's environment – usually referred to as "environmental change". Anthropogenic climate change from increased greenhouse gases in the atmosphere is one driver of this change, whose effects are directly related to changes in climate system, and in particular to those affecting water and energy cycling. These changes, and projection of future change, have been documented in the IPCC reports, resulting in calls to mitigate future changes by reducing the release of carbon-based greenhouse gases. It's unclear that sufficient reductions will take place to mitigate the projected changes to the water cycle, or that other drivers of change (population increases, land conversion, reservoir construction, river modifications, urbanization, irrigated agriculture and so forth) will significantly impact the mean and variability of water cycle. The end result is that any performance evaluation of water resource systems must adapt to a wide variety of current and projected water cycle changes.

Hydrological time series are no longer non-stationary due to water cycling influences from a variety of sources (Milly et al., 2008) – changes brought about due to human activities to secure clean and reliable water supplies for drinking water, irrigated agriculture, energy production and manufacturing as well as from climate change. Engineering hydrology is concerned with developing water resource designs that alleviate the situation of too much water (flooding), too little water (drought) and coping with natural hydrologic variability (reliable water supplies) – basically extremes. Hydrologists use long-term data on which to base water resources designs, implying that hydrologic design by its nature is "risk-based design" and needs statistical models to represent the data. Are the underlying statistical distributions stationary or non-stationary? If the latter, how are the moments changing, can they be "predicted" and what are the implications for the reliability of current and future water structures?

Subject to current and projected environmental, population and climate changes, there is evidence that hydrologic and water cycle time series are becoming non-stationary. This is a significant challenge to the hydrology and water resources scientific and management community, and it is important to determine the best methods to model non-stationary processes and to develop procedures for incorporating non-stationarity into hydrological and water resources designs. We refer as hydrologic adaptation science the development of these new methods and tools needed for water resource systems to adapt to climate and environmental change in a non-stationary world. Developing this science is a major challenge for hydrology.

Actions needed to develop a scientific basis and tools to adapt to climate and environmental change include not only addressing non-stationarity, but also establishing the scientific basis of water sustainability. This will require enhanced investments in hydroclimate process science, land change science, precipitation prediction, hydrologic ensemble generation, model building and calibration, earth system model development, advancing land-atmosphere coupled models, including human dimensions in models, and developing risk-based uncertainty metrics.

In the water resources context, adaptation also involves achieving a balance between water supply and demand and easing water quality issues, thereby making more water available for human and environmental use. Improvements in water supply or availability could take many forms, for example:

- Enhancing groundwater recharge by slowing runoff, using pervious paving methods, etc.
- Reducing evaporation through proper forest management, improved irrigation practices, reductions in open water area, canal coverings, or landuse optimization. Reduced evaporation may also improve water quality.
- Rainwater harvesting from rooftops.
- Water treatment and reuse.
- Weather modification.
- Enhanced below and above-ground water storage.
- Water conveyance from wet to dry areas.
- Desalination and water treatment science and technology.

- Alternative energy development that does not require thermal water cooling, such as wind, solar, and air-cooling.
- High efficiency appliances, toilets, showers, etc.
- Drought-tolerant landscaping and agriculture.
- Water pricing and economic incentives
- Improved water distribution system efficiency (reduce pipe leaks and canal losses)

NAWP – Adaptation Example

Shifting Probability Distributions

The probability distribution of climate variables can shift in a changing climate – impacting the frequency of extreme events. This figure demonstrates the various ways: through a shift in the mean, the variance or both, that can change significantly the frequency of extreme events. This shift affects the risk of extreme events, as illustrated in Figure 2, where the European 2003 summer heat wave air temperature is shown relative to the 1864-2002 observations (top panel), the distribution of 1961-1990 climate model simulations and 2071-2100 climate model projections. It is unclear whether the 2003 European heat wave temperatures was a very extreme event or a harbinger of the future climate given it falls in the middle of the distribution for future (2071-2100) air temperatures. If the latter, how should water managers plan for cooling water related to energy or water demand for irrigation?

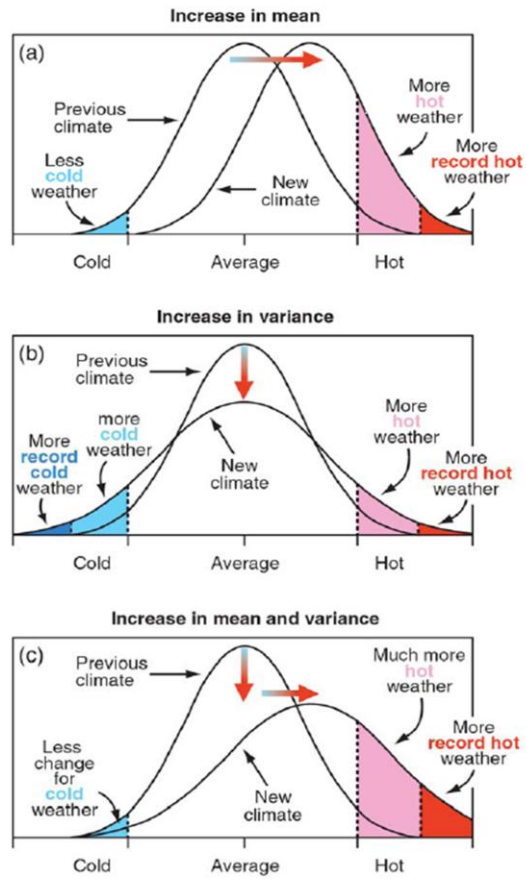

Figure 3: Potential changes in the distribution of climate variables, with subsequent changes in the risk of extremes. (Folland et al., 2001)

Challenge 2: Benchmarking

Benchmarking is the process of improving performance by identifying, understanding, adapting and implementing best practices and processes. For NAWP, benchmarking involves the creation of partnerships to exchange information on processes and measurements, bridging observational and prediction gaps, and setting realistic water cycle knowledge and prediction improvement goals. Effective benchmarking is a process framework within which indicators, best practices, and effective environmental management are continuously improved.

Models provide a key resource in our understanding of weather and climate, allowing/providing predictions that are used by national sectors on seasonal to climate time scales. Numerical simulation and prediction of water, in all its phases, presents challenges at many time and space scales. Improving model capabilities rely on consistent high quality benchmark data and methods. NAWP represents a collective effort to address the understanding of water on the continent.

While there is a great need for analyzed precipitation to close water and energy budgets, it is a difficult parameter to predict, even on short time scales. Surface evaporation is not directly observed and relies on theory and calculations. There exists many similar gaps in our observational knowledge if the water cycle over North America. Higher spatial and temporal field studies can provide much needed independent observations of these critical parameters thereby exposing weaknesses in the numerical approaches that can be corrected to improve predictions. The current observing network has the capacity to provide certain measures of meteorology and climate, but the current lack of availability, integration and quality control between disparate observational networks limit their usefulness for model benchmark investigations.

Single observations, even with uncertainty values, are often not a reliable benchmark. Multiple estimates from varying approaches can provide a range and better sense of the uncertainty for a parameter. However, it is unrealistic for a single organization to accurately develop multiple approaches to measuring all the water quantities needed, given the specialized knowledge required for each. As such, a community collaborative effort (such as NAWP) would be the most reliable approach to gain success in reducing uncertainties of the current analyzed regional water cycles and its prediction.

Actions needed to understand hydroclimate sensitivity and benchmark prediction models and decision tools include reanalyzing hydroclimate change and documenting its uncertainty, conducting field verification across regions and hydroclimate gradients, leading field campaigns focused on regions of high prediction uncertainty, developing prediction and operational support capabilities, and establishing water and energy budget closure methods across scales.

Figure 4 shows the temporal anomaly correlation of summer precipitation of the most recent reanalyses precipitation over 30 years. Precipitation is used here as an example, because the observations are well maintained and easily comparable, and model predictive skill is typically weak. High quality observations of the processes involved are needed to address modeling issues. For example, the DoE Atmospheric Radiation Measurement program sites provide great detail and use for this. However they are limited in spatial coverage. Satellite data provide more spatial coverage, at the expense of a high frequency of measurement. Enhanced observing campaigns have provided core convergence of the detailed observation and expertise to make progress on problems. Since special field campaigns do not typically extend for climatologic time periods (recognizing that climate reference networks are under development), the existing surface station network should be more fully leveraged. Yet, surface meteorology observations can provide indicators and benchmark metrics for the regional hydroclimatology. Over the United States, the surface station network is quite dense. Many climate observation reprocessing efforts utilize only the air temperature. Moisture, wind and cloudiness observations could be better used in benchmarking studies, to reinforce the understanding of processes in the context of the field campaign data.

NAWP – Benchmarking Example

Summertime precipitation variability in the United States is a critical component of extreme weather and climate variability that directly impacts a multitude of societal sectors. Representation of the climate variations of summer precipitation in seasonal and climate predictions is highly uncertain, despite a dense observing network. This is because the processes that produce precipitation, including horizontal and vertical motions must also be accurately simulated and benchmarked in the predictive models. Given the sparse network of wind observations, observational analyses and reanalyses are often the best way to characterize the horizontal moisture transport.

Even reanalyses which assimilate the observed wind, temperature and moisture profiles have difficulty in simulating instantaneous precipitation. However, they are improving in representing the interannual variations of precipitation. Figure 3 shows the temporal anomaly correlation of summer precipitation of the most recent US and EU reanalyses precipitation over 30 years. Each set of bars relate to the various regions defined by the USGCRP National Climate Assessment (NCA) shown in Figure 3b. While these comparisons show that reanalyses are producing the precipitation associated with interannual variability reasonably well, some regions (Midwest for example) are quite close to having quality so low as to not be useful in an applied sense. Numerical predictions would be that much less.

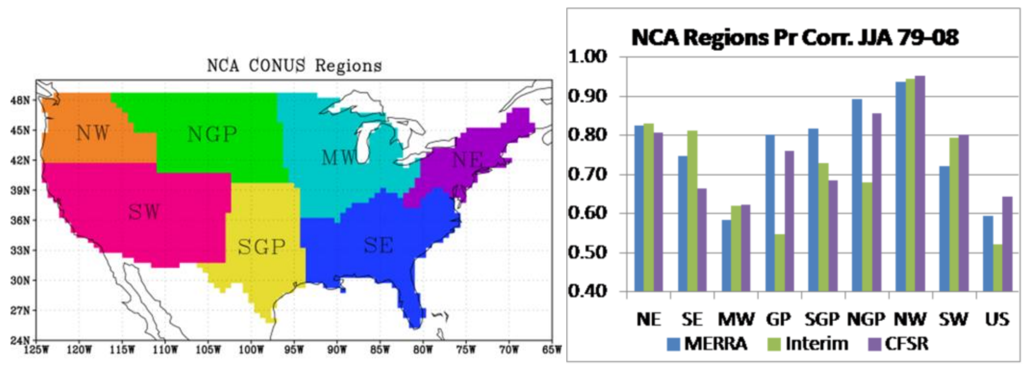

Figure 4: Regional study map as defined by the National Climate Assessment (left). Global reanalysis precipitation correlation to gauge observations for summer seasons from 1979-2008 for the NCA regions(right).

Challenge 3: ***Science informing decisions***

Water cycle variability and extremes affect all aspects of society and the environment. Decisions are made every day to help communities, farmers, industries and the environment effectively minimize (mitigate) and prepare for (adapt to) to changing water availability and demand. The water science community has created a strong scientific foundation for informing decision makers who need science to understand and envision a range of potential water-sector impacts, risks, vulnerabilities, opportunities and trade-offs. NAWP will add a decision maker focus to better inform decisions—one that will conduct fundamental, user-inspired research, while delivering credible, relevant, timely and accessible information.

Central to the success of NAWP to inform water decisions is strengthening the dialogue and engagement between the science and decision making communities. This collaboration and coordination at the interface of science and decision making requires new methods and a framework for multidirectional information exchange, including:

- Facilitating meaningful partnerships between science and decision making: to assess decision needs, science capabilities and requirements; identifying knowledge gaps and inspire a use-focused research agenda; and establishing sustained dialogues including development of communities of practice, training and outreach forums and technology transfer.
- Providing easy access to science knowledge and operational practices: through integrated water

NAWP – Adaptive Management

Adaptive management is a structured, iterative process of optimal decision making in the face of uncertainty, with an aim to reducing uncertainty over time via system monitoring. In this way, decision making simultaneously maximizes one or more resource objectives and, either passively or actively, accrues information needed to improve future management. Adaptive management is a tool which should be used not only to change a system, but also to learn about the system. Because adaptive management is based on a learning process, it improves long - run management outcomes. The challenge in using the adaptive management approach lies in finding the correct balance between gaining knowledge to improve management in the future and achieving the best short - term outcome based on current knowledge. Adaptive management is particularly applicable for systems in which learning via experimentation is impractical (such as hydrologic non-stationary or hydroclimate change).

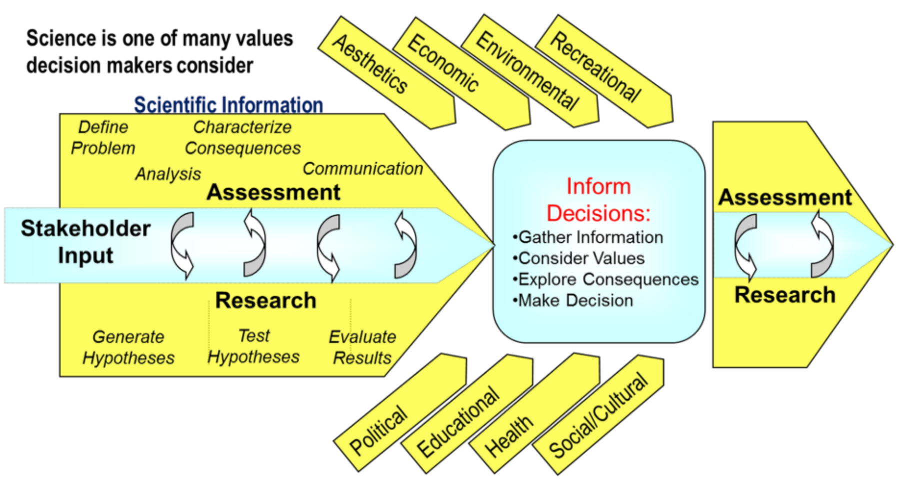

Figure 5: Adaptive management model for science informed decision making. In this model, science and management objectives are integrated to simultaneously optimize decision making and scientific learning.

information, decision tools and operational status; and develop simulators, libraries and forums to make research available to the larger community.
- Guiding and coordinating water science efforts to ensure they are relevant to informing water management decisions: benchmark uncertainties of the observational record, model predictions, and operational needs; develop new methods to transfer climate predictions into decision space (downscaling, application sector modeling); develop operational observation capacity to validate and improve operational products; and identify and transition research products into operational applications.

In developing a strategy for informed decisions, it is recognized that scientific knowledge is only one part of a much broader decision process. For instance, information may be scientifically relevant without being decision relevant. Therefore, NAWP will help to define a framework for informing decisions that connects to the broader decision process. The desired framework will include approaches to assess the value of proposed decision support information, provide support for understanding risk management options, and communicate uncertainties associated with data and projections. It is envisioned that science can inform decision making, along with other critical information, in an adaptive management framework as described in Figure 5.

NAWP – Science Informing Decisions Example

One of the notable and sustained adaptive management efforts in the United States is the Glen Canyon Adaptive Management Program. The program includes representatives of roughly two dozen groups including federal and state agencies, environmental groups, Indian tribes, and power and recreation interests. The program also features a science center, composed of full-time staff, who is responsible for monitoring Colorado River ecology to help improve understanding of the downstream effects of Glen Canyon Dam operations. Experimental flows have been conducted in which high water flows were released from the dam to simulate the spring rise that, in pre-dam conditions, transported sediment and helped restore beach habitat. Low water flow experiments have also been conducted in an effort to enhance conditions for native fish species. These experiments were extensively monitored and the results used in subsequent deliberations about dam operations.

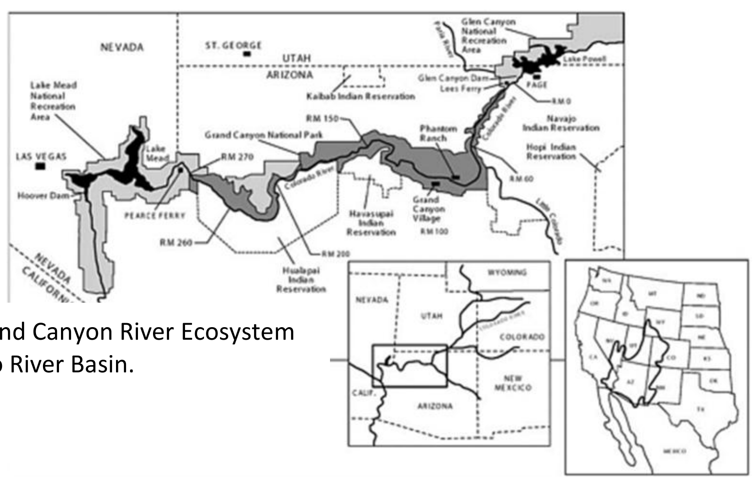

Figure 5: Grand Canyon River Ecosystem and Colorado River Basin.

Opportunities and Linkages

NAWP is proposed as a scientific examination of the issues of hydroclimatic variability and change in resources crucial to the continent. It represents s potential collaboration among multiple agencies and academic institutions to draw on key expertise and capabilities. For each of the objectives, the NAWP strategy will rely on developing strong partnerships with governmental and non-governmental institutions, resource managers across national, state, regional and local levels, and with international organizations in order to bridge the gap between scientific research and policy and public action on continental to decision-scale water issues. Potential NAWP activities include:

Adaptation: Scientific basis and tools to adapt to climate, population and environmental change.

- *Analysis*: Describe and analyze variations, trends and extremes in hydroclimate quantities.
- *Processes:* Develop approaches to improve process-level understanding of energy and water cycles in support of improved models and predictions.
- *Prediction*: Determine the contribution of land surface states and their changes to regional. hydroclimate prediction; improve continental precipitation, cloud and hydrology prediction through accelerated development of coupled atmospheric and land models.
- *Assessment*: Determine the impacts of the specific adaptation measures on water resources availability and residual effects on other sectors

Benchmarking: Water cycle sensitivity to change; prediction skill for improved water management.

- *Data*: Develop climate data records of atmosphere, water, land and energy-related quantities, including metadata and uncertainty estimates.
- *Field Studies*: Conduct targeted field studies that explore regions of low hydroclimate prediction skill, or transects across hydroclimate variability.
- *Forecasting and operational support capabilities*: Develop advanced hydroclimate models that seamlessly ingest satellite observations and measurements to help monitor and forecast water availability and change.
- *Establish water & energy budget closure across scales*: Close observational gaps and reduce uncertainties to the point where water storage, fluxes and balances can be quantified.

Science informing decisions: Developing the capacity for science-informed water resource decisions.

- *Solutions:* Attribute causes of variability, trends and extremes; determine the predictability of energy and water cycle changes and mitigative strategies on a continental basis.
- *Technology transfer:* Develop and transition new observations, models, diagnostic tools and methods, data management and other research products to national operational applications.
- *Capacity building*: Promote and foster capacity building through training, outreach, and the development of strategic collaborations both domestically and internationally.

Synthesis & Summary

The North American water crisis is upon us. We need a decisive and coordinated effort to systematically quantify water storages and fluxes, improve water cycle prediction skill, and develop reliable methodologies to translate those predictions into enlightened water resource management – this is the motivation for the North American Water Program (NAWP). Atmospheric and terrestrial rivers, and therefore hydroclimactic processes transcend eco-regions, states and countries requiring a continental-to-global scale synthesis.

These challenges are inherently complex and global in nature, and can only be addressed and overcome through a comprehensive, continental and interagency activity that engages water agencies, universities and the private sector. We recommend that NAWP integrate and coordinate the vast array of North American observational and prediction resources available, to significantly advance skill in assessing, predicting and managing variability and changes in water resources. By addressing the three

NAWP challenges, ***adaptation***, ***benchmarking*** and ***informing decisions***, NAWP will provide solutions for North America's freshwater sustainability challenges.

To be successful, the NAWP vision outlined above must evolve with broad science community and stakeholder participation. By developing science and implementation plans, organizations can take ownership and responsibility for key NAWP components. In the near term, we recommend that a NAWP scientific discovery team be convened to finalize the NAWP vision, establish organizational terms of reference, recommend interagency/international partnerships and draft a science plan. NAWP forums at relevant agencies and organizations can help to build consensus and refine the vision. Establishment of a project office will help coalesce partnerships, disseminate information and organize workshops. As NAWP evolves, working groups must be developed to refine and implement the NAWP challenges, opportunities and linkages and the leads of these working groups will represent the first NAWP steering team. There are clear needs and roles for a wide variety of governmental, academic, non-profit and private sector organizations to lead various NAWP initiatives toward solutions for North America's freshwater sustainability challenges.

Acknowledgements

*The development of the North American Water Program vision started in 2010 with recognized need for an interdisciplinary, international and interagency effort to make significant contributions to North American hydroclimate science and solutions. This vision culminated in an April 2011 "Terrestrial Regional North American Hydroclimate Experiment" (TRACE) workshop in Maryland. Over 75 participants from the academic, the private sector, government, and international organizations provided valuable insights, wisdom, consensus and mandates for embarking on such an ambitious effort. The TRACE planning team consisted of: Paul Houser, Peter van Oevelen, Robert Schiffer, Sushel Unninayar, Christopher Castro, Ruby Leung, Richard Lawford, Eric Wood, David Gochis, Michael Ek, Michael Bosilovich, Ernesto Hugo Berbery, Deborah Belvedere, Raymond Arritt, and Adam Schlosser. Following the TRACE workshop, the vision was reworked and renamed the North American Water Program (NAWP), resulting in this white paper, largely written by: Paul Houser, Eric Wood, Michael Ek, Michael Bosilovich, C. Adam Schlosser, Robert Schiffer, Peter Van Oevelen, and Jared Entin. We envision that this white paper and the NAWP vision will continue to evolve and mature as it is shared with wider audiences, and we acknowledge those that will contribute to its future success. For inquiries or suggestions, please see **www.nawaterprogram.org** or email **prhouser@gmu.edu***

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