U.1 Executive Summary

U.1.1 Background

The potential impacts of climate change and hydrologic variability on the Colorado River have been subjects for discussion for many years. The continuing drought in the Colorado River Basin coupled with recent advances in scientific knowledge regarding the potential impacts of climate change has heightened this interest.

The recent drought has emphasized that the principal influence on water availability is the amount of runoff in the basin. The conventional assumption used in water resources planning is that the past record of runoff can be used to represent future conditions; that the future will look like the recent past. Reclamation, like most water management agencies, has, until recently, relied on this conventional assumption in its planning activities.

Reclamation has recognized the limitations of the conventional assumptions for some time, but the continuing drought conditions accelerated efforts in the agency to investigate alternative assumptions which may be used in its planning and operations. Furthermore, considerable evidence from paleo records concluded that the observed record of the last 100 years did not capture the full range of variability of historical streamflows in the Colorado River.

Reclamation's Lower Colorado Region initiated a multi-faceted research and development program in 2004 to enable the use of other methods for projecting possible future inflow sequences for Colorado River planning studies. The research and development effort has been designed to provide information for the near-term (e.g., some facets have already been completed), as well as the longer-term that involves collaboration with other research organizations (e.g., National Oceanic & Atmospheric Administration and United States Geological Survey). The effort is focused on two key areas:

- collaboration with other federal agencies and universities to conduct research to gain knowledge and understanding of the potential impacts of climate change and climate variability on the Colorado River, and

- improvement of Reclamation's decision support framework, including modeling and data handling capabilities, in order to utilize the new information when it becomes available.

To assist in the direction and prioritization of these efforts, particularly over the next few years, a group of experts in meteorology, climate and hydrology, referred to as the Climate Technical Work Group (Work Group), was empanelled to provide information to Reclamation about the state of knowledge regarding climate science and future climate conditions and their impact on water resources, particularly on the Colorado River Basin.

In addition, the Work Group ran parallel with and informed Reclamation's development of the final environmental impact statement (EIS) for the proposed adoption of interim operational guidelines for Lake Powell and Lake Mead on the feasibility of considering long-

term projections of climatic conditions in its assessment of alternative proposed guidelines. Contributions from the Work Group as well as the research and development program were invaluable in advising the analysis and content in the final EIS to address future hydrologic variability and the potential for increased hydrologic variability due to climate change.

Reclamation convened a meeting of the Work Group on November 8, 2006. In addition to the outside expert invitees, a number of Reclamation staff and contractors also attended the meeting. The members of the Work Group and attendees at this meeting are listed in Attachment 1. The November 8 meeting provided the opportunity for a face-to-face discussion between the climate experts and Reclamation staff. Following the meeting, a smaller group of Reclamation staff, contractors and outside experts developed this report. The members of this drafting group are listed in Attachment 1. The drafting group developed an initial outline which was circulated to the entire Work Group in February 2007. Based on feedback on the outline, a draft of this report was developed and circulated to the Work Group for review in April 2007. Comments were received from the Work Group and other interested parties including climate scientists, water resource engineers, and Reclamation personnel. The Work Group revised the document and transmitted it to Reclamation in its final form in August 2007. Reclamation pre-published the final report as an appendix to the final EIS for the proposed adoption of Colorado River interim guidelines for Lower Basin shortages and coordinated operations for Lake Powell and Lake Mead in October 2007.

U.1.2 Findings

U.1.2.1 State of Climate Change Science

There is strong scientific consensus that the earth has been warming, that this warming is driven substantially by human emissions of greenhouse gases, and that warming will continue. Climate models project that temperatures will increase globally by 1 to 2ºC in the next 20-60 years. The projections are fairly consistent for the next 20 years, with a 1ºC increase, but exhibit larger uncertainty in the 40-year projections. Scientists agree on some of the important broad-scale features of the expected hydrologic changes, the most likely of which will be an increase in global average precipitation and evaporation as a direct consequence of warmer temperatures.

U.1.2.2 Potential Impacts to the Colorado River Basin

The impact of climate change on the region of the Colorado River Basin (CRB) is less certain; however, it is expected that regional temperatures will also increase. Regional precipitation response is less certain with comparable evidence suggesting wetter or drier conditions. There is some consistency to indications of a general drying for mid-latitude regions such as the CRB, but this indication must be tempered by the limited precision of existing atmospheric models in resolving the topography of the southwestern U.S.

The potential impacts of climate change on the CRB's water resources have been a subject of research for several decades. Although an aggregate message from these studies may be that a decrease in runoff can be expected, runoff response across these same studies *ranges from increase to decrease*. These studies show that system storage is very sensitive to changes in mean inflows as well as to sequences of dry and wet years.

The degree to which current methods can provide reliable information about future streamflow variability remains a question.

U.1.2.3 Options for Relating Climate Change Projections to Reservoir Operations

There are several options available for translating climate projections into operations response information. The three core steps for long term operations analysis under assumed climate change include: (i) selecting a simulated climate scenario that overlaps with observed historical conditions and extends into a future planning horizon, has been bias-corrected, and has been downscaled to a basin-relevant resolution; (ii) relating the downscaled climate conditions over the basin to natural runoff response; and (iii) relating simulated natural runoff response to water supply and operations response. After these core steps are defined, it is necessary to consider other options about how variability in water resources conditions will be addressed.

In addition to the uncertainties inherent in projections of greenhouse gas concentrations, and in simulation of future climate conditions using General Circulation Models (GCMs), there are various uncertainties associated with relating climate projections to runoff and operations. These include the assumptions on converting simulated climate time series into a meteorological input sequence for runoff analysis, assumptions on how to convert meteorological input to runoff, assumptions on how to represent system operations within the operations model under a changing climate, and assumptions on future land use and land cover.

U.1.2.4 Paleoclimatic Information

Paleoclimatic information for the Colorado River basin is extensive, with the most notable, and reliable, streamflow reconstructions being for Lees Ferry (dividing point between Upper and Lower basin). The streamflow reconstructions there go back as far as AD 762 and have been used to create hydrologic scenarios for planning studies. The main limitation in the use of paleoclimatic information is when reconstructed flow values are beyond the "predictor space" on which the model is based. These values may be less reliable than other reconstructed values. There is an emerging area of research on how paleoclimatic information can be used with climate change projections. The main idea is to combine the variability in the paleohydrologic records with the more certain future warming for assessing possible future scenarios.

U.1.2.5 Interannual and Interdecadal Variability

There is an increasing awareness that in addition to gradual changes (long-term trends) in climate conditions, there is also a large degree of interannual and interdecadal variability in climate, which may dominate the climate experienced in a basin in the short term (10-20 years in the future). The well known El Niño-Southern Oscillation (ENSO) has linkages in the Lower Basin where El Niño events bring generally wetter conditions and La Niña events bring drier conditions. A limitation on research relating interannual and interdecadal variability is the relatively short time periods available for the analysis. The use of paleoclimatic data may enhance the understanding of these multidecadal phenomena. The impacts from interannual and interdecadal climate variability on streamflow may be significant for planning studies with short planning horizons (e.g., 20

years). This could be just as important as evaluating the impacts of climate change that may not really be noticed in the basin for 20-50 years.

U.1.3 Recommendations

U.1.3.1 Planning Studies

Shorter Look-Ahead Studies: For studies and management decisions involving shorter look-ahead horizons (e.g., less than 20 years), an appropriate level of analysis might involve a qualitative discussion of climate change and interannual-to-decadal variability within the study's look-ahead horizon. If the role of shorter-term climate is critical to the study, the proposed qualitative discussion might be accompanied by a quantitative sensitivity analysis based on instrumental record and paleoclimate evidence.

Longer Look-Ahead Studies: For studies and decisions concerned with greater than 20-year look-aheads and being evaluated on the near-term, it is suggested that a quantitative sensitivity analysis be conducted on operations response to projected climate change using approaches previously mentioned in ES 2.3. By comparing system performance using projected climate change hydrology to historical hydrology, useful knowledge about system sensitivity should be ascertained.

U.1.3.2 Research and Development

Improved Availability and Temporal Resolution of Regional Climate Projection Datasets: Currently, there is limited access to bias-corrected and downscaled climate projection datasets over the Colorado River basin. An archive of bias-corrected and spatially downscaled GCM outputs should be made available to researchers and the public. In addition, as dynamically downscaled datasets become available, these datasets should be added to the archive.

Improved Ability to Model Runoff Under Climate Change: Currently there are only a few runoff models available to generate CRB natural flow given climate inputs, and Reclamation does not have easy access to these models. Reclamation needs to build internal staff expertise with available runoff model applications in the basin, and build coalitions with external groups that use such applications. Ideally, such runoff applications would also report other hydrologic processes' response to climate change (e.g., soil moisture, evapotranspiration, groundwater interactions with surface water).

Investigate Paradigm for Colorado River basin Precipitation Response: While there is an evolving paradigm for how the American Southwest and other existing dry subtropical areas of the globe should respond to climate change, it is not clear how nearby relatively wet mountainous areas such as the Rockies should respond. In addition, the ability of GCMs to simulate future precipitation conditions at this spatial scale is questionable. Reclamation should encourage and support work to improve scientific understanding of precipitation response to climate change.

Diagnose and Improve Existing Climate Models Before Adding Additional Features: Given known GCM limitations in simulating regional precipitation, climate research groups should focus a portion of their efforts on diagnosing and correcting biases in the current collection of climate models.

Investigate Changes in Modeled Climate Variability at Multiple Time Scales: It is well appreciated that the Colorado River is sensitive to changes in mean flow. However, variability as represented by drought spells, wet refill periods, and extended decadal and longer periods of above and below-average flow are also critical for determining system yield. Therefore, investigation of such variability in modeled sequences of precipitation, runoff and other climatic variables is critical.

Improve Understanding of Surface water, Groundwater and Land cover Interaction: Because rivers and groundwater are intimately connected, understanding the entire recharge process and its response to climate change is critical. Hence, research is required on groundwater recharge and movement at scales relevant to regional runoff analysis, and this in turn requires understanding the aggregate process of mountain block recharge and the role of riparian and root zone vegetation. The latter leads to additional research questions on how basin land cover and natural evapotranspirative demand will respond to global climate change.

Improve Prediction of Interdecadal Oscillations: The predictability of interdecadal climate oscillation phases and their associated hydrologic impacts on the Colorado River basin are not well understood. Shorter-term planning may be more influenced by these oscillations than by projected changes in climate means. Reclamation should actively support, either materially or otherwise, efforts in the science and applications community to advance knowledge in this area.

Investigate use of Paleo Record to Inform Modeled Streamflow Variability: Reclamation has funded some research on how to use information from the paleoclimate record in modeling studies. While the past will not repeat, the paleo record contains a wealth of information on natural variability that should not be ignored. For example, there may be valuable ways of combining paleo data with modeled and or historical data to modify the variability in these sequences in useful ways.

Interact with Federal Climate Change Science Program and Other Climate Change Research Initiatives: Although Reclamation can pursue and fund some of the Research and Development work described above, many of these problems will require the assistance of the larger scientific and engineering community. The Department of the Interior is one of thirteen agency members of the approximately $2 billion per year federal Climate Change Science Program, the umbrella under which all federal climate change activity is pursued. In order to raise the profile of these issues and obtain resources to help solve them, Reclamation should engage the CCSP. In addition, Reclamation should collaborate with NOAA, the National Center for Atmospheric Research, and the University research community.