Preliminary Responses to Charge Questions **Attachment 2**

Climate Change Expert Feedback

Document Purpose

This is an overview of preliminary responses to a set of questions posed by the Metropolitan Water District of Southern California for the IRP process and the May 25, 2021 Board Workshop with the Climate Expert Panel. *This document is intended to inspire discussion and additional questions for discussion with the Climate Expert Panel during the Board workshop.* The following responses are structured to provide an overview of key points and suggested data and resources to guide a more in-depth review of the literature and science relevant to specific questions being asked related to climate change and water supply and demand for the primary geographies of interest (Southern California, Eastern Sierras, State Water Project, and the Colorado River Basin).

Useful definitions

- **Emissions:** The production or release of heat-trapping gases like carbon dioxide, methane, and nitrous oxide.
- **GCM:** General Circulation Models (GCM) are mathematical models that represent the general circulation of the atmosphere or ocean. These models are used to simulate future climate changes. Also known as Global Climate Models.
- **Downscaling:** Techniques employed to make global-scale information more applicable to regional or local scales.
- **Scenario:** Here we refer to two types of “scenarios”: 1) *Emission scenarios* (e.g., Representative Concentration Pathway (RCP) 4.5, 8.5), and 2) the scenarios being used by Metropolitan in the IRP process called the *Metropolitan's Future Scenarios* (A. low demand, stable imports, B. high demand stable imports, C. low demand, reduced imports, D. high demand, reduced imports). In general, a scenario is a plausible and often simplified description of how the future may develop based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios may be derived from projections, but are often based on additional information from other sources, sometimes combined with a narrative storyline (IPCC, 2012).
- **Uncertainty:** Uncertainty is often categorized in two ways: 1) the kind that will always exist (e.g., inherent randomness natural to a process) and, 2) the kind that can be reduced with improved understanding or data (e.g., improving model structures or parameters, improving quality of observations) (from SECURE web portal).
- **Drivers:** Impacts that influence supply and demand outcomes that are outside Metropolitan's control.
- **Climate Drivers:** Key determinants of our overall climate. For example, temperature, precipitation, wind speed, dew point, soil moisture, and sea surface temperatures.
- **Drivers of climate drivers:** Various feedbacks of the Earth system that influence the climate drivers (e.g., emissions of greenhouse gases, how much carbon will be taken up by forests globally, will oceans continue to be a carbon sink, ice loss from Antarctica, feedbacks from warming polar regions like changes in albedo and methane releases from melting permafrost).
- **Signposts:** In other contexts for the IRP, ‘signposts’ are data and/or signals that help managers determine trajectories of variables of interest such as supply and demand. In the climate context, for this document, the only ‘signposts’ of interest are the ‘drivers of climate drivers’.

Q1. What major components contribute to the range of future climate outcomes?

Key Points:

- California is already warming and experiencing a range of impacts of a changing climate.
- These impacts span everything from changing precipitation patterns, rising sea level, declining snowpack, increased drought, increased extreme precipitation events and an expansion in the area burned by wildfires. All of these impacts have implications for understanding future supply and demand for water resources in California
- How much climate changes and the extent to which we experience changes in the intensity or severity of many of these impacts is related to global emissions of greenhouse gases which directly determine how much warmer the planet will get and how well we plan and manage for these changes.
- How well we can project future climate changes is limited by global, regional and local climate and hydrologic modeling techniques. However, models have performed well against observed warming (Figure 3) and are the best source of information we have to understand future climate.
- Being a savvy consumer of future climate change information is required to ensure proper use and application of these data in water resources management and planning (see Q2-4 for more on modeling techniques and Q8 for more on planning with this uncertainty) .

First, we know that climate change, and the impacts of a changing climate, are already here. We also expect many of these impacts to worsen in the future. Figure 1, from the 4th National Climate Assessment (2018), shows that widespread warming is already occurring across the Western United States.

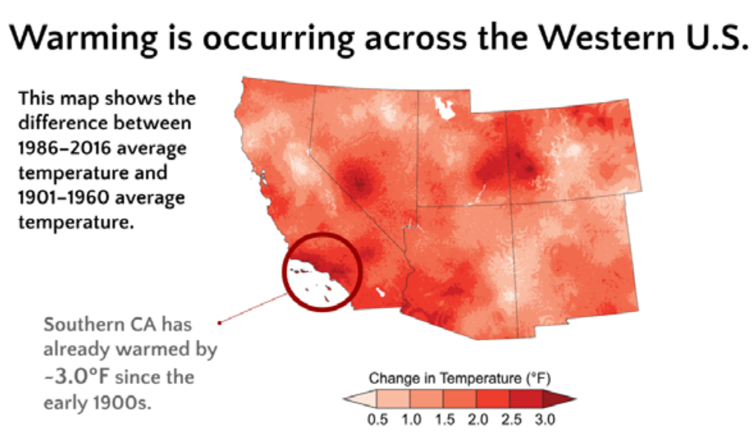

Figure 1: This map shows the difference between 1986-2016 average annual temperature relative to average annual temperature from 1901-1960. Southern California has warmed by nearly 3.0°F since the early 1900s. Source: Modified from the 4th National Climate Assessment Southwest Chapter, 2018.

California’s Fourth Climate Change Assessment summarized the impacts and direction of change expected to be experienced in California as the region continues to warm (Figure 2).

CLIMATE IMPACT	DIRECTION	SCIENTIFIC CONFIDENCE FOR FUTURE CHANGE
TEMPERATURE	WARMING ↗	Very High
SEA LEVELS	RISING ↗	Very High
SNOWPACK	DECLINING ↘	Very High
HEAVY PRECIPITATION EVENTS	INCREASING ↗	Medium-High
DROUGHT	INCREASING ↗	Medium-High
AREA BURNED BY WILDFIRE	INCREASING ↗	Medium High

Figure 2: A summary of California climate impacts, the anticipated direction of change, and the scientific confidence associated with each impact. Source: California's Fourth Climate Change Assessment, 2018

When thinking about how to understand the range of outcomes for these impacts in the *future* we have to consider the following primary components:

1. Human choices:

- ***Emissions Scenarios:*** The principal driver of long-term warming is total emissions of carbon dioxide (CO_2) and other greenhouse gases. This is a human choice. The Representative Concentration Pathways from the Intergovernmental Panel on Climate Change (IPCC) and Coupled Model Intercomparison Project (CMIP) climate model (Moss et al., 2010; Collins et al., 2013), have been designed to cover a wide range of possible magnitudes of climate change driven by different socioeconomic pathways, that include differing amounts of greenhouse gas emissions.
- ***Systems management:*** Choices made today to be proactive rather than reactive to future climate impacts in how systems, like water infrastructure, are managed and designed.

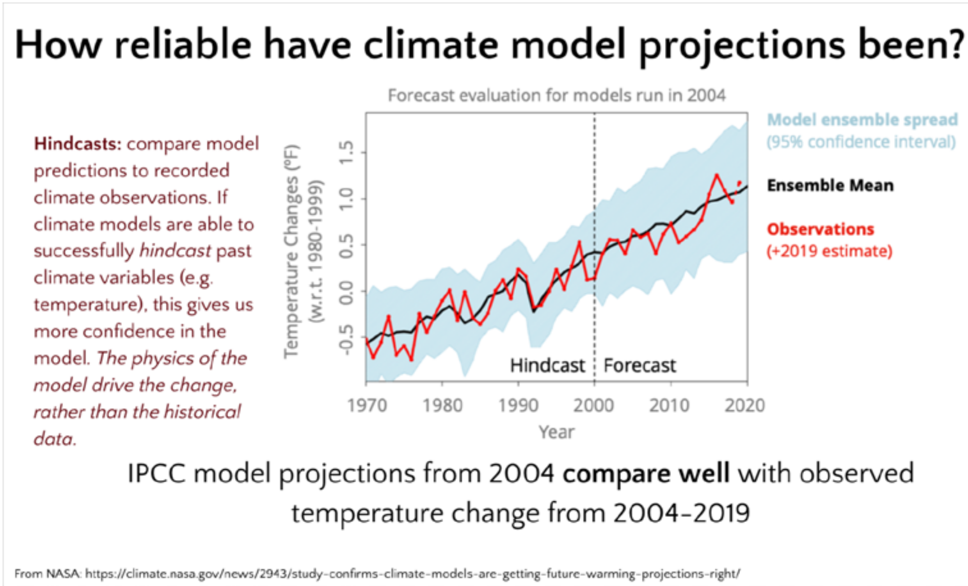

Figure 3: This graph from NASA shows how climate models run in 2004 to project change out to the year 2020 performed against actual observed change in temperature. The data show that model projections compare well with the observed temperature change that occurred between 2004 and 2019.

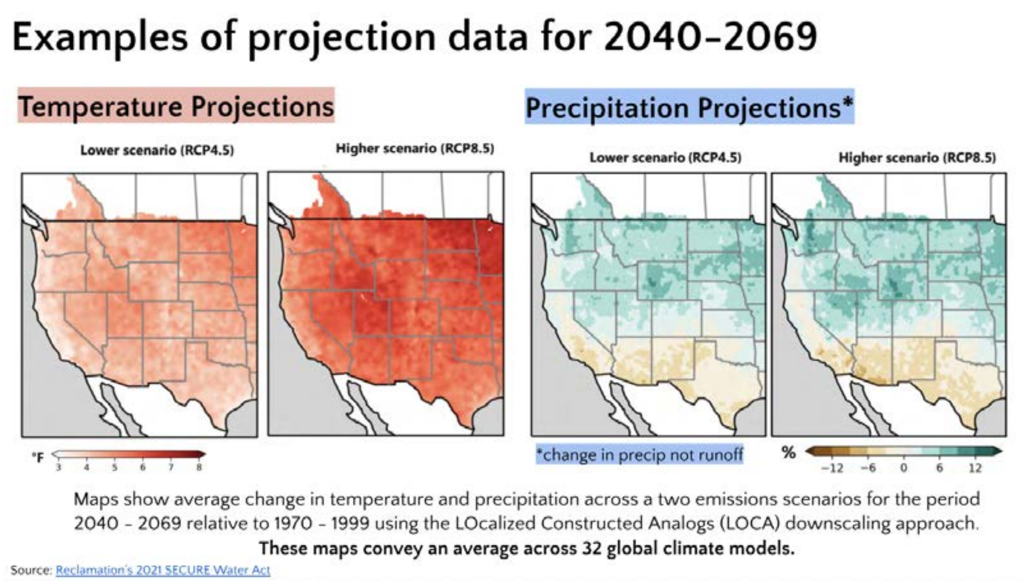

Figure 4: Examples of climate projection data from the LOcalized Constructed Analogs (LOCA) downscaling approach. The panels show temperature (left) and precipitation (right) projections for mid-century (2040-2069) under both low and high emissions scenarios. The change shown is relative to the time period 1970-1999. Note that precipitation projections are not runoff projections. Source: Modified from Reclamation's SECURE Water Act report (2021).

2. Natural Variability:

Natural variability is influenced by processes internal to the climate system that arise, in part, from interactions between the atmosphere and ocean, such as El Niño/La Niña events. The sun, volcanic eruptions, and changes in the orbit of the Earth around the sun all influence the climate. Natural variability and human-caused climate change work together to shape the climate at any given point in time. In global climate models, internal variability is often used as a proxy for natural variability.

3. Model Uncertainty:

Representing complex Earth climate systems and sociopolitical pathways in global climate models, downscaled and regional climate models and hydrologic models all lead to some uncertainties in future climate conditions.

The primary sources of uncertainty in future climate projections include uncertainty related to the emissions pathway, model uncertainty, and internal variability (see Figure 6). The Bureau of Reclamation's West-wide Assessment (2021) provides more details, and summarizes these factors well in the following statement:

> "Uncertainties in future projections stem from the inability to predict future global socio-political developments, incomplete understanding of complex system processes, imperfect representation of those processes in models, and irreducible natural variability. Numerous decisions must be made to generate usable projections, and each has associated uncertainties: choice in scenarios of greenhouse gases (uncertainties in human behavior); choice of models used for global climate simulation; choice of model initial conditions; choice of climate downscaling techniques; and, choice, configuration, and calibration of hydrologic models, as examples."

Q2. How do we apply global climate model outputs that examine climate change over a long timeframe to the shorter 25-year IRP planning horizon?

Key points:

- While changes are not as big as those seen by the end of the 2100s, climate changes are still apparent in the GCMs in the next 25-40 years. These changes are still significant to water management, especially when you consider the range of future projections (not just averages). Both the higher and lower ends of the mid-21st century range would provide useful comparison points.
- The sources of uncertainty (i.e., the range of future projections) differ depending on what time period you are most interested in exploring.

A. An illustration of the ranges from mid-21st and late-21st century projections:

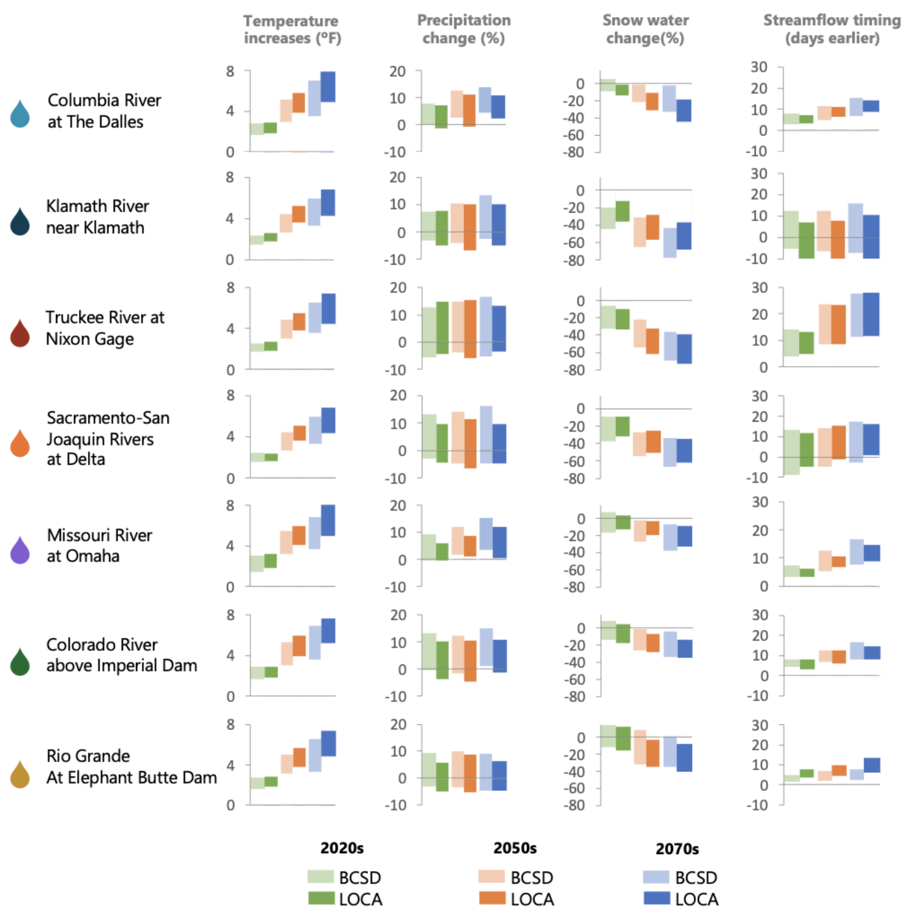

Figure 5: Climate change projection in seven basins across the Western US over the next century. Values represent the mid-range (the 25th to 75th percentiles) of future hydroclimate projections from future decades relative to 1990 - 1999. These include values from the 2016 SECURE Report using BCSD (one type of downscaling) with RCP2.5, RCP4.5, RCP6.5, and RCP8.5 (displayed as lighter shades on the left), and from another type of downscaling, LOCA

projections using RCP4.5 and RCP8.5, on the right. Source: [Reclamation's SECURE Water Act report](), see report for a map of the locations and additional details.

Take away from Figure 5 as it relates to the question: The ranges of the orange (2050s) have changes that are large, even if not as large as the full range of the blue (2070s), they are still important to consider.

B. How uncertainties differ depending on the time period of interest: In global climate models, the source of uncertainties--internal variability, model uncertainty, or global emission scenario uncertainty, as outlined in Q1 above--depends on how far into the future the projections are.

Figure 6 provides an illustration. For global temperature, the uncertainty (i.e., range in projections) in the mid-21st century is from both model uncertainty and global emission scenarios (blue and green lines). At the end of the century, global emission uncertainties have a greater influence on the range in future projections than model uncertainty (green line increases over time).

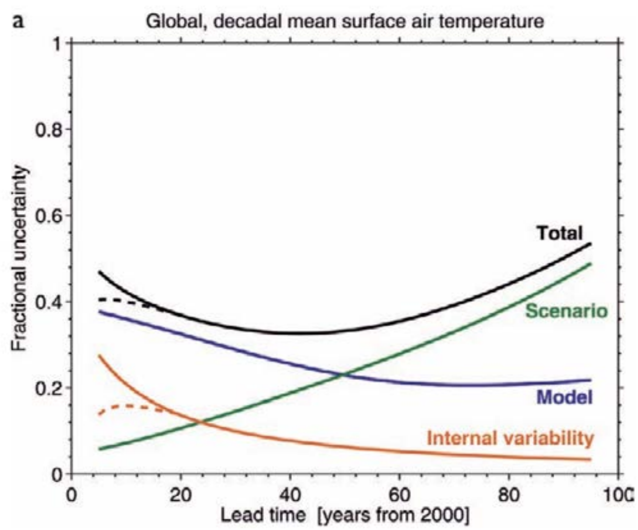

Figure 6: The relative importance of each source of uncertainty in decadal mean surface temperature projections is shown by the fractional uncertainty (the 90% confidence level divided by the mean prediction) for (a) the global mean, relative to the warming from the 1971–2000 mean. Source: Hawkins and Sutton 2009

Q3. What approaches or methodologies do you recommend for quantifying how climate change (e.g., changing temperatures and precipitation) affect Southern California and its imported supply watersheds

Key points:

- To better understand potential impacts of global climate change at regional or local scales, there are many methods one can use.
- Hydrologic projections (otherwise known as "climate change scenario studies" or "chain-of-models approaches") are commonly used in climate change assessments.
- Regardless of the method/s used (see Q4 on ways to select an appropriate method), it is important to recognize there should be a range of possible outcomes. Models, while helpful tools in exploring possible futures, cannot predict the future.

A. Details on different methods: Below is a brief overview of four approach categories from Vano et al (2018) "Dos and Don'ts." This is not an inclusive list, as more exist, and more will likely be developed.

1) Climate change scenario studies: These approaches are often characterized as a chain-of-models approach where global climate model projections are downscaled and the downscaled climate change information (e.g., 30 years of daily precipitation, temperature) is then used as input to hydrology models, which generate streamflow and snowpack information, which can be used as input to reservoir operations models. This type of study is often the focus of existing guidelines because it most explicitly uses global climate model information and often requires decisions on model selection to translate global information to a local scale.
2) Paleoclimate studies: Paleoclimate or paleoflood information is generated using information collected from the environment which can be proxies for past climate and flood events that date back further than the instrumental record (e.g., the width of tree rings can be correlated with streamflow) (Woodhouse et al. 2006). These analogs from the past can date back thousands of years, and provide improved perspectives on natural variability, such as the length of dry periods (Woodhouse and Lukas 2006), the characteristics of past floods (Raff 2013) or how sensitive river basins are to temperature increases (Lehner et al. 2017a). Studies have also used a combination of scenario-based and paleoclimate studies to evaluate future change (Reclamation 2011a; McCabe and Wolock 2007).
3) Stochastic hydrology studies: stochastic precipitation and hydrology timeseries can be used to stress test a system (Rodriguez-Iturbe et al. 1987; Salas 1993; Wilks and Wilby 1999; Yates et al. 2003; Erkyihun et al. 2016). The perturbations can be informed by historical information (e.g., paleoclimate information) or by global climate model trends. These techniques aim to avoid some of the uncertainties associated with using global climate models directly, yet address risk-based issues analytically (Olsen et al. 2015). In many cases, stationarity is assumed, although there are techniques that have

included non-stationary stochastic methods (Kilsby et al. 2007; Erkyihun et al. 2016). It is, however, important to recognize that these timeseries are based on statistical models that do not capture process-based understandings, which limits how these can be used to interpret future change.

4) Climate-informed water system vulnerability analysis: These approaches are commonly referred to as decision support modeling and include techniques such as decision scaling (Brown et al. 2012), scenario-neutral approaches (Prudhomme et al. 2010), and robust decision making (Lempert et al. 2003). Typically, the focus is first on defining the decision context and exploring sensitivities by perturbing the climate incrementally to identify system vulnerabilities to changes in temperature, precipitation, or other climate variables before considering whether and how to apply climate change information (Brown et al. 2012; Brown and Wilby 2012; Weaver et al. 2013). EPA and CWDR (2011) describe strengths and limitations of using different decision support tools.

B. More details on hydrologic projections (also referred to as climate change scenario studies): For hydrologic projections, a commonly used approach, each step in the climate impacts modeling chain (first column of the Figure 7 below) has uncertainties. While several studies have sampled the range of possible outcomes by varying elements at each step (second column), they are typically limited. Larger ensembles can reveal a more complete range, but can be computationally impractical in applications, and thus require the development of innovative methods to assess climate impacts.

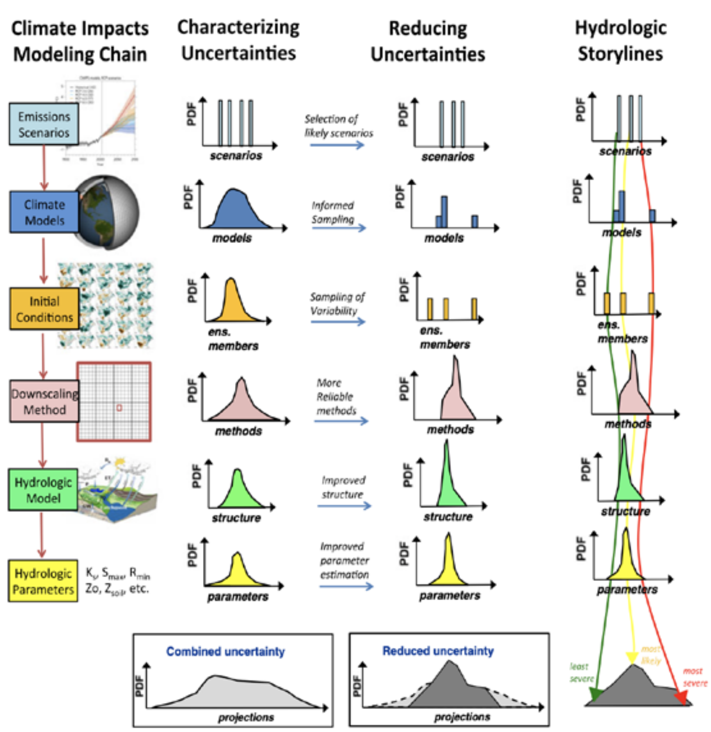

Figure 7: Schematic on approaches to explicitly characterize and reduce uncertainties in assessments of hydrologic impacts of climate change. Source: Clark et al. 2016

C. More details on how models can be useful tools: Vano et al. (2018) "Dos and Don'ts" provides useful advice about how models can be used appropriately:

"Models are useful tools, if used appropriately. Watershed-relevant climate change scenarios can provide information useful in assessing how the system is vulnerable to climate change and help identify adaptation options.

To generate climate change information at the global, planetary scale and make it relevant to local watersheds, many methodological choices must be made by both information producers (on how to generate the datasets) and users (on how to apply the climate data to their decision). In the U.S., for example, the U.S. Army Corps of Engineers has 21 regional reports (http://www.corpsclimate.us/rccciareport.cfm) and Appendix A in Bureau of Reclamation's (Reclamation) Literature Synthesis on Climate Change Implications for Water and Environmental Resources (Reclamation 2013) lists over 300 papers that could be leveraged as examples. In Europe, the Service for Water Indicators in Climate Change Adaptation (SWICCA) currently provides 15 case studies (http://swicca.climate.copernicus.eu).

Models, including global and regional climate models, as well as watershed models, are used to explicitly characterize possible futures as well as historical and current conditions. These simulated futures, often referred to as projections, when used together with simulated historical conditions, can then be used to assess potential changes. More specifically, evaluating relative differences (modeled historical vs. modeled future) in system performance over time can provide improved perspectives on potential improvements as well as risks . In this, it is important to recognize that **model outputs are not intended to be predictions, and should be treated instead as possible future 'scenarios' which can complement existing monitoring and performance evaluation systems.** They provide an opportunity to explore how natural and managed systems may respond to and influence future changes and to investigate uncertainties (Weaver et al. 2013; IPCC 2014b; Milly et al. 2015; Reclamation 2016). Scenarios can be viewed as narratives that can be used to stress-test water systems and infrastructure (Moss et al. 2010; Weaver et al. 2013). As such, a single stress test can be misleading when viewed in isolation; multiple stress tests, especially when they span a range of possible stresses, are preferred and can be added to as resources and time permit.

In performing these stress tests, current approaches often capitalize on "ensembles of opportunity" – that is, collections of available datasets – to evaluate the range of future impacts and their uncertainties. This may be the most appropriate path forward at present; although as the field of climate change impacts advances and computing capacity improves, it will be possible to better understand and quantify underlying uncertainties (Harding et al. 2012; Gutmann et al. 2014; Clark et al. 2016), evaluate and account for model dependencies (Knutti 2010b; Knutti et al. 2013; Bishop and Abramowitz 2013), and improve how models are selected for use including ensuring they capture features that make them appropriate for particular uses (Knutti 2010a; Tebaldi et al. 2011; Sanderson et al. 2015)."

The DOS AND DON'TS review important considerations when designing studies so models can be useful tools in exploring future change.

Another relevant resource is the Climate Change Handbook for Regional Water Planning. It was created in the California Department of Water Resources in partnership with the U.S. Environmental Protection Agency, Resources Legacy Fund, and The U.S. Army Corps of Engineers. It is on a list of resources for water managers, where they describe the report as: a framework for considering climate change in water management planning. Key decision considerations, resources, tools, and decision options are presented that will guide resource managers and planners as they develop means of adapting their programs to a changing climate.

Q4. What models and downscaling techniques are available and appropriate for the relevant regions?

Key Points:

- Downscaling refers to techniques employed to make global-scale information more applicable to regional or local scales. There are a variety of different downscaling techniques that are used to produce regionally downscaled climate information. These techniques are continually underdevelopment and significant advancements have been made in recent years, and this work is likely to continue to evolve.
- Practitioners should consider what variables (e.g., seasonal temperature changes, annual precipitation) are of greatest interest to help identify models that would be most appropriate.
- There is a range of data available to support modeling efforts.

A. Detail on different types of downscaling techniques.

Neil Berg at UCLA's Center for Climate Science shared details on different types of downscaling techniques during a technical training in 2018. See the presentation here.

Typically downscaling is thought of as either statistical or dynamical, although increasingly there are approaches that are hybrids. As such, it is helpful to view these approaches as lying along a continuum of increasing methodological complexity, and acknowledge that they have various tradeoffs: physical realism v. computational cost; single realizations v. ensembles; explicit physics/feedbacks v. simplicity. Which approach is best depends on the question being asked.

Statistical downscaling: Commonly used approaches include BCSD and LOCA which have been used in the National Climate Assessment, Reclamation's SECURE Water Act report and MACA which has been used in water demand analysis within Reclamation's SECURE report and fire simulations (Abatzoglou & Williams, 2016). (all these provide values that are across the West)

Dynamical downscaling: Because they require more computing time, they are often used more locally in individual studies. There are, however, some efforts to do intercomparisons across regional climate models in the US (e.g., NARCCAP, CORDEX).

Hybrid dynamical-statistical approaches: Two examples: Alex Hall at UCLA has led the development of a hybrid approach; it was used in a precipitation study done over Los Angeles. Ethan Gutmann at the National Center for Atmospheric Research has led the development of a hybrid approach (ICAR), which has datasets for the US.

B. How to determine appropriate models: Vano et al. (2018) "Dos and Don'ts" provides useful advice about how to determine appropriate models based on the impact/s being evaluated. This advice applies to models and downscaling techniques.

"Ideally, models should represent all relevant processes well. If certain processes are poorly captured, the model's ability to simulate the climate sensitivities of dominant processes could be in question. Yet models will always be limited by being simplifications of the real world (Clark et al. 2008; Carslaw et al. 2018). Therefore, for practical purposes, models are most often evaluated on how well they do at simulating key, measurable processes, especially those relevant to the impact of interest. For example, if the decisions relate to flooding, then hydrology model performance on short timescales matters. If, however, the decisions relate to water needs for drought, performance on shorter timescales may be less relevant. Evaluations should include how well model outputs are simulated historically (what is the current ability to simulate the variable of interest) and how sensitive they are to an altered climate. The latter can be done through evaluating whether modeled values respond accurately to a range of different climate conditions or through simple perturbations of the most relevant climate variables (e.g., Vano et al., 2012). This does not provide a comprehensive evaluation of how well future changes can be simulated, as this may not be knowable, but it can provide confidence that model sensitivities are physically reasonable and that further exploration using a model or approach is warranted. Additionally, techniques exist that can be used to evaluate how well a model performs under climatic conditions significantly different from those it was developed to simulate (Refsgraad et al. 2013)."

Here are a series of questions (shared during a technical training), that can be useful in identifying what models to use:

- Where is the area of interest?
- How large of an area?
- What is the impact of interest?
- When in the future?
- Does event sequencing matter?
- What type of climate uncertainty is important?
- What is available?

C. Examples of Available Data (shared during a technical training)

Statistical Approaches and Hydrology simulations are on the Green Data Oasis portal
- BCSD (12km), LOCA (6km)
- VIC streamflow

Dynamical Downscaling
- NARCCAP (50km),
- CORDEX (limited 25km)
- Others over regional domains or limited time periods

USGS GeoDataPortal
- Collection of different archives

Many others (NASA NEX, ARRM)

Q5. If the models and downscaling techniques differ for each region, how do we ensure internal consistency within the analysis?

Key points:

- This is not an uncommon challenge. It is better to use the model that captures the impact of interest for a particular question/region vs. trying to use a model that is universal.
- The most important thing is to be sure choices are placed in context. To be consistent, one approach would be to use similar GCMs, downscaled in ways most appropriate to the questions of interest. Another approach would be to consistently look at an ensemble of models and results that are 90% and 10% of the range (see example below for why Reclamation decided to use 90% and 10%, Metropolitan may choose different percentiles.)
- No model is perfect and cannot provide all the answers. They are one tool in the toolbox.

More details on defining the range:

For example, see the description in Reclamation's report in 2016 on "Considerations for Selecting Climate Projections for Water Resources, Planning, and Environmental Analyses"

"*Define the Range of Uncertainty to be Considered:* For each metric, study teams must define the range of uncertainty to be considered in their analysis. The range of uncertainty is typically represented as a range of percentiles that correspond to the higher end of the range of projected change, the middle or central tendency, and the lower end of the range of projected change. The central tendency is defined by the 50th percentile (median). In order to represent the range of projected climate change, the 10th and 90th percentiles, for example, encompass 80% of the values of a given metric while excluding the highest 10% and lowest 10% of values; similarly, the 20th and 80th percentiles encompass 60% of values while excluding the highest 20% and lowest 20%. Selecting a larger range of uncertainty results in considering a broader range of future climate conditions in the study, but bears the risk of including outlier values. By contrast, selecting a smaller range of uncertainty results in considering a narrower range of future climate conditions, but reduces the risk of including outlier values. In general, selecting projections based on the 10, 50 , and 90 percentiles is appropriate for most studies."

Q6. What hydrologic changes are anticipated for the relevant regions?

Key Points: This is a question that lengthy reports are written on. We will expand on this question throughout the course of our work with Metropolitan. To provide an illustration of some of the material we could provide, we share some highlights below. New information shared here focuses on the Colorado River basin.

Southern California and Eastern Sierra Precipitation: We provided Metropolitan a document addressing the question "*What are the plausible ranges in the quantity and pattern/timing of precipitation with a specific focus on Southern California and the Eastern Sierra (supply source for the LA Aqueduct)?*" The key summary points are copied below; see the document for more details.

In the future, in both Southern California and the Eastern Sierra:

1. Wet extreme events are projected to increase (e.g., storms bring more water)
2. Dry years are projected to increase (e.g., droughts increase)
3. Wet and dry swings are expected to be amplified
4. Annual average precipitation changes (e.g., averaged over 30 years) are small and unclear
5. Seasonal changes indicate statewide increases in precipitation in winter, decreases in spring
6. Snowpack will decline, increasing cold season and decreasing warm season streamflow (most relevant to Eastern Sierra)

Climate Changes in the Colorado River:

1. Warming temperatures are increasing evaporation which in turn is decreasing the amount of precipitation that turns into runoff
2. Colorado River runoff will likely decline by mid-century, potentially by large amounts
3. Reservoir evaporation will increase
4. Crop water demands will increase
5. Spring runoff will occur earlier
6. The Salton Sea is expected to continue to decline

Colorado River Basin Runoff Projections

Multiple studies since 2007 have attempted to assess how runoff in the Colorado River Basin will change in the 21st century. Current best guess runoff projections range from approximately +5% to -40% by mid-century with most projections indicating a decline (See Milly and Dunne, 2020, Lukas and Payton, 2020). Rising temperatures are a certainty and will increase ET, which in turn will reduce river flow. Because ET is about 80% of precipitation, every 1% increase in ET translates to a substantially larger 5% drop in river flow. Changes in precipitation can either reduce these temperature-induced declines or enhance them. Confidence in modeled precipitation is much lower than temperature and is the main reason why the range is so great. With no changes in long term precipitation[1], a reasonable assumption would be river flow declines -15% to -25% by mid-century. (Note that the current ~20% decline is approximately split between a temperature-induced decline and a precipitation decline. Thus, a future -15% to -25% decline due solely to temperature increases would become -25% to -35% with the current precipitation decline.

It is important to note the precipitation is not runoff, and that increases in precipitation may not lead to increases in runoff. It is quite possible that additional precipitation turns into evapotranspiration, as does approximately 80% of all precipitation in the Colorado River Basin now. Studies on future megadroughts indicate that megadroughts can occur even with substantial additional precipitation if it is warm enough.

Five important peer-reviewed papers in the last 5 years have provided useful insights into future flow. We know that runoff efficiency for a given amount of precipitation has declined (Woodhouse et al., 2016) that up to half of the approximately 20% flow decline since 2000 is due to human causes (Udall and Overpeck, 2017, Xiao et al, 2018, Hoerling et al, 2019, Milly and Dunne 2020) and that warming temperatures of over 1°C are reducing the flow by up to nearly 10% per degree Celsius temperature increase. Two papers have projected flow losses of up to 40% by mid-century (Udall and Overpeck, 2017, Milly and Dunne, 2020). An additional paper states that the American Southwest is now in a 19-year long 'megadrought' as measured by the 2nd lowest soil moisture in the last 1200 years (Williams et al, 2020). Without human-caused warming, this drought would be modest.

Most of these papers have focused on the impacts of the unequivocal, human caused, greater than 1°C temperature increase since the mid-20th century. The modest recent precipitation decline (~3%) could be natural variability, but one paper found human fingerprints on this deficit (Hoerling et al, 2019). If true, there are reasons to believe that the decline will not only continue but get worse, greatly amplifying the known temperature-induced flow losses. Such precipitation declines, along with temperature increases, are what push some runoff projections to -40% by mid-century.

In addition, recent runoff trends are worrisome. In the last two years, reasonable winter snowpacks have turned into very low runoff, with 100% of snowpack becoming 52% of runoff in 2020 and this year 80% turning into less than 30%. Record setting hot and dry periods in the summers of 2019 and 2020 dried soils significantly. Dry soil moisture from the previous year must be filled before runoff occurs in the next year. We should expect more, and worse, of these dry and very hot summer periods going forward, not fewer.

Changing Colorado River Runoff Patterns

Modeled future precipitation consistently shows a North to South gradient, with declining precipitation in the south and increasing in the north. The dividing line is often near the middle of the state of Colorado, but varies by model. Modeled precipitation in the Lower Basin is robustly projected to decline but the impacts of this have been little studied. Of particular concern to MWD would be declines of inflows in the Grand Canyon. These inflows are about 750 kaf/yr, about 5% of the total flow. Declines in these flows would translate directly into water availability in the Lower Basin and increases in Lower Basin shortages. Importantly, they are not part of the Colorado River Compact Section III (d) 75 maf over ten-year “delivery” clause and thus there is no valid claim that these flows are owed to the Lower Basin. In the overall scheme of Colorado River water deliveries to the Lower Basin, declines of up to half of these flows would be about 5% Lower Basin deliveries (375 kaf out of 8.25 maf), but such declines would increase the already substantial pressures to reduce water consumption in the Lower Basin and Arizona, especially.

Changes in Colorado River Runoff Timing

Runoff timing has advanced by 1 to 4 weeks (Clow, 2010, Lukas and Payton, 2020), and is expected to advance several weeks more by mid-century. (See figure below that shows a peak in early May compared to mid-June historically.)

Changes in Colorado River runoff timing do not have direct implications for MWD, as the water can generally be captured in storage. (This is not true for direct flow diverters in the Upper Basin who may have to change practices to utilize earlier runoff.) However, there are important indirect effects. Early runoff promotes greater ET as soils are exposed for longer periods of the year which in turn promotes more evaporation and transpiration by plants. This then can lead to runoff reductions in the following year (Das et al., 2012).

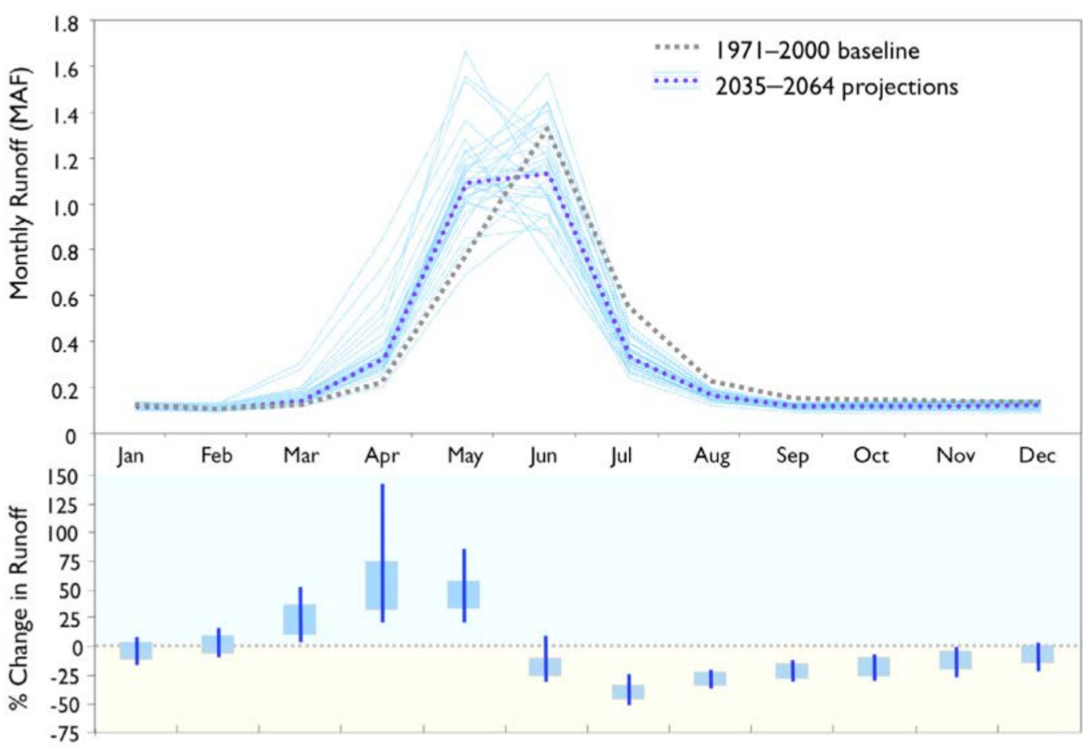

Figure 9: Projected monthly runoff change for the Colorado River headwaters from ~2050 (2035-2064) under moderate emissions (RCP4.5) from the CMIP4-BCSD. Projected average monthly flows for 31 projections (light blue lines) and the ensemble median (dark blue dotted line) compared to the 1971-2000 baseline (gray dashed line). The bottom panel shows the corresponding ranges of the monthly runoff changes from the model ensemble; the dark blue bars show the range from the 10th to 90th percentile and the light blue boxes show the 25th to 75th percentile. **As the hydrography shifts earlier, March-May runoff increases while June tends to decrease, and July-September runoff sharply decreases in all projections**. For original figure caption and data please see the State of the Science, 2020, https://wwa.colorado.edu/publications/reports/CRBreport/.

Dust on Snow Impacts on Colorado River Flow

Dust on snow has been found to advance runoff timing by up to 3 weeks and to reduce river flow by up to 5% (Painter et al., 2010). Drought in the Southwest has been associated with increases in the dust deposition that is responsible for runoff reductions and early melting. It has been hypothesized that severe future droughts could cause additional dust. Were dust to increase, the flow would decline modestly to 6% but runoff timing would advance by an additional 3 weeks (Deems et al., 2013) The advances in runoff timing due to dust are substantially larger than caused by warming. Dust physically darkens the snowpack which allows for much more solar energy to be absorbed thus hastening melting. There is some evidence that human interventions could reduce some of the impacts of dust (Duniway, 2019).

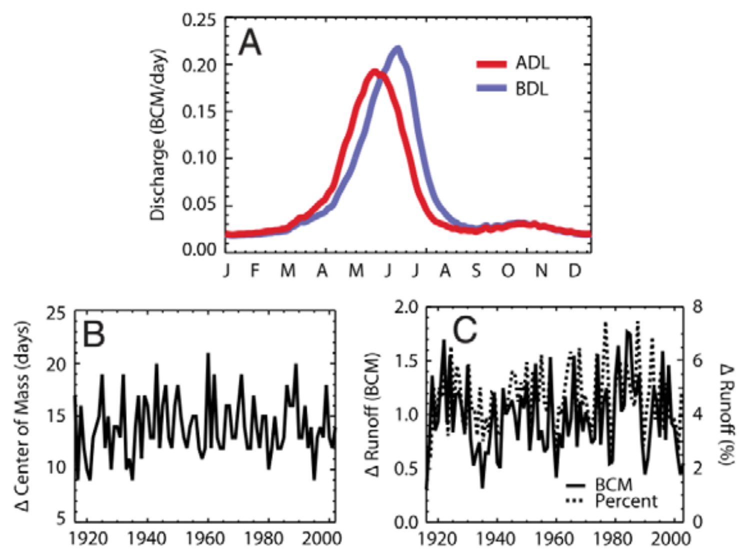

Fig. 2. Differences in runoff timing and volume between ADL and BDL dust scenarios. (*A*) Mean discharge at Lees Ferry, AZ on the Colorado River for ADL and BDL scenarios across the period 1916–2003. (*B*) Time series of BDL versus ADL Δ runoff in billion cubic meters across 1916–2003. (*C*) Time series of BDL versus ADL Δ runoff in percent of ADL runoff.

Figure 10: Differences in runoff timing and volume at Lees Ferry between After Dust Loading (ADL) and Before Dust Loading (BDL). Total runoff volumes are the areas under the curves. Note that the red ADL line shows earlier and lower total runoff -- i.e., the enclosed area from the red line to the blue line on the left is smaller than the enclosed area from the red line to the blue line on the right. Source: Painter et al., 2010.

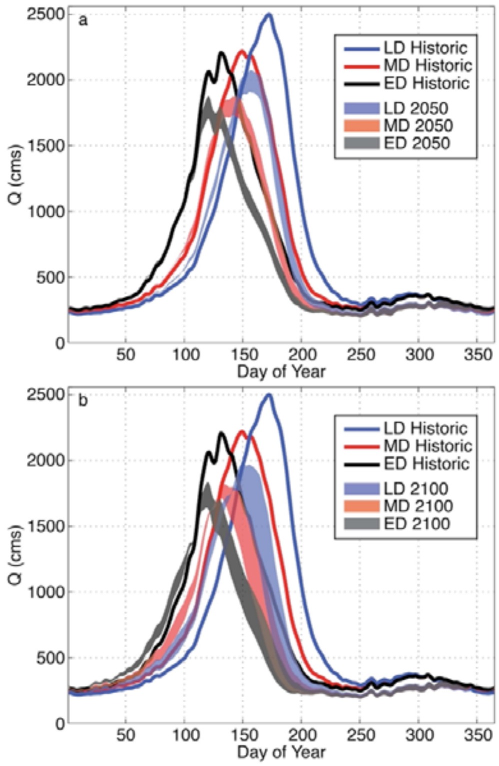

Fig. 8. (a) Mean annual hydrograph at Lees Ferry, showing moderate dust (MD), low dust (LD), and extreme dust (ED) historic traces and mean annual hydrograph for all three dust/albedo scenarios, for decade centered on 2050; colored areas show the range in hydrograph response between B1 and A2 emissions scenarios; and **(b)** as in **(a)**, but for the decade ending 2100.

Figure 11: Lees Ferry runoff at 2050 (a) and 2100 (b) under Low (LD), Moderate (MD) and Extreme (ED) dust. The lines are for the historic period and the ribbons represent future warming under lower (B1) and higher (A2) greenhouse gas emissions. Under historic conditions (lines) MD and ED lines shift to earlier runoff but show about the same runoff volumes. Under climate change (ribbons) LD shows both a shift in runoff timing and lower runoff volume. MD and ED under climate change show similar volumes but ED runoff timing is advanced into spring. Source: Deems et al, 2013.

Increasing Colorado River Evapotranspiration (ET) Demand

Multiple studies as noted above have shown that increasing ET is the root cause of up to half of the decline in Colorado River flows. These data are often not directly published but would be available as hydrology model outputs. Data from Milly and Dunne (2020) show increases in basin wide ET of approximately 3% since the 1930s, with much of these increases occurring during the last 20 years. Milly and Dunne note the importance of the earlier loss of snowpack, which decreases the Earth's reflectivity ("albedo"), and that in turn allows for increases in all forms of evaporation, including transpiration. Winter sublimation, the direct conversion of snow to water vapor, will also increase as it warms although this amount has not been projected. Sublimation is very dependent on wind and future changes in wind are not well understood.

Increasing West Wide Crop Demands

Reclamation studied how climate change will affect crop demands in 2015. They found a 12% increase across the West, with greater increases occurring in the South (Rio Grande) and lesser increases in the north (Columbia). Perennial crops increased the most, while annual crops may be able to be planted and harvested earlier, minimizing the impacts of increasing temperature on ET. The study used a modern, physically-based method to calculate ET, unlike some older studies using inaccurate temperature-based methods.

BCSD Irrigation Demand and Reservoir Evaporation Projections

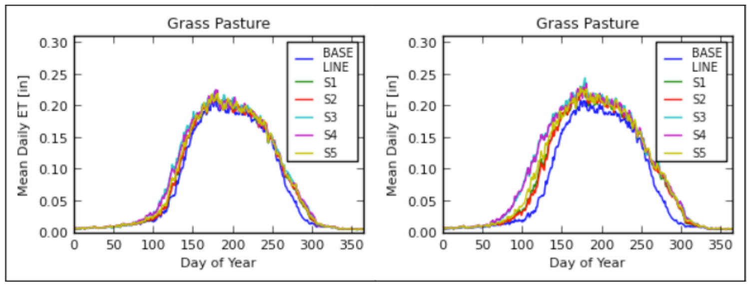

Figure 20.—Colorado River Basin – COOP station WY6555 (Mountain View, WY). Baseline and projected mean daily grass pasture evapotranspiration for all scenarios and for time periods 2020 (left) and 2080 (right).

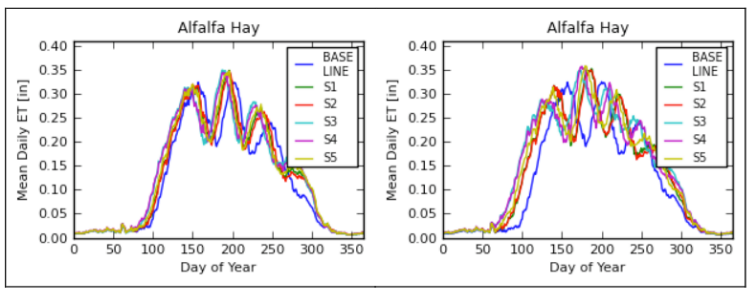

Figure 21.—Colorado River Basin – COOP station UT5969 (Myton, UT). Baseline and projected mean daily alfalfa evapotranspiration for all scenarios and for time periods 2020 (left) and 2080 (right).

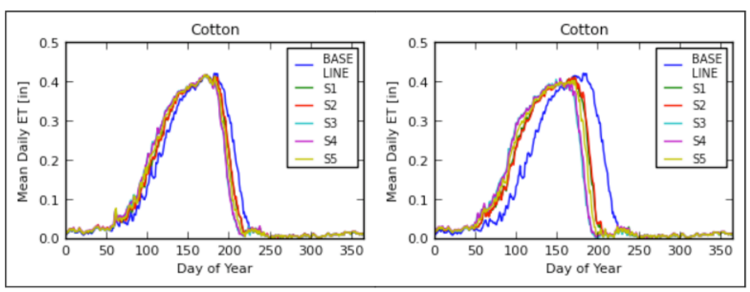

Figure 22.—Colorado River Basin – COOP station AZ9656 (Yuma, AZ). Baseline and projected mean daily cotton evapotranspiration for all scenarios and for time periods 2020 (left) and 2080 (right).

Figure 12: Evapotranspiration now versus different future scenarios (S1 thru S5) with higher temperatures. Note that for Grass Pasture and Alfalfa Hay the growing period starts earlier and ends later, enlarging consumptive use. For cotton, the growing period starts earlier but also ends earlier, offsetting some of the consumptive use increases. Source: Reclamation, 2015.

Increasing Colorado River Reservoir Evaporation

There has been only one comprehensive study on changes in lake evaporation due to climate change, a 2015 study by Reclamation (Reclamation, 2015). That study suggests a roughly linear thru time 10% increase in evaporation at Lakes Mead and Powell by 2100. If current Lake Mead evaporation is approximately 600 to 800 kaf / year, this means additional losses of 60 to 80 kaf

/ year by 2100 with similar but slightly smaller losses at Powell. These losses are dependent on reservoir contents, with lower reservoirs having less surface area and thus lower losses. Combined, the two reservoirs might thus lose an additional 120 kaf / year by 2100 and perhaps 60 kaf / year by 2050. These are reasonably small numbers in the context of the entire river, but are part of the larger trend of increasing ET losses everywhere.

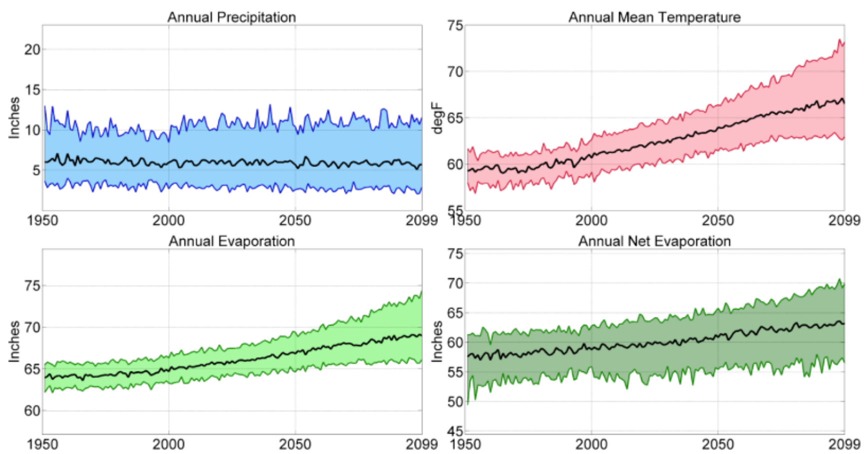

Figure 23.—Colorado River Basin – Lake Powell ensemble median and 5th and 95th percentile annual precipitation, temperature, reservoir evaporation, and net evaporation.

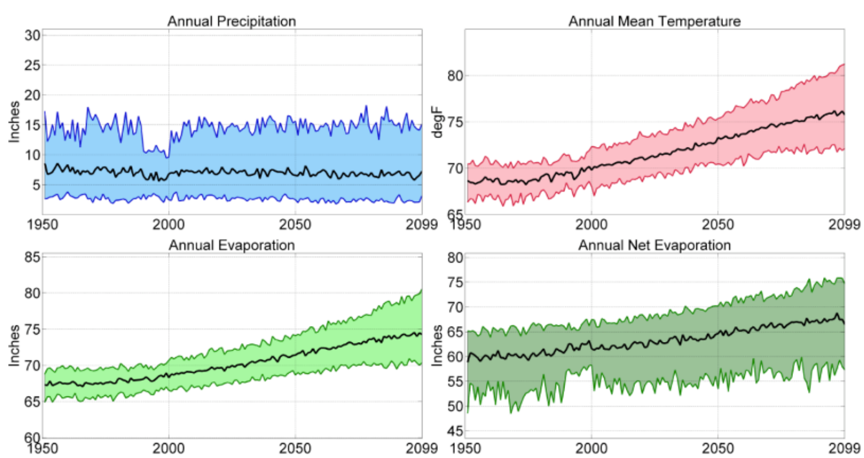

Figure 24.—Colorado River Basin – Lake Mead ensemble median and 5th and 95th percentile annual precipitation, temperature, reservoir evaporation, and net evaporation.

Figure 13: Changes in precipitation, annual mean temperature, annual evaporation and annual net evaporation (evaporation less precipitation) at Lake Mead from 1950 to 2099. Note the approximately 10% increase in evaporation from 2000 to 2099. Source: Reclamation, 2015.

Impacts to the Salton Sea

Salton Sea levels are directly and most importantly influenced by return flows from the Imperial Irrigation District. Those return flows are in turn influenced by total IID deliveries, and more importantly, on farm practices in IID. Evaporation is also a determinant of levels. Most projections for Salton Sea levels are for steadily declining levels over the next few decades due to an emphasis on improved irrigation efficiency, which means fewer return flows. It is unclear how future evaporation increases will affect the sea, but a reasonable guess would be increased evaporation in line with that projected at Lakes Powell and Mead. Salton Sea levels may be less of an issue of climate change and more related to water transfer agreements from IID. Were IID to face delivery shortages due to low reservoir levels in Lake Mead, this would likely lead to even lower levels in the Salton Sea than currently envisioned. Low Salton Sea levels lead to a variety of impacts from human health issues due to dust to significant environmental issues from the Sea turning hyper-saline. We are not aware of studies that directly tie climate change to impacts at the Salton Sea.

Q7. What are the important underlying climate change drivers that influence demands, and how do they affect demands in each of the three major demand sectors (single family residential, multi-family residential, commercial/industrial)?

Key Points: Temperature, and to a lesser extent precipitation, are the major climate drivers influencing water demand. Here, We describe the impact of climate drivers on major end uses and the extent to which each of these end uses is associated with the three major demand sectors: single-family residential, multi-family residential, and non-residential (or commercial, industrial, and institutional).

Effect of Climate Change on End Uses of Water:

A. **Landscape Irrigation:** Landscape water demand is sensitive to temperature and, to a lesser extent precipitation. Irrigation demand is higher in hot and/or dry periods and lower during cool and/or wet periods. As a result, irrigation is a major driver of intra- and inter-annual variability in water demand. Because precipitation in California typically occurs between October and May, the effect of precipitation on irrigation demand is likely to be greatest during the winter months and early Spring. In contrast, the effect of temperature on irrigation demand is likely to be year-round, peaking in summer and fall.

   A range of techniques are available for estimating how changes in climatic factors (temperature, wind speed, humidity, solar radiation, etc.) affect evaporation and plant transpiration. For example, the FAO Penman-Monteith equation is widely used for evaluating climate impacts on irrigation demand. Crop coefficients are useful for accounting for variations from the reference condition due to, for example, crop type, phenological development, harvests, and stress.

B. **Building Cooling:** Temperature also determines building cooling requirements, with warmer temperatures increasing cooling needs. Most buildings use either air or water for cooling, although some may use geothermal processes. For those that use water for cooling, a major determinant of the water requirements is whether the building uses single-pass (or once-through) cooling, evaporative cooling, or cooling towers. Where water is used for building cooling, changes in temperature will have a direct effect on building water requirements. A related important consideration is the penetration rate of cooling systems. In much of coastal California, residential homes are built without air conditioning, but as average temperatures rise, demand for air conditioning will increase, with concomitant impacts on energy demands and the water associated with energy production.

C. **Building Heating Systems:** Temperature also affects building heating requirements, with warmer temperatures reducing heating requirements. Where water is used for building heating, such as in boilers, changes in temperature can have a direct effect on building water requirements. For water-based heating systems, a major determinant of the water requirements is whether they are equipped with a closed-loop system that returns the water and steam condensate to the boiler for reuse or an open-loop system that expends the water or steam without return to the boiler.

D. **Electricity Generation:** Temperature also affects electricity generation. Warmer temperatures, particularly during the summer months, can increase building energy use for cooling while also reducing the thermal efficiency of power plants. This could, in turn, increase electricity generation and, depending on the energy technology employed, energy-related water use. Most renewables, like wind and solar photovoltaics, use minimal water during operation. However, thermoelectric power plants, like natural gas-fired plants or solar thermal plants, use water in boilers and, to a greater extent, in cooling systems. These cooling systems may be cooled by air or water, with once-through cooling systems more water intensive than recirculating cooling systems.

Effect of Climate Change on Major Demand Sectors: Generally, climate impacts on water demand will vary across each of the major demand sectors according to (1) the magnitude of climate change impacts on the end use, and (2) the proportion of total water use the end use represents.

A. **Single-Family Residential:** Landscape irrigation is common in single-family residences, accounting for up to 70% of household water use in some areas. As a result, climate impacts on landscape irrigation will affect household water demand. Most single-family homes do not use water-based heating and cooling systems, and consequently, temperatures would have no effect on water demand for those end uses. However, some single-family homes use evaporative coolers, such as swamp coolers, that require water during operation. For these households, warmer temperatures would increase water demand. While there are limited data on the use of evaporative coolers in California households and their water requirements, the Department of Water is studying these systems to support implementation of AB 1668/SB 606.

B. **Multi-Family Residential:** Like single-family residences, landscape irrigation is common in multi-family residences, and climate change would affect water requirements for this end use. Additionally, multi-family buildings may use water for cooling and heating systems. Typically, low-rise residences and small commercial buildings use air-based cooling systems, whereas larger buildings may use water-based cooling systems.

C. **Non-Residential (CII):** Landscape irrigation is common in the CII sector, and climate change would affect total CII water demand. Compared to the residential sector, however, landscape irrigation typically represents a lower percentage of total water use, and thus the effect on total demand is likely to be less. Buildings in the CII sector may use water for cooling and/or heating systems. While small commercial buildings typically use air-based systems, larger buildings are more likely to use water-based cooling systems.

Q8. What other recommendations do you have for our planning?

Prudent Planning and "Reasonable Worst Case Future: By this we mean, planning for a future that is both politically possible to plan for, and climatologically possible without being on the extreme tail. This requires balancing the politically possible and the "climatologically problematic". That is to say, some futures are too hard to plan for politically and too uncertain to plan for based on climate models. For example, given the strong tie between flow reductions over the last 21 years and rising temperatures in the Colorado River Basin, prudence dictates that planning use flows less than the last 21 years. It remains an active area of inquiry about how much less. Planning for California would likely require some very wet, flood prone scenarios along with drought scenarios. Ultimately, the determination of a 'reasonable worst case future' is a policy decision informed by qualitative weighting of certain and less certain science.

From Reclamation's West-Wide Climate and Hydrology Risk Assessment on what Deep Uncertainty is: "Because of the amount and nature of the uncertainty in future hydroclimate projections, however, it is also appropriate to consider concepts and techniques that provide decision makers with actionable information that does not rely on probabilities, using a subfield of decision science that deals with a deeply uncertain future. Deep uncertainty arises when, among other factors, the likelihoods of future conditions cannot be stated with confidence, and when experts do not agree on the most appropriate way to represent complex interactions between factors influencing a planning context (Lempert et al., 2003; Marchau et al., 2019).

The Society for Decision Making Under Deep Uncertainty is a great resource for additional information: https://www.deepuncertainty.org/

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