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Executive Summary

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EXECUTIVE SUMMARY

Background and Objectives

Colorado faces increasing demands on its water supply for both traditional consumptive (agriculture, municipal, industrial, commercial and other) uses and for non-consumptive (recreational and environmental) uses. Population growth, recent drought, energy development, and potential climate change generate concern about the adequacy of Colorado's water supplies. The Colorado River Water Availability Study (the Study or CRWAS) was authorized by SB 07-122 and HB 08-1346 of the Colorado General Assembly. These bills direct the Colorado Water Conservation Board (CWCB) to conduct the Study 1) in collaboration with the Interbasin Compact Committee (IBCC) and the State's river "basin roundtables" (BRTs) and 2) with consideration for current and potential future in-basin consumptive and non-consumptive needs.

The CWCB, working closely with the IBCC, concluded that the Study be conducted in two phases, with Phase I (the subject of this report) presenting a water availability assessment based only on existing levels of water use. For Phase I, water uses (also referred to as water demands) were limited to current levels of water demands served by water rights that are currently being used ("perfected" or "absolute" water rights). Phase I is also restricted to interpretations of current operating and management practices for water diversion, storage and conveyance facilities. Assessments of water availability to meet future water needs are reserved for Phase II of the CRWAS.

The draft Scope of Work for Phase I posed the following types of questions to help guide the Study:

- *How much water from the Colorado River Basin System is available to meet Colorado's water needs?* Phase I of the CRWAS provides important information to help Colorado prepare for a range of future hydrologic conditions and to deal with uncertainty in making water management decisions.

- *What is a reasonable base of existing uses for Phase I of the CRWAS?* Each year the State of Colorado, like other Colorado River basin states, prepares assessments of the State's water consumption and losses. These reports support on-going inter-state water management activities and help assure agreement that Colorado's water management is in general compliance with inter-state agreements (river compacts and the "Law of the River" documents). The estimate of Colorado's current consumptive use (developed in Phase I) helps provide a basis for comparing future water availability with current conditions. It does not, however, supersede the official estimates of consumptive uses and losses submitted by the State in accordance with defined inter-state water management protocols.

- *How does historical hydrology compare to a longer hydrologic trace based on tree ring analysis?* Careful analysis of the width of annual growth rings in tree trunks and statistically correlating them with wet and dry weather patterns is one method to assess long-term or "paleo" hydrology prior to streamflows being recorded by man. For Phase I of the CRWAS, historical hydrology is extended back more than 1200 years using paleohydrology developed by others.

- *What is a reasonable projection for hydrology affected by climate change?* A CWCB-sponsored report, *"Climate Change in Colorado – A Synthesis to Support Water Resources Management and Adaptation"* (CWCB and CU-NOAA Western Water Assessment, 2008) provides a comprehensive review of greenhouse gas emission scenarios, global climate models, and resulting climate projections. Readers interested in the "storylines" supporting the development of these projections

should review this report and reference the definitions in the glossary of the report. For the CRWAS, climate projections previously developed by others were used to estimate potential changes in temperature and precipitation, which were then used to develop changes in streamflows.

- *How much water is available to Colorado for future consumptive use given certain compact assumptions?* The results and conclusions of this Study are based on assumptions made for study purposes only. Phase I of the CRWAS presents the amount of water that may be available for future consumptive use in Colorado solely for the purposes of this Study and is neither the State of Colorado's nor any party's compact interpretation.

A study team led by AECOM and including AMEC Earth and Environmental, Canyon Water Resources, Leonard Rice Engineers and Stratus Consulting began work in late 2008. To date, more than 30 public presentations of the CRWAS have been made to various groups including the CWCB, IBCC, BRTs, Colorado Water Congress and others. The Phase I results presented below provide important information to Colorado water users, managers, policy makers and stakeholders on future water availability in the Colorado River basin.

The process of defining the potential future water demands that will be used in Phase II is currently underway through the State's IBCC processes in coordination with CWCB. Phase II will update and further refine the hydrologic computer models and the data supporting them. Categories of water use in Phase II will include beneficial uses recognized under Colorado water law and other potential "non-water right" future consumptive and non-consumptive uses. Future water demands and potential project portfolios to meet those demands are being developed through several processes facilitated by the CWCB's Water Supply Planning Section. Phase II will also provide information essential for wide ranging programs of the CWCB. The study will provide estimates of streamflows and reservoir levels to support water supply, flood management, instream flow protection, water conservation, endangered species recovery, and other intra-state, interstate and federal programs.

Technical Approach and Findings

The CRWAS Phase I Study is comprised of five inter-related components or steps as follows.

1. Update and expand the State's water availability computer simulation tools based on input solicited from water users (consumptive and non-consumptive) through the BRTs.

2. Assess potential future water availability using records of historical water supplies.

3. Use scientific analyses previously developed by others to estimate streamflows over the past several hundred years using annual growth of trees (especially as an indicator of transitions between wet and dry years and as an indicator of the potential lengths of dry and wet periods) and use this extended hydrology to assess remaining water availability as if today's water uses existed throughout the extended period.

4. Superimpose the effects of potential changes in precipitation and temperature from previously developed global climate models (GCMs, also known as General Circulation Models) to reflect hydrologic conditions that may exist in 2040 and 2070 if the greenhouse gas emissions occur as postulated in the various scenarios ("storylines") simulated by the GCMs.

5. Consider the effects of potential compact constraints, using certain assumptions, on water use in the State of Colorado.

In addition to the five step process described above, the Study also reviewed the practicality of modeling the hydrologic effects of forest change. Forest disturbance, such as forest fire, disease or logging may cause an increase in runoff volume[1] because less precipitation is lost through the processes of evaporation and plant transpiration. The U.S. Forest Service, in conjunction with the CWCB and the North Platte River Basin Roundtable, is completing a multi-year study to collect information regarding forest change processes that most influence the hydrology of disturbed forests within Colorado. Information from the study is expected to better describe corresponding hydrologic processes and to constrain assumptions to be used in future hydrological models. It is therefore appropriate to re-assess the potential for quantifying the impact of forest change on water availability when results of that ongoing work become available and the science of forest change assessment advances.

Water availability studies like the CRWAS compare supply and demand to determine whether there is enough water to meet either current demands or future demands based on the "supply-and-demand equation": **Supply – Demand = Water Available for Future Consumptive Use**

CRWAS Phase I holds the demand side of the water availability equation constant at current levels and considers three different conditions for the water supply side of the equation as follows:

1. Historical Hydrology–Traditionally, water supply agencies have used recorded historical information on water supply as an indication of likely future conditions; the premise being that history tends to repeat itself. Many agencies in Colorado used streamflow records dating back to at least 1950 so they could consider the impacts of the 50's multi-year drought on the reliability of their systems. The State has developed hydrology back to 1909 in the Colorado River basin in Colorado, but this required filling missing records or records for discontinued stream and weather gages with scientifically estimated values. For the purposes of this Study, a 56-year study period is used to represent historical hydrology (1950 through 2005). This period includes both very wet and very dry years, contains the most reliable historical data upon which to base comparisons of the effects of climate change, and uses information that Colorado River stakeholders can relate to through their own experiences. Historical hydrologic conditions are characterized by the record of natural flows at hundreds of points throughout the basin, basin-scale record of precipitation, temperature, and wind disaggregated to thousands of cells in a rectangular grid covering the entire Colorado River Basin, and a record of local weather recorded at 54 weather stations within Colorado.

2. Paleohydrology–This approach extends historical records using information from more than 1200 years of previously published tree-ring records. The CRWAS reviews alternative methods for correlating annual tree growth with streamflow and concludes that a "re-sequencing" approach best serves the needs of the Study. This approach focuses on the probabilities of transitioning back and forth between wet and dry years. The lengths of the wet periods and dry periods have significant effects on water availability for future use, especially when combined with the effects of climate change. This Study concludes that development of 100 equally probable 56-year-long flow traces is appropriate to test the effects of more severe droughts on water supply and management in Colorado and on the state's amount of water available for future consumptive use as potentially constrained by the compacts.

[1] In addition, forest disturbance can impact the timing and rate of snow pack and snow melt (earlier peak flows) and water quality.

3. Climate-Adjusted Hydrology–This approach assesses the magnitude of future water supply availability considering the effects of climate change scenarios. This Study reviews many methods to use information from the climate projections that are available for the Colorado River basin. After coordinating with the State's Climate Change Technical Advisory Group (CCTAG) that is comprised of many federal, state and private scientists, water resource engineers and managers and also coordinating with the Front Range Climate Change Vulnerability Study (FRCCVS), this Study uses five projections for each of the 2040 and 2070 planning horizons (ten total). The Variable Infiltration Capacity (VIC) model is used to translate changes in temperature and precipitation from the Global Climate Models (GCMs, also known as General Circulation Models) to changes in natural flows throughout the river basin. In Colorado, the potential climate-induced changes have been introduced into two models comprising the State's Colorado Decision Support System (CDSS). First, "State-CU" is used to estimate altered consumptive use of water by crops resulting from higher temperatures and longer growing seasons. Second, "StateMod" is used to simulate the altered water management (for example, diversions, return flows, reservoir operations and instream flows) that would result from changes in natural flows. Input of the BRTs during Phase I significantly enhanced the performance of the models in the CDSS.

Some climatologists question the science supporting climate change projections, the work of the Intergovernmental Panel on Climate Change (IPCC), and the effects of greenhouse gas emissions, in particular, the contributions of anthropogenic (human-caused) factors like carbon dioxide emissions to climate change. Phase I of the CRWAS compares the effects of three alternative water supply scenarios (historic hydrology, paleohydrology and climate change hydrology) as described above. While the projections of future climate represented by the GCMs are possible representations of future conditions, the Study provides other hydrologic scenarios to allow water managers, policy makers and stakeholders to base their decisions and actions on a broad range of future possibilities.

Assessments of all the potential hydrologic scenarios presented in this report are supported by the updated CDSS computer tools made possible through interaction with the BRTs. These tools allow the most detailed analysis performed to-date of water supply and use in the Colorado River basin. All three hydrologic scenarios are useful to Colorado River stakeholders in assessing their potential policies and programs. Consideration of all three approaches will help each organization further define its roles and positions in water management, the resources available to it to adapt to alternative potential futures and select its tolerance or appetite for risk of water shortage.

The Study's consulting team recognizes the challenges of using GCMs to create scenarios on which to base assessments of future water availability, and on interpreting the results of those assessments. Until more detailed GCMs are created, including "regional" climate models that can more directly simulate the weather processes that affect temperature and precipitation of the Colorado River basin, (including summer monsoons and the orographic effects of the basin's rugged topography), the scientific information used in this Study is currently the best available for a study of this nature. This Study is likely the most rigorous and detailed study performed to date that utilizes GCM output and extends the analysis of potential effects to potential impacts on all the water uses (consumptive and non-consumptive) in an entire river basin.

Table 1 summarizes the ***technical approach*** for CRWAS Phase I. Table 2 summarizes the ***primary findings*** of CRWAS Phase I.

Table 1 – Phase I Technical Approach Summary

- Historical Hydrology includes hydrology observed for period 1950-2005.
- Paleohydrology is based on an extended record dating to AD 762 (more than 1200 years ago)
  - Provides estimated streamflow duration / frequency / intensity for years prior to gage data.
  - Estimated using statistical models applied to tree ring data.
  - Paleohydrology flow magnitudes are derived from the historical flow record (1950-2005).
  - Flow sequences are derived from paleohydrology flow record to provide more robust variety of year to year flow sequences than historical record.
  - Re-sequencing – Future sequences of wet and dry years cannot be predicted; therefore, 100 different 56-year hydrologic traces were developed.
    - Represents 100 alternative possible future sequences of wet and dry years.
    - Each of the 100 alternative possible futures is equally probable and differs from the other 99.
    - Although more sequences would have been statistically more valid, 100 traces are sufficient for the purposes of the Phase I Study and are considered the maximum practical number of traces given the Study's funding and schedule.
- Climate-Adjusted Hydrology is based on five climate projections selected in consultation with the State's Climate Change Technical Advisory Group.
  - Five climate projections were chosen for each of the 2040 and 2070 planning horizons (these are the same ten projections selected by the participants in the FRCCVS).
  - Subsequent analysis of the selected projections showed that the 2040 projections were representative of streamflow conditions at both time frames, while the 2070 projections were biased toward dry conditions. For this reason, the 2040 projections are used as the basis for values in this report.
  - Each of the selected climate projections is equally probable; but differs from the others.
  - Projections are "downscaled" to the Colorado River basin and temperature and precipitation changes were translated into effects on hydrology using the VIC hydrologic model. Flow sequences (dry/wet spells) were derived from those used in the paleohydrology flow record because it has been shown in the literature that GCMs alone do not simulate flow sequences reliably.
- Water Available for Future Consumptive Use under Compact Assumptions: Two methods are used to assess the amount of water that may be available for future consumptive use: 1) CRSS – Bureau of Reclamation model used for Federal planning and recent negotiations and 2) Hydrologic Determination – Mass balance analysis used in the 2007 Hydrologic Determination. Analysis also incorporates two separate assumptions, for purposes of this study only, for the Upper Division's potential compact obligation at Lee Ferry (75 MAF and 82.5 MAF) and the assumptions listed below:
  - Reservoirs
    - Simulated major federal reservoirs
    - Capacity adjusted for estimated sedimentation through 2060 per the Hydrologic Determination
    - Allowed use of CRSP minimum power pools
  - Evaporation
    - Consistent with Hydrologic Determination
    - Includes Lake Powell, Flaming Gorge and Aspinall reservoirs
    - Other evaporation chargeable to states
  - Inflows
    - Mass balance conducted at Lee Ferry
    - Hydrologic Determination used total inflow above Lees Ferry (not including Paria River)
    - CRWAS Phase I used total inflow above Lee Ferry (including Paria River inflow)
  - Depletions
    - Applied Upper Basin water use from the 2007 Hydrologic Determination.
    - Assumed that all Upper Basin states are physically using their full apportionments.
  - Estimated by StateMod
    - 1950-2005 natural flows and weather
    - Current irrigated acreage and M&I demands
    - Simulates diversions, crop CU, and evaporation
    - Excludes evaporation from Aspinall Unit and Navajo evaporation chargeable to NM
    - Excludes exports to New Mexico
  - Colorado Current Consumptive Use (~2.6 MAF)

Table 2 – Primary Phase I Findings Based on 2040 Climate Projections

Compared to current conditions, CRWAS Phase I findings show that projected future climate conditions may lead to the following changes to hydrologic conditions in the Colorado River Basin:

Temperature
- Increases basin-wide by 3.3 to 3.7 degrees Fahrenheit (deg F)
- Lower elevations show largest increase
- Increase occurs each month of the year

Winter Precipitation (Nov-Mar)
- Increases basin-wide by 6 to 13 percent
- Increases more in the northern part of the river basin
- Increases more at higher elevations
- Shifts from snow to rain in the shoulder months

Summer Precipitation (Apr-Oct)
- Decreases basin-wide by 4 to 10 percent
- Decreases more in the southern part of the basin
- Decreases less at higher elevations

Crop Irrigation Requirement (based on acreage and crop types identified in a 1993 acreage inventory)
- Increases basin-wide (2.6 to 6.7 inches per year for pasture grass)
- Increases basin-wide by 20 percent (based on current estimated acreage and crop types)
- Growing season for perennial crops increases basin-wide by about 15 to 22 days
- Increases more at lower elevations

Natural Flow
- Annual flow increases in some possible futures and decreases in others
- Annual flow generally increases in parts of the Yampa River basin and at higher elevation watersheds
- Annual flow generally decreases in south-western watersheds and at lower elevations
- Shifts toward earlier peak runoff
- Flow decreases in late summer and early fall

Modeled Streamflow
- Annual modeled streamflow decreases basin-wide, except in the Yampa River basin, and higher elevation locations in the Upper Colorado River basin
- Modeled Flow increases in April and May and decreases in later summer and fall months

Water Available to Meet Future Demands
- Higher elevations generally have less annual flow available to meet future demands, as a percent of modeled streamflow
- Available flow generally increases in April and May, corresponding to the shift in natural flow hydrographs

Use of Reservoirs
- Reservoirs show increased use (pool levels fluctuate more than historical)

Modeled Consumptive Use
- Increases in Yampa, White, Upper Colorado, and Gunnison basins by 4 to 18 percent
- Decreases in the San Juan and Dolores basins by 8 percent

Water Available for Future Consumptive Use based on Specific Compact Assumptions
- Estimates overlap with range of previous studies
- Water available under Colorado's compact apportionment may be limited under drier climate projections
- Same or higher unused water under its compact apportionment for the wetter climate projections (compared to historical period estimates)

Results presented in Table 2 are based on comparing conditions for the 2040 climate projections compared with historical conditions. The five 2040 projections selected for CRWAS proved to be representative of the distribution of the 112 available global climate projections, while the five 2070 projections selected for CRWAS proved to be not as representative of the distribution of the 112 available global climate projections as they are clustered on the low end of the distribution of 112 climate projections. Comparison of the distribution of 2040 and 2070 projections show that climate-induced effects on streamflow are very similar for the two time frames. Therefore, results presented in Table 2 and in the body of the report focus on the 2040 time frame. Results associated with the 2070 time frame are included in the report's appendices. Limitations to the modeling approaches used in the analyses and exceptions to the general findings in Table 2 are discussed in detail in the main report.

Conclusions and Recommendations

The CRWAS responds to the General Assembly's direction to the CWCB to provide information on how much water is available from the Colorado River basin to meet the State's water needs. As a starting point, the Phase I work presented in this report provides a water availability assessment based on existing levels of water use (also referred to as water demands) served by water rights that are currently being used ("perfected" or "absolute" water rights) and by interpretations of current operating and management practices for water diversion, storage and conveyance facilities. Assessments of water availability to meet future water needs are reserved for Phase II of the CRWAS.

Conclusions of the Phase I Study are summarized below:

- Interaction with the BRTs provided essential information to update and refine the State's hydrologic planning tools (including CDSS); improving model calibration and enhancing the representation of current water management.

- Computer models used in Phase I (including CDSS) proved appropriate to simulate current water uses (demands) and alternate hydrologic scenarios (historical, paleohydrology, and a broad range of equally-probable climate projections). The models were effective in simulating a broad range of possible future conditions associated with crop irrigation requirement, streamflow, consumptive use, and water availability that vary (in magnitude and time) with elevation and geographic region of the state.

- Phase I demonstrates a broad range of water availability for future Colorado consumptive use under various compact assumptions used for purposes of this Study. The upper end of this range lies within the range of previous studies, while the corresponding lower range suggests that Colorado may have no or limited additional water available for development.

- The primary underlying drivers for the broad range of Phase I results are 1) the inherent uncertainties in the available global climate models in projecting the magnitude and nature of future greenhouse gas emissions; 2) the complexity of modeling atmospheric circulation; and 3) down-scaling the resulting effects of changed temperature and precipitation on natural flows in an area the size of the Colorado River basin.

- Phase I results are based only on current water uses (consumptive and non-consumptive water demands). Stakeholders demonstrated strong interest in more than 30 Study presentations to expand analysis to include future demands and operating conditions.

The following recommendations are offered for consideration:

- *Continue refinements to the CDSS* – This Study, with its large geographic scale and detailed analysis, would not have been possible without the availability of the CDSS system. The process of presenting the Study's approach and tools in Phase I through the use of BRT meetings should continue in Phase II in close collaboration with the processes and programs of the CWCB Water Supply Protection Section and the Bureau of Reclamation's Colorado River Basin Study. A key element in developing additional CRWAS refinements is demonstrating openness and transparency in displaying hydrologic data, modeling procedures and calibration results. Specific CDSS refinements that should be considered include the following:
    - Revise baseflows in Plateau Creek based on information currently being developed by Collbran Water Conservancy District and the Division of Water Resources. Delivery of water from Vega Reservoir through the Southside Canal has a significant effect on both baseflows and the ability to meet future demands in Plateau Creek basin. Historical delivery records and locations of direct delivery to irrigated lands are being compiled and provided to the CRWAS study team. Incorporating this information into the Upper Colorado River StateMod model will greatly improve calibration and, therefore, confidence in simulated results.
    - Consider alternatives to representing the USFWS fish flow recommendations for the 15-mile reach in the Upper Colorado River model. As discussed in this report, the USFWS recommendations are modeled as an instream flow agreement. Although the flows are modeled as junior to other basin demands (therefore they cannot "place a call" on the river), the approach used in the current modeling effort allocates water to the demands, thereby decreasing the reported water available for future uses upstream.
    - Revise current release rules for reservoirs that operate for flood control to account for changes in timing of peak runoff. Four reservoirs in the Study basin (Green Mountain, Ruedi, Lemon, and Vallecito reservoir) release water for flood control based on target rules that reflect current inflow hydrographs. The climate projections indicate a shift in the peak runoff that would likely result in a change to flood control operations.
    - Consider revisions to Aspinall Unit reservoir operations. The Aspinall Unit reservoirs (Blue Mesa, Morrow Point, and Crystal) operate primarily for non-consumptive uses within and outside of Colorado. An EIS is currently in draft form that will revise reservoir operations.
    - Incorporate alternative transbasin demands affected by climate change. In Phase I, transbasin demands were not revised to reflect the effects climate change may have on current levels of demands in the South Platte River and Arkansas River basins. In addition, transbasin demands are dependent on eastern slope supplies. The State should continue their efforts to develop a South Platte StateMod model that can be used, along with the current western slope models, to better represent the basin inter-dependence. Combined with an Arkansas River StateMod model, the entire State could be modeled together to better understand how future statewide demands will be met under climate change.
    - Remove New Mexico structures from the San Juan/Dolores StateMod model. The current StateMod model for the San Juan and Dolores basins includes structures that divert and consume water in New Mexico. These structures, along with Navajo Reservoir, were included in the model to assist the State in identifying options to meet recommended fish flows for the San Juan Recovery Program. New Mexico structures are modeled as junior to Colorado demands, therefore, they cannot "place a call" on the river. However, the current modeling effort allocates water to these demands, thereby decreasing the reported water available for future uses upstream.

- *Incorporate new water management strategies and interpretations of existing operating rules and agreements* – Stakeholder input (in Phase I) shows that there are many potential interpretations of the methods in which water can be managed in accordance with state water law. Phase II should identify additional interpretations to compare the effects of additional future consumptive and non-consumptive water demands.

- *Use the CRWAS to support the CWCB / IBCC programs and continue use of the CCTAG* – The data and models used in Phase I should be used to support the many on-going programs of the CWCB and the IBCC. Phase I demonstrated the benefits of independent input from these groups. Colorado is in an enviable position in terms of its resident professional expertise in water resources planning and management, including climate change expertise in the state. Future studies should take advantage of the multiple CWCB / IBCC programs and the CCTAG as a cost-effective source of key technical review and enhanced credibility.

- *Recommendation to Stakeholders* – Phase I results help Colorado River stakeholders better understand potential effects of climate change on water available for future uses in Colorado. These results can be used by stakeholders to prepare for a range of future hydrologic conditions, to better deal with uncertainty in their water management decisions and to support development of their individual policies and programs. It is recommended that each stakeholder interpret the broad range of future water availability from its own perspective, considering its own assessment of the possible future conditions, its role in water management, the resources it has to adapt to alternative potential futures, and its tolerance for risk.