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CONTENTS

Water Policy Options as Arizona Adapts to a Drier Colorado River: A Perspective

Sharon B. Megdal

The Colorado Basin Context

On August 16, 2021, the U.S. Bureau of Reclamation announced the first-ever Tier 1 Colorado River shortage. The water delivery cutbacks, which went into effect on January 1, 2022, per the "Colorado River Interim Guidelines for Low Basin Shortages and Coordinate Operations for Lake Powell and Lake Mead" (2007 Interim Guidelines), are most significant for the Central Arizona Project (CAP). Governed by the Central Arizona Water Conservation District, CAP delivers water into Central Arizona for use by tribal, municipal and industrial, and agricultural users. The reason that CAP water users face the most severe cutbacks is because that, in order to secure approval of the 1968 Colorado River Basin Project Act authorizing CAP construction, Arizona had to agree that water delivered through the CAP canal would be junior in priority to California's Colorado River water deliveries. This means that in deep shortage conditions CAP deliveries could be cut in their entirety before California would experience any cutbacks in water deliveries.

To say management of the Colorado River is complex is an understatement. Colorado River water is shared by seven states, 30 Tribal Nations, and Mexico. Within the U.S., the Colorado River Basin is divided into an Upper Division and a Lower Division. Different formulas govern the distribution of water. Upper Basin water is distributed on a percentage basis but each of the Lower Basin states have a set amount of water that is expected to be delivered in non-shortage years. The 1944 Treaty for Utilization of Waters from the Colorado and Tijuana Rivers and of the Rio Grande between the United States and Mexico, which is implemented by the International

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Colorado River Basin

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Boundary and Water Commission, includes a requirement that the U.S. deliver 1.5 million acre feet of water annually.

The 2007 Interim Guidelines were developed because, prior to their development, there had been no framework for sharing shortages of Colorado River water. The Colorado River storage system includes the huge Lake Powell and Lead Mead reservoirs. The low-flow conditions of the early 2000s signaled that it was time to establish a framework for shortage conditions. Though the basin has been experiencing low flows for most of the first 20 years of this century and the 2007 Interim Guidelines have been in place, the Lake Mead water level had not met the criterion for a Tier 1 shortage until this year. This is true despite there being what has been termed a “structural deficit” in the Lower Basin, meaning that more water is allocated to Arizona, California, and Nevada annually than can be expected during average river flow conditions. About 10 years ago, water managers finally acknowledged what many had argued was the case – the Colorado River is overallocated compared to average flow conditions. The Lower Basin was overdrawing its water savings account (the water stored in Lake Mead). Unfortunately, over the past 20-plus years, deposits to storage have not kept up with withdrawals. Despite innovative, sometimes voluntary, approaches to “propping up” Lake Mead, the status of and prognosis for the system indicated that more actions were necessary.

Renewable Natural Resources Foundation

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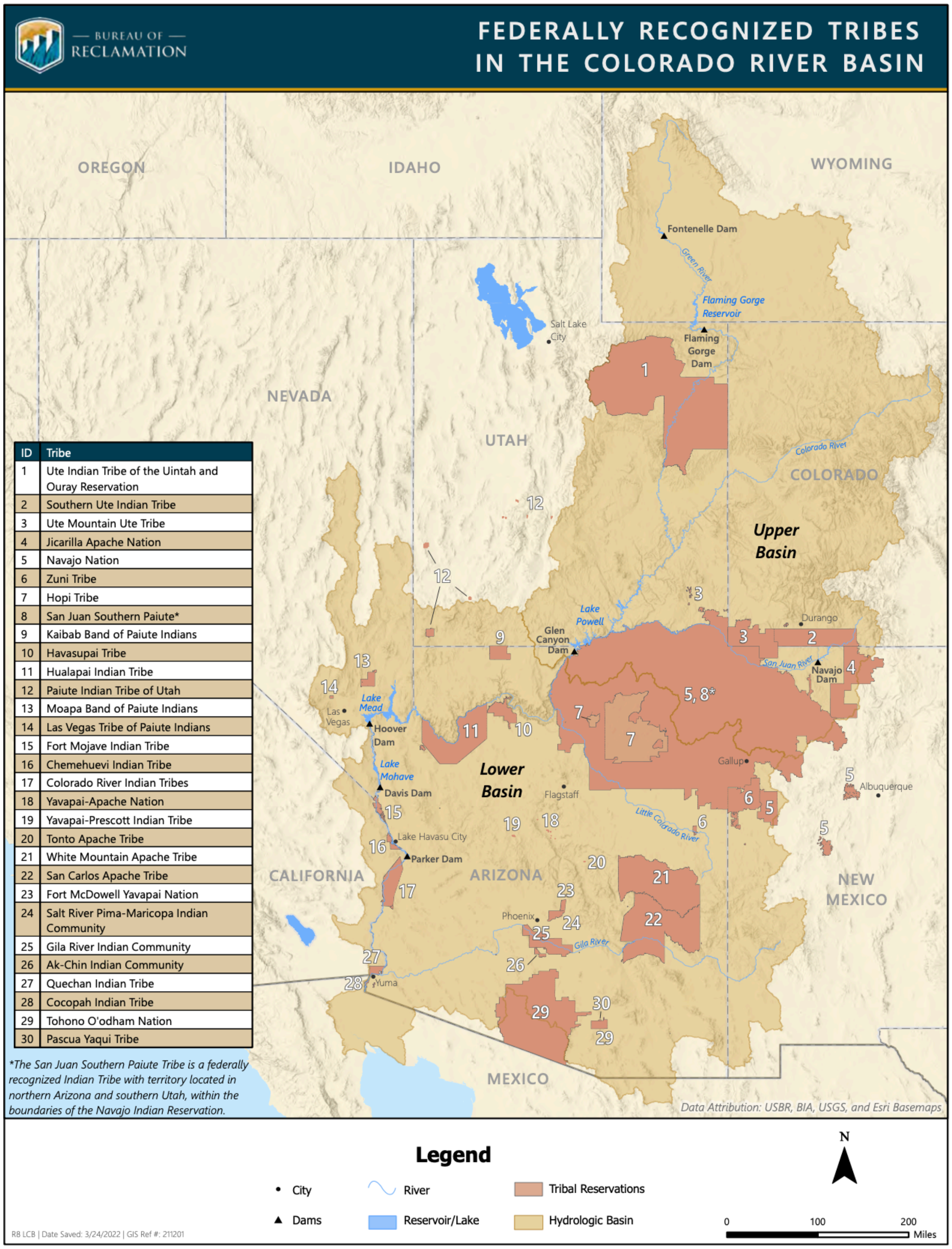
Collaboration among the many water actors led to the Spring 2019 federal enactment of the Drought Contingency Plans (DCPs). The DCP for the Lower Basin called for implementation of Tier 0 cutbacks in water deliveries at Lake Mead elevation level of 1,090 feet above sea level. Tier 0 governed water deliveries for 2020 and 2021. Under Tier 0, CAP experienced cutbacks of 192,000 acre feet. The Tier 1 shortage in 2022 added another 320,000 acre feet, making the total cutback equal to 512,000 acre feet, about one-third of CAP’s annual deliveries under normal conditions and about 18 percent of Arizona’s annual Colorado River allocation of 2.8 million acre feet. Unfortunately, the health of the Colorado River system is only getting worse; the probabilities of deeper cuts are increasing by the month. Based on Reclamation’s monthly modeling, charts like those below are shared each month. The picture is getting worse more quickly than anyone expected. So, while one can hope or pray for the best, doing so will not prepare you for the adverse conditions that are in fact the “new normal.”

Implications for Arizona

What do these Tier 1 cutbacks mean for Arizona water users? How is Arizona, which continues to grow, positioning itself for a long-term reality of less Colorado River water? The theme of complexity continues as we delve into a look at the Arizona water supply picture. Until the recent cuts in CAP water deliveries, about 40 percent of the 7 million acre feet used across Arizona was Colorado River water, with about an equivalent but growing percentage coming from groundwater. The remaining sources were other surface water supplies, such as Salt River Project waters, and reclaimed or recycled water. Groundwater is regulated pursuant to Arizona's 1980 Groundwater Management Act, as amended, in Active Management Areas (AMAs) only. The Central Arizona AMAs for the most part fall within CAP's service area and encompass Phoenix, the fifth largest city in the U.S., other cities in the Phoenix area, the Tucson region to the southeast, and large agricultural areas.[1] Lands of five Tribal Nations fall within AMA boundaries; however, the water use of sovereign Tribal Nations is not subject to state regulations.



ID	Tribe
1	Ute Indian Tribe of the Uintah and Ouray Reservation
2	Southern Ute Indian Tribe
3	Ute Mountain Ute Tribe
4	Jicarilla Apache Nation
5	Navajo Nation
6	Zuni Tribe
7	Hopi Tribe
8	San Juan Southern Paiute*
9	Kaibab Band of Paiute Indians
10	Havasupai Tribe
11	Hualapai Indian Tribe
12	Paiute Indian Tribe of Utah
13	Moapa Band of Paiute Indians
14	Las Vegas Tribe of Paiute Indians
15	Fort Mojave Indian Tribe
16	Chemehuevi Indian Tribe
17	Colorado River Indian Tribes
18	Yavapai-Apache Nation
19	Yavapai-Prescott Indian Tribe
20	Tonto Apache Tribe
21	White Mountain Apache Tribe
22	San Carlos Apache Tribe
23	Fort McDowell Yavapai Nation
24	Salt River Pima-Maricopa Indian Community
25	Gila River Indian Community
26	Ak-Chin Indian Community
27	Quechan Indian Tribe
28	Cocopah Indian Tribe
29	Tohono O'odham Nation
30	Pascua Yaqui Tribe

**The San Juan Southern Paiute Tribe is a federally recognized Indian Tribe with territory located in northern Arizona and southern Utah, within the boundaries of the Navajo Indian Reservation.*

Source: U.S. Bureau of Reclamation

There are different priorities of water deliveries within the CAP system. Historically, the lowest priority water

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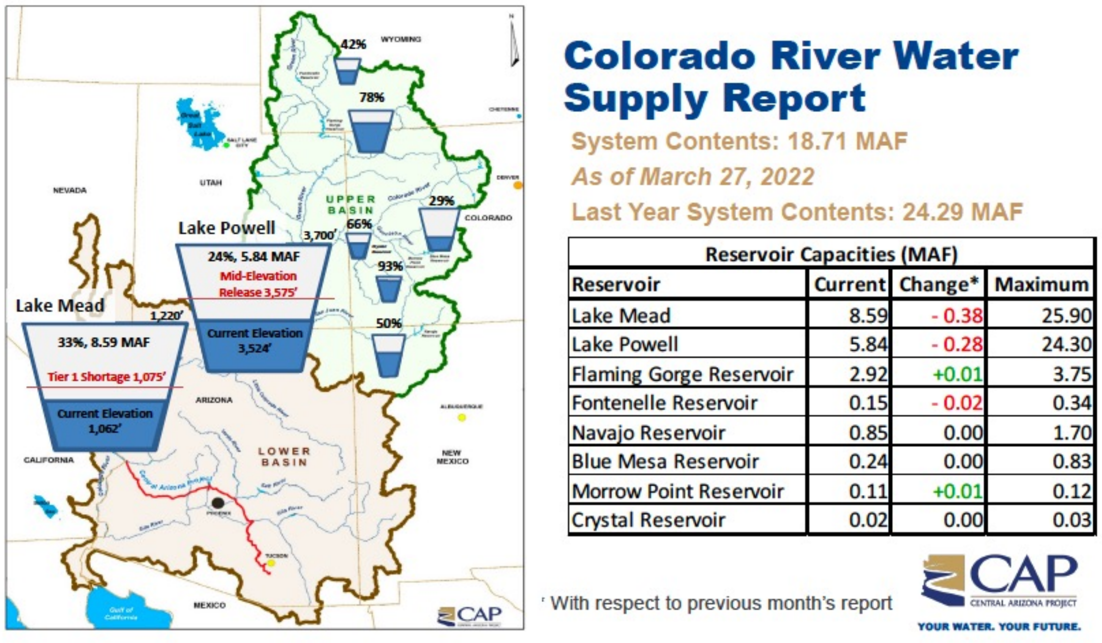
[1] AMA boundaries are not coincident with county boundaries but rather depend on hydrologic mapping. The three-county CAP service area includes Maricopa, Pinal, and Pima Counties.



Colorado River Water Supply Report

System Contents: 18.71 MAF

As of March 27, 2022

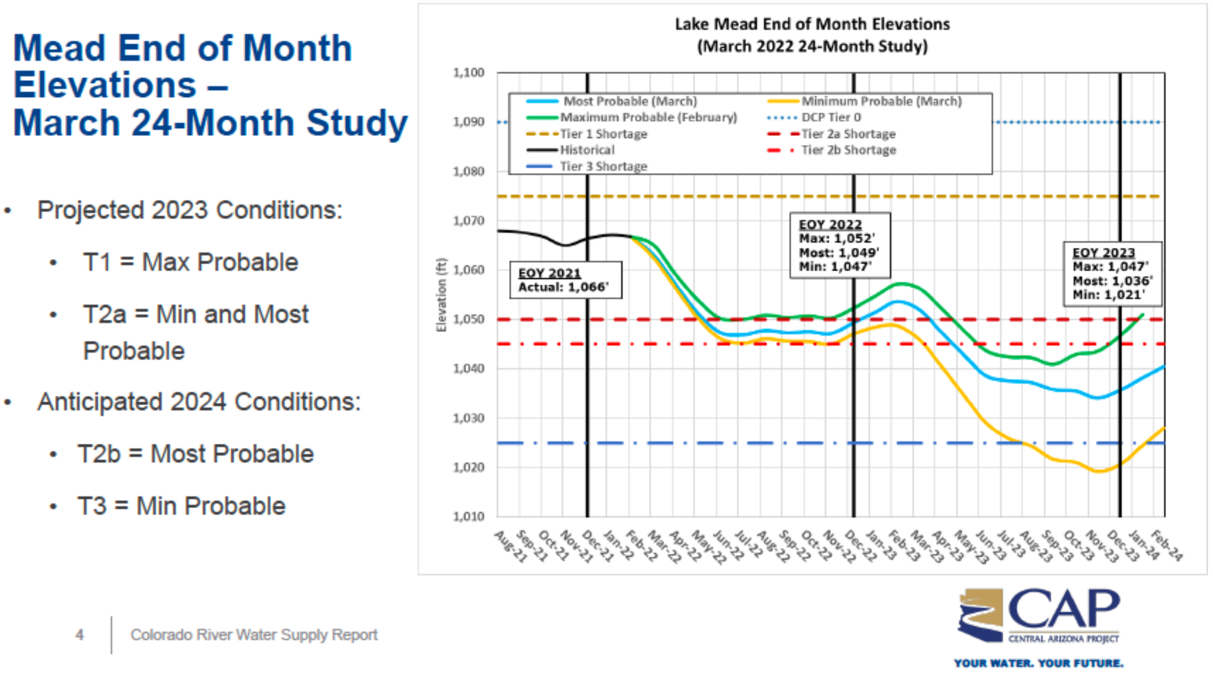
Last Year System Contents: 24.29 MAF

Reservoir Capacities (MAF)			
Reservoir	Current	Change*	Maximum
Lake Mead	8.59	- 0.38	25.90
Lake Powell	5.84	- 0.28	24.30
Flaming Gorge Reservoir	2.92	+0.01	3.75
Fontenelle Reservoir	0.15	- 0.02	0.34
Navajo Reservoir	0.85	0.00	1.70
Blue Mesa Reservoir	0.24	0.00	0.83
Morrow Point Reservoir	0.11	+0.01	0.12
Crystal Reservoir	0.02	0.00	0.03

* With respect to previous month's report

CAP CENTRAL ARIZONA PROJECT

YOUR WATER. YOUR FUTURE.



Mead End of Month Elevations – March 24-Month Study

- Projected 2023 Conditions:
  - T1 = Max Probable
  - T2a = Min and Most Probable
- Anticipated 2024 Conditions:
  - T2b = Most Probable
  - T3 = Min Probable

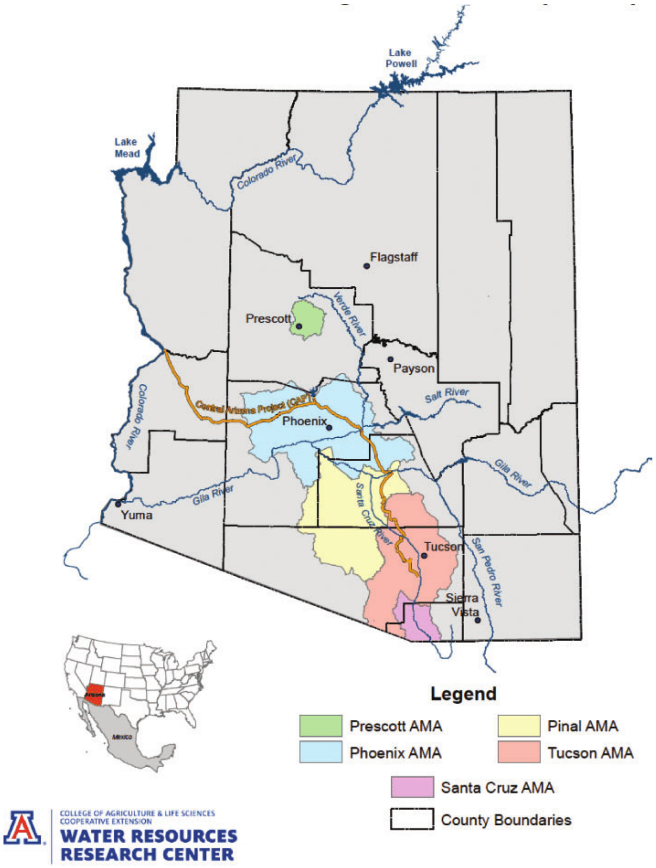
4 | Colorado River Water Supply Report

CAP CENTRAL ARIZONA PROJECT

YOUR WATER. YOUR FUTURE.

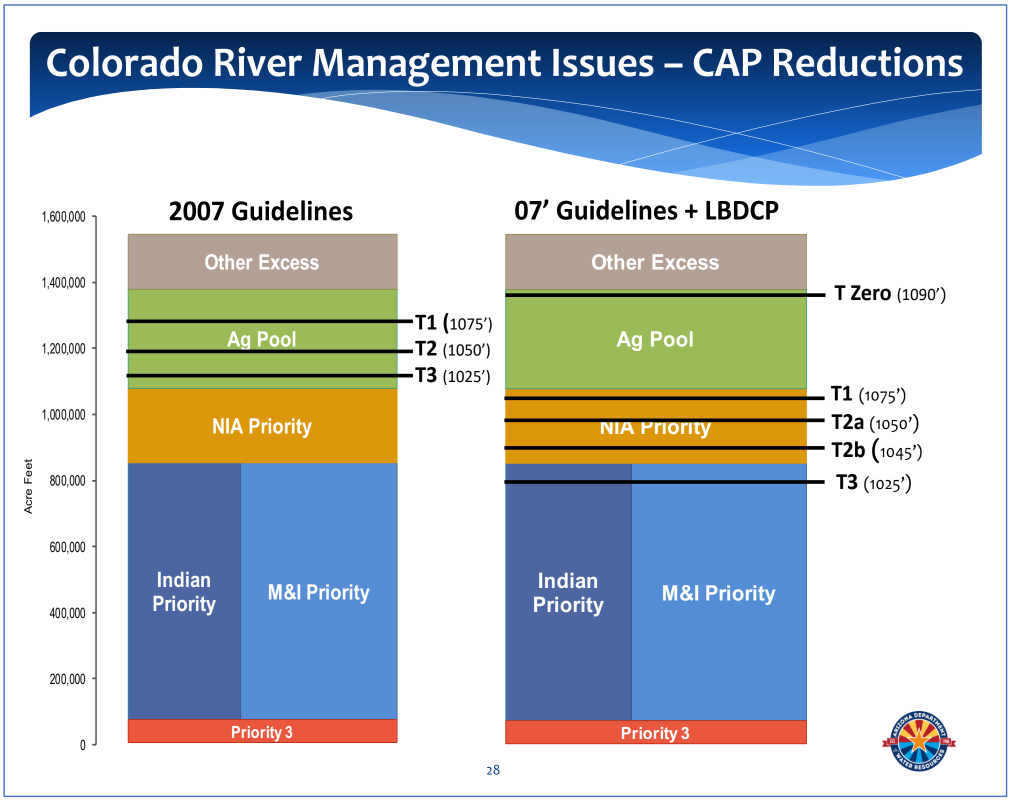
Source: Central Arizona Project, April 2022 Colorado River Water Supply Report to the Central Arizona Water Conservation District

has been what has been called "excess water" or water that was not ordered in a given year but available for use. Recent cutbacks have wiped out the prospects of there being excess water for water banking or other uses. The next lowest priority is water use by agricultural users within the CAP system. The Tier 1 cutback in CAP water deliveries has eliminated all the water known as "ag pool" water. Though there may continue to be some CAP water available to non-Indian agricultural users in the Central Arizona AMAs, the loss of the entire 300,000 acre-foot ag pool is severe and has significant ramifications. It should be noted that on-river agricultural users of Colorado River water, such as those in the Yuma region and Tribes do not experience these cutbacks. These distinctions in priorities are important. All of Arizona Colorado River water use is not junior to California, and not all agricultural water use is of lower priority to non-agricultural water use. CAP water deliveries overall are junior, and, within the CAP, water deliveries to non-Indian agriculture are of low priority. After ag pool water is cut, the category known as non-Indian agricultural (NIA) priority water is next to be cut. This category's name is a remnant of past plans for how agricultural water use of water delivered by the CAP would convert to municipal and industrial water use as agricultural lands were developed. Those holding contracts for NIA water are not agricultural water entities but rather Tribal Nations, cities, and others. The highest priority water categories within the CAP system are Indian and Municipal & Industrial (M&I). Note that some entities hold water contracts for multiple types of CAP water. Even these high priority uses risk being cut should Tier 3 cutbacks be ordered. There is one category of water delivered by the CAP that is of higher priority than other deliveries of water, as shown at the bottom of the block diagram. The diagram shows cutbacks in CAP water deliveries under the 2007 Interim Guidelines on the left compared to cutbacks with the 2019 Lower Basin DCP (LBDCP) overlay.



Map showing Arizona AMAs. *Source: University of Arizona Water Resources Research Center*

Recognizing the low priority of CAP water deliveries, Arizona has not been sitting idly by. In the mid-1990s, when more Colorado River was available than could be used directly, Arizona utilized a strong legislative and regulatory framework for water recharge and established the Arizona Water Banking Authority (AWBA) (Megdal and Seasholes (2014) and Seasholes and Megdal (2021)). The AWBA has stored underground millions of acre feet of Colorado River water for firming the water supplies of M&I and Indian priority water users when shortages hit those sectors. To date, that water remains in storage. Fortunately, some water



Source: Ken Slowinski, Arizona Department of Water Resources suppliers have not had to rely on their current CAP water allocations to meet current demands and have stored water for their future use.

Arizona water users have engaged in innovative partnerships to leave water in Lake Mead and/or ameliorate the burden of delivery cutbacks. Because Arizona's designated negotiator on Colorado River matters – the Director of the Arizona Department of Water Resources – requires legislative approval to sign on to interstate-federal water agreements, Arizona's negotiations on these challenging matters are necessarily inclusive. Arizona is alone among the Basin States in requiring legislative approval. Though intra-Arizona deliberations have at times been turbulent, many have pointed to Arizona's DCP consultative and deliberative process as exemplary. Not all the within-state actions are embraced by all Arizona parties. For example, actions to financially support the irrigation districts as they increase groundwater pumping to partially replace the lost surface water, concern those who see a return to greater groundwater reliance as counter to Arizona's efforts to reduce groundwater overdraft. Yet the irrigators have rights to use groundwater. Not only was their support needed at the Legislature, but there are serious concerns about the economic dislocation to farmers, along with their connected businesses and communities.

It is the Pinal AMA, a largely agricultural AMA in the central part of Central Arizona that is the epicenter of questions about the Colorado River shortage impacts. The Pinal AMA has a groundwater management goal different from the other AMAs, who all aspire to achieve safe-yield or a balance of groundwater withdrawals with natural and artificial recharge. The statutory management goal of the Pinal AMA (PAMA), however, is to allow the development of non-irrigation water uses and to preserve existing agricultural economies in the PAMA for as long as feasible, consistent with the necessity to preserve future water supplies for non-irrigation uses (A.R.S. § 45-562(B)). This region between Phoenix and Tucson continues to attract non-agricultural businesses and their workers. Update to the Arizona Department of Water Resources' groundwater model for the region has brought attention to the imbalance between the expected groundwater demands and groundwater supplies available for use per existing groundwater regulations. Coupled with the focus on the region's agricultural water use have been serious questions about the ability of the non-agricultural development to occur as expected by landowners and developers.

In fact, non-renewable groundwater remains a primary water source for many. Growing populations and economic activity have stressed groundwater resources throughout Arizona, especially in areas outside the AMAs, where there are no groundwater regulations, nor are there water conservation or metering requirements. Groundwater's "invisibility" makes it difficult to know water in storage, and water quality information can be limited. Recognizing these water pressure points, Arizona's Governor Ducey established the Governor's Water Augmentation, Innovation, and Conservation Council to assess the challenges and consider options to address them. In addition, in 2022 Governor Ducey proposed formation of and funding for an Arizona Water Authority, with legislative authorizing language being formulated during the ongoing legislative session. At the same time, some local communities are advocating for formation of new AMAs, something that has not occurred since the Santa Cruz AMA was "carved out of" the Tucson AMA in 1994. In actuality, no new lands have become subject to AMA groundwater regulations since the 1980 adoption of the Groundwater Management Act. In the past and currently, legislative proposals to authorize other regional approaches to water management have stalled due to lack of consensus. Nevertheless, many of the policy options are under discussion. While not all are new, pilot projects, renewed interest, and/or variations in their characterization are generating more robust discussions. Others remain on the back burner. The following discussion summarizes some of these options.

Policy Options and Opportunities

Conservation: No one questions the value of using less water, though there may be questions about what happens to the water conserved. Is it used to support growth? Or more cropping if by the agricultural sector? Though there may be great potential in some places for water savings due to conservation, many water users or suppliers in the AMAs have water conservation programs in place. What could help guide investment in incremental water conservation programs is an approach like that of Southern Nevada Water Authority, where they have calculated the expected impacts of water conservation programs on gallons-per-capita-per-day water consumption. (Pellegrino (2022))

Greater efficiency: Especially in the agricultural sector, conservation is not necessarily the same as more efficiency. (Frisvold et al. (2018)) Installation of novel drip irrigation systems through pilot programs are enabling measurement of the change in water use as well as yields as farmers irrigate fields previously receiving flood irrigation with drip irrigation that relies on gravity-fed rather than highly pressurized water deliveries. Recent legislative activity has considered providing incentives for installation of higher efficiency irrigation technologies. Some of the pilots are being undertaken without incentives; others involve partnerships among water agencies and farmers, including tribal farming entities. Research and pilots related to different crops, such as guayule, which is used for production of rubber products, continue.

Water reuse: In many parts of Arizona, water reuse is a substantial component of water supply portfolios. For years, effluent from metropolitan Phoenix has been used as cooling water for the Palo Verde Generating Station operated by Arizona Public Service. Many communities have ordinance requiring golf courses irrigate with reclaimed water. Some recharge their treated wastewater for meeting non-potable demands for water through storage and recovery. Rules have been adopted in Arizona allowing for direct potable reuse, although no water provider is currently engaged in direct potable reuse. It is recognized that wise reuse is every bit as important as wise “first use” of water. An advantage of water reuse is that the water is locally generated. Included in this category is grey water use at individual households. Increased use of gray water by households means less water flowing into centralized wastewater treatment plans for use by the owners of plant outflows. Also, as water use becomes more efficient, household wastewater flows may decrease.

Desalination: Though Arizona does not abut a sea or an ocean, seawater desalination has been of interest, particularly in collaboration with Mexico. Through the International Boundary and Water Commission, a binational study (**Full Report** and **Executive Summary**) of the potential for large-scale seawater desalination in the Sea of Cortez was completed in 2020. Though this highly collaborative study suggested feasibility, there are many yet-to-be explored questions about such a binational effort in terms of cost, environmental implications, and institutional feasibility. Some talk about it in the context of an exchange: Arizona would help pay for production of water to be used in Mexico in exchange for some of Mexico’s Colorado River allocation. Others speak to the possibility of piping the water into the United States. It is clear that working through the many jurisdictional layers and across multiple election cycles at the state and federal levels would be necessary. Possibilities to desalinate in-state brackish groundwater exist, but regulations for disposal of the brine are pending and legal questions regarding the groundwater itself, particularly in the AMAs, have been raised. Though there are some mechanisms for multi-party collaboration within Arizona to fund infrastructure that would be too expensive for a single entity, these opportunities are not active. Questions about the feasibility of restarting or rebuilding the Yuma Desalting Plan also remain.

Moving water: Moving water from one part of Arizona to another comes up in different contexts. One is the transport of Colorado River water from the western boundary of Arizona into Central Arizona. This option, which is unpopular with many along the Colorado River, is seen as an option for meeting growing water needs in Central Arizona. The transfer from landowners in Cibola, Arizona to Queen Creek, Arizona, pending approval by the federal government, is an example. Others have been proposed but not realized for various reasons. Another opportunity is moving groundwater. Though in the late 1980s Arizona enacted legislation limiting movement of groundwater from one basin to another, some exceptions were allowed. One area from which groundwater can be moved is the Harquahala Valley west of Phoenix. Per the CAP’s System Use Agreement, the CAP canal could be used for transport of that water, provided that water quality requirements are met. These and related issues are active, including legislation that would enable a private entity to join public entities as eligible to build infrastructure needed for the project. Note that both options discussed here do not augment Arizona water supplies. The first transfers use from agricultural lands in Western Arizona to municipal use in Central Arizona. The second would also transfer water that would/could be used by agriculture in the

Harquahala Valley for municipal use in Central Arizona. A key difference is that the first would be considered renewable water because it is mainstem Colorado River water. In the second instance, the water to be moved is non-renewable groundwater. Some “out-of-the-box” and out-of-region options for moving water include moving water from another region of the United States to Arizona. Multiple ideas have been articulated, including moving floodwater from the Midwest to Arizona via a northern route that could feed into Lake Powell. While some consider such ideas as totally infeasible, others would like to see them investigated, much like the opportunity for binational desalination has been investigated.

Marketing and other mutually agreed-upon transactions: The two examples above can be considered examples of water marketing. In general, market mechanisms involving multiple buyers and sellers interacting through some sort of platform is non-existent in Arizona. Yet, there is a market for the long-term water storage credits that have been accrued pursuant to Arizona’s water storage (recharge) and recovery framework (Bernat and Megdal (2020)). Other opportunities typically involve private negotiations between a buyer and a seller. Private negotiations are allowed of public entities, with only the final vote for the transaction being made public for bodies subject to open meeting laws. A large purchaser of long-term storage credits has been the **Central Arizona Groundwater Replenishment District**, which is required to replenish groundwater use by its Central Arizona members. Efforts to meet required water cutbacks or voluntarily leave water in Lake Mead have involved payment for non-use of water as agricultural lands are fallowed. The contexts for these transactions are many and can be complex.

Rainwater and stormwater capture: Individual household efforts to capture rainwater either actively through cisterns or passively, through swales and directing gutter water to trees, can help augment indirectly the water supplies of a region by substituting rainwater for water delivered through the potable water system. How much of that water would have eventually made its water into the water system relied upon by water suppliers is not quantified, but considerations of whether some of that might have become surface water subject to appropriation by downstream users does not seem to be an obstacle. Arizona law is quite permissive as to individual household installation of rainwater systems, as it is for individual gray water systems. Questions about rainwater harvesting for larger footprints do exist and are indicative of need for study of what water would make it into a stream versus lost to evaporation, for example, and the costs of mechanisms to capture stormwater for recharge.

Designing the built environment: An opportunity for improving the supply-demand imbalance is designing communities and building for lower water use. As a state that continue to grow, with large, planned communities, innovative design could contribute to reduced calculations of water demands. Arizona has the potential to lead in showing how to live in the desert.

Moving Forward

Arizona is a large and diverse state. Population and business growth continues. Agricultural activities are growing in some parts of the State. Colorado River water is an extremely important source of water for Arizona, but it is not the only Arizona water source facing stress. Many parts of Arizona rely almost exclusively on non-renewable groundwater. Some areas are facing the same groundwater overdraft problems that led to the enactment of the 1980 Groundwater Management Act. In addition, water management issues remain for the Active Management Areas. The policy options and opportunities discussed above are not necessarily new. Many, though not all, were discussed in the **2014 Arizona Strategic Vision for Water Supply Sustainability**. However, that document has not been used to guide regional and statewide water planning. While stakeholders have participated productively in meetings of various steering groups, councils, and committees, Arizona does not have a State Water Plan to guide its forward direction. Discussions to form a statewide Arizona Water Authority to pursue options for augmentation include significant funding, funding that has not previously been on the table. There are many questions regarding the scope and governance of the authority. What sorts of projects would it undertake? How would local communities engage? What kinds of partnerships are envisioned? The need for action is recognized statewide, though perhaps not surprisingly, not all agree on the forum or approach.

Robust discussion and debate are welcome – if they lead to action. Bold actions are required so that Arizona can chart its water future. As many note, one can hope or pray for the best, but the necessary course of action is to plan for the worst. Unfortunately, Colorado River conditions are only getting worse. No one holds the crystal ball to know how bad they will go. In April 2022, concerns about the level of Lake Powell resulted in unprecedented actions to keep Lake Powell from falling below the level necessary for electricity generation and for the regular flow of water downstream of the dam. Actions to increase releases into Lake Powell from Flaming Gorge reservoir and decrease releases from Lake Powell to Lake Mead were announced by the Department of the Interior and agreed to by the seven Basin States. Much more is needed, particularly in Central Arizona, which bears so much of the brunt of the expected cutbacks. Collaboration and partnerships are needed so that we can adapt to these drier conditions. Some of the efforts require significant advance planning. A key question is whether we in Arizona will identify the pathways forward proactively or respond reactively to crisis. Perhaps adapting to drier Colorado River conditions will require both proactive and reactive actions as we maneuver these uncharted waters.

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Climate Change in the Arctic with Biophysical and Economic Impacts

Congressional Research Service

An array of climate changes in the Arctic is now documented by observing systems, with more expected with future greenhouse gas-driven climate change. Observed physical changes in the Arctic include warming ocean, soil, and air temperatures; melting permafrost; shifting vegetation and animal abundances; and altered characteristics of Arctic cyclones. These changes continue to affect traditional livelihoods and cultures in the region, infrastructure, and the economy, as well as the distribution and health of animal populations and vegetation. The changes raise risks of pollution, food supply, safety, cultural losses, and national security. The state government of Alaska concluded that observed climate changes "have resulted in a reduction of subsistence harvests, an increase in flooding and erosion, concerns about water and food safety and major impacts to infrastructure: including damage to buildings, roads and airports."[1]

A monitoring report of the Arctic Council concluded in 2019 that

> the Arctic biophysical system is now clearly trending away from its previous state [in the 20th Century] and into a period of unprecedented change, with implications not only within but also beyond the Arctic.[2]

This article is an excerpt from the Congressional Research Service report "Changes in the Arctic: Background and Issues for Congress." This section was prepared by Jane Leggett, Specialist in Energy and Environmental Policy, Resources, Science, and Industry Division.

A few broad points raise particular concerns about changes in the Arctic:

- Long lag times between cause and full effects: Changes once set in motion prompt further and often slow effects in different components of the Arctic system, such as the influence of rising atmospheric temperatures on ocean and permafrost temperatures. Scientists expect the full effects of near-term climate changes to play out over a period of decades to many centuries.
- Feedbacks that mostly further increase warming: GHG-induced warming leads to positive (enhancing) and some negative (dampening) feedbacks within the Arctic system, which scientists expect in net to amplify warming and pursuant effects. For example, temperature-driven melting sea ice reduces reflection of incoming solar energy, leading to absorption by the Arctic Ocean and further warming of the ocean and the planet.
- Abrupt change risks: The freezing point for water, including permafrost, is one example of thresholds that certain Arctic systems may cross, leading to rapid state changes.
- Risks of irreversibilities: Some Arctic climate impacts, such as loss of sea ice and glaciers, may lead to system changes that scientists expect would be irreversible on a human timescale, even if temperatures stabilize (at a higher level than today).

Understanding remains incomplete regarding future Arctic climate changes and their implications for

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[1] Department of Commerce, Community, and Economic Development, "Climate Change in Alaska." The Great State of Alaska. Accessed February 2, 2022. https://www.commerce.alaska.gov/web/dcra/ClimateChange.aspx.

[2] Jason E Box et al., "Key Indicators of Arctic Climate Change: 1971–2017," Environmental Research Letters 14, no. 4, April 2019.

human and natural systems. With current knowledge, projections point to growing risks, as well as some opportunities.

The Arctic is interconnected to the rest of the globe through circulation of water, energy (e.g., heat), and carbon, including through the atmosphere and oceans. It is also connected through human systems of transport, energy and mineral production, tourism, and security. Consequently, Arctic changes are of import to both Arctic and non-Arctic regions of United States and the rest of the globe.

This section summarizes a variety of observed and projected climate changes in the Arctic and identifies some of their impacts on human and ecological systems.[3] Other sections in this report provide further discussion of implications for, for example, national security and energy production.

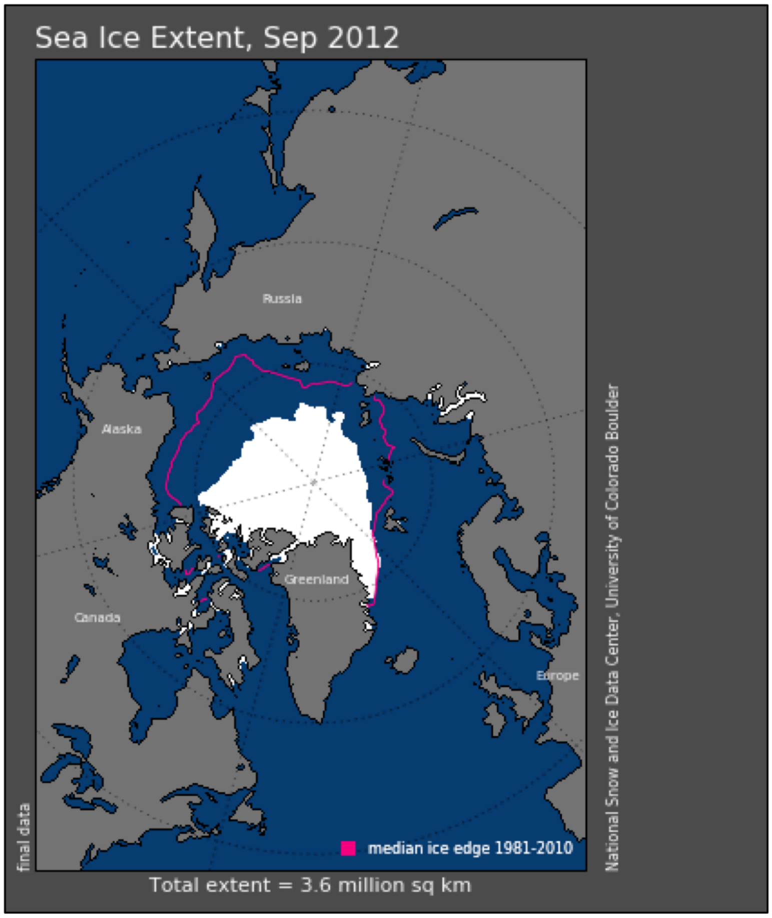

Figure 1. 2012 Record-Low Sea Ice Extent compared with long-term median. *Source: National Snow and Ice Data Center, Sea Ice Index, accessed February 28, 2022.*

Warming Temperatures and a More Intense Water Cycle

The Arctic warmed at approximately three times the global average rate from 1971 to 2019, with the region's surface temperature increasing by more than 3°C (5.5°F).[4] Summers have warmed more than winters. In tandem are trends of fewer cold days, cold nights, frost days, and ice days in the North American Arctic.[5] Researchers found that warming trends as well as climate cycles, including the North Atlantic Oscillation and the Arctic Oscillation, influence observed extreme temperatures, ice distribution, and other facets of the Arctic system.[6] In addition, positive feedbacks from the loss of summer sea ice and spring snow cover on land have amplified warming in the Arctic.[7]

With warming, the water cycle has become more intense. The Arctic has experienced increasing precipitation and an increasing share of precipitation falling as rain. The first recorded rainfall at Greenland's 10,500-foot Summit Station was on August 14, 2021.[8]

Warming and increasing rainfall have led to permafrost thaw, glacier melt, and sea ice decline, leading to greater flows of organic

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[3] Although much of Greenland is above the Arctic Circle, and many of the changes and implications apply also to Greenland, this section emphasizes other parts of the Arctic and does not attempt to summarize the often large and complex change in Greenland.

[4] T.J. Ballinger et al., "Surface Air Temperature," Arctic Program, Arctic Report Card 2021.

[5] Alvaro Avila-Diaz et al., "Climate Extremes across the North American Arctic in Modern Reanalyses," Journal of Climate 34, no. 7, April 1, 2021.

[6] Ibid.

[7] Intergovernmental Panel on Climate Change, "Summary for Policymakers," Special Report on the Ocean and Cryosphere in a Changing Climate, 2019, https://www.ipcc.ch/srocc/chapter/summary-for-policymakers/. (Hereinafter, SROCC SPM 2019.)

[8] National Snow and Ice Data Center, "Rain at the Summit of Greenland," August 18, 2021.

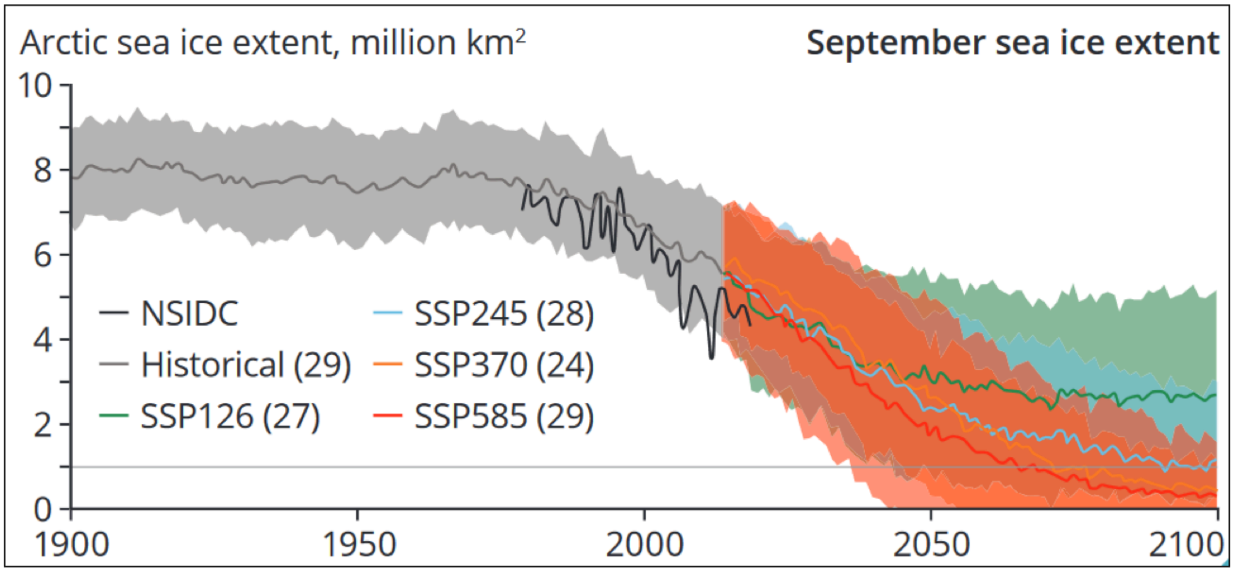

Figure 2. Estimated Historical, Observed, and Projected September Arctic Sea Ice Extent. *Source: Arctic Monitoring and Assessment Programme (AMAP), "Arctic Climate Change Update 2021: Key Trends and Impacts. Summary for Policy-Makers," Arctic Council, May 21, 2021.* **Notes:** NSIDC is the U.S. National Snow and Ice Data Center, the source that synthesized the satellite observation data (the bold black line) in this figure. The "historical" values result from model simulations, showing the modeled mean and the ranges. The projections (in colors) are for a range of greenhouse gas scenarios and associated climate changes, with the means of results represented by lines. SSP means "Shared Socioeconomic Pathway" scenarios produced in support of the International Panel on Climate Change depicting high (SSP585), medium high (SSP30), low (SSP245) and very low (SSP126) scenarios. The shaded areas represent the ranges of numerical model estimates (number), either historical and projected. The horizontal line represents sea-ice areal extent of 1 million square kilometers, below which scientists consider the Arctic to be practically ice-free.

matter and nutrients to Arctic near-coastal zones, with implications for algae, ecosystems, fisheries and other systems.

Sea Ice Decline and Mobility

Arctic sea ice has declined in extent, area, and thickness over recent decades; it has become more mobile and its spatial distribution has shifted. The record low extents of Arctic sea ice in 2012 and 2007 (**Figure 1** and **Figure 2**), as recorded by U.S. National Snow and Ice Data Center, increased scientific and policy attention on climate changes in the high north, and on the implications of projected ice-free[9] seasons in the Arctic Ocean within decades. Recent late summer minima may be unprecedented over the past 1,000 years.[10] (Some implications are discussed in sections of this report on Commercial Sea Transportation; Oil, Gas, and Mineral Exploration; and others.) The 2021 Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) concluded that "human influence is very likely the main driver of ... the decrease in Arctic sea ice area between 1979–1988 and 2010–2019 (about 40% in September and about 10% in March)."[11]

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[9] In scientific analyses, "ice-free" does not necessarily mean "no ice." The definition of "ice-free" or sea ice "extent" or "area" varies across studies. Sea ice "extent" is one common measure, equal to the sum of the area of grid cells that have ice concentration of less than a set percentage—frequently 15%. For more information, see the National Snow and Ice Data Center, http://nsidc.org/seaice/data/terminology.html.

[10] SROCC SPM 2019.

[11] Intergovernmental Panel on Climate Change, "AR6 Climate Change 2021: The Physical Science Basis - Summary for Policy Makers," August 9, 2021. https://www.ipcc.ch/report/ar6/wg1/.

Simulations under a wide range of future climate change scenarios indicate that the Arctic could be ice-free in late summers in the second half of this century in model simulations of low to very high greenhouse gas scenarios (**Figure 2**).[12] The first instances of an ice-free Arctic in late summers could occur by mid-century in all scenarios, although model simulations provide a wide range of results.[13] The mean results of model simulations reach ice-free seasons in the 2070s in the highest and low warming scenarios, and later in the very low scenarios. In an analysis of the most recent modeling, a selection of those models that "reasonably" simulate historical sea ice extent indicated that practically ice-free conditions may occur at global temperature increases of 1.3°C to 2.9°C above preindustrial levels.[14] Although sea ice would remain variable in extent and distribution, modeling of future sea ice conditions indicate opportunities for transport through the Northwest Passage and the Northern Sea Route, extraction of potential oil and gas resources, and expanded fishing and tourism, though also increasing competition and potential security risks and of oil spills and maritime accidents.

The U.S. Arctic Report Card 2021 noted, in addition, the importance of melting of Arctic land- based ice to experienced sea level rise globally:

> In the 47-year period (1971–2017), the Arctic was the largest global source of sea-level rise contribution, 48% of the global land ice contribution 2003–2010 and 30% of the total sea-level rise since 1992. Temperature effects are dominant in land ice mass balance.

A special report of the IPCC stated that "for Arctic glaciers, different regional studies consistently indicate that in many places glaciers are now smaller than they have been in millennia."[15]

The Arctic Ocean has been undergoing additional changes: It has been acidifying—with some parts acidifying more rapidly than the Atlantic or Pacific Oceans.[16] Some scientists estimate that acidification of the Arctic Ocean may increase enough by the 2030s to significantly influence coastal ecosystems.[17] Primary production in the ocean has increased, due to decreases in sea ice and increases in nutrient supply.

Land-Based changes

Climate changes in the Arctic have important implications for human and natural land-based systems, through permafrost thawing, erosion, instability, and ecosystem shifts.

The U.S. Geological Survey (USGS) concluded that an increase in coastal erosion on the North Slope of Alaska was "likely the result of several changing Arctic conditions, including declining sea-ice extent, increasing summertime sea-surface temperature, rising sea level, and possible increases in storm power and corresponding wave action."[18] The USGS found that erosion has been occurring at an average rate of 1.4 meters annually and

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[12] Arctic Monitoring and Assessment Programme (AMAP), "Arctic Climate Change Update 2021: Key Trends and Impacts. Summary for Policy-Makers," Arctic Council, May 21, 2021; Marika Holland, Cecilia M. Bitz, and Bruno Tremblay, "Future abrupt reductions in the summer Arctic sea ice," Geophysical Research Letters 33, no. L23503 (2006). But see also Julien Boé, Alex Hall, and Xin Qu, "Sources of spread in simulations of Arctic sea ice loss over the twenty-first century," Climatic Change 99, no. 3 (April 1, 2010): 637-645; I. Eisenman and J. S. Wettlaufer, "Nonlinear threshold behavior during the loss of Arctic sea ice," Proceedings of the National Academy of Sciences 106, no. 1 (January 6, 2009): 28-32; Dirk Notz, "The Future of Ice Sheets and Sea Ice: Between Reversible Retreat and Unstoppable Loss," Proceedings of the National Academy of Sciences 106, no. 49 (December 8, 2009): 20590-20595.

[13] Global climate models do not, in general, simulate past sea ice change realistically and tend to produce less decline in sea ice extent than the latest 15-year trend.

[14] The current temperature increase above the 1850-1900 average is about 1.1oC.

[15] SROCC SPM 2019.

[16] Di Qi et al., "Increase in Acidifying Water in the Western Arctic Ocean," Nature Climate Change 7, no. 3, March 2017.

[17] U.S. Global Change Research Program, "Climate Science Special Report," Fourth National Climate Assessment, Volume 1, October 2017, https://science2017.globalchange.gov/.

[18] Pacific Coastal and Marine Science Center, "Climate Impacts to Arctic Coasts," U.S. Geological Survey, October 15, 2021.

that, while some areas are accreting, others are eroding at rates as high as 20 meters per year. Coastal erosion poses risks for native communities, oil and gas infrastructure, and wildlife; adaptations to mitigate and manage adverse impacts can be costly and risky.

Warming temperatures have increased thawing of near-surface permafrost. “The majority of Arctic infrastructure is located in regions where permafrost thaw is projected to intensify by mid- century,” according to the IPCC special report on the cryosphere.[19] Existing infrastructure was not generally placed or engineered for the instability, posing risks to human safety and property, and potentially disruption. The IPCC report assessed that “about 20% of Arctic land permafrost is vulnerable to abrupt permafrost thaw and ground subsidence,”[20] increasing risks of sudden failures. According to one study, 30%–50% of critical circumpolar infrastructure may be at high risk by 2050. “Accordingly, permafrost degradation-related infrastructure costs could rise to tens of billions of U.S. dollars by the second half of the century.”[21] Other costs could be incurred for relocation of infrastructure and villages, and to manage habitat for subsistence wildlife and endangered and threatened species.

Impacts of climate change on species have been positive and negative. Longer growing seasons have resulted in vegetation growth around the Arctic with overall “greening,” though also some “browning” in some regions in some years. Woody shrubs and trees are projected to expand to cover 24%–52% of Arctic tundra by 2050.[22] Vegetation changes can provide amplifying feedbacks that increase temperature and permafrost instability. In particular, scientists have assessed significant methane emissions from some thawing peat bogs.

Potential area burned by wildfire could increase by 25% to 53% by 2100. This could affect, for example, forage for caribou and shifting competition between caribou and moose, with likely detriments to subsistence users of caribou.[23]

The IPCC special report on the cryosphere also found that

> On Arctic land, a loss of globally unique biodiversity is projected as limited refugia exist for some High-Arctic species and hence they are outcompeted by more temperate species (medium confidence).[24]

It identified negative impacts also on food and water security in the Arctic, “disrupt[ing] access to, and food availability within, herding, hunting, fishing, and gathering areas, harming the livelihoods and cultural identity of Arctic residents including Indigenous populations.”[25] More broadly, warming and ecosystem shifts have “increased risk of food- and waterborne diseases, malnutrition, injury, and mental health challenges especially among Indigenous peoples.”[26]

Few studies have investigated the potential economic effects of the array of physical impacts. A report for the state of Alaska on the economic effects of climate change

> estimated that five relatively certain, large effects that could be readily quantified would impose an annual net cost of $340–$700 million, or 0.6%–1.3% of Alaska’s GDP. This significant, but relatively

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[19] SROCC SPM 2019.

[20] SROCC SPM 2019.

[21] Hjort, Jan, Dmitry Streletskiy, Guy Doré, Qingbai Wu, Kevin Bjella, and Miska Luoto, “Impacts of Permafrost Degradation on Infrastructure,” Nature Reviews Earth & Environment 3, no. 1 (January 2022): 24–38, https://doi.org/ 10.1038/s43017-021-00247-8.

[22] SROCC SPM 2019.

[23] SROCC SPM 2019.

[24] SROCC SPM 2019.

[25] SROCC SPM 2019.

[26] SROCC SPM 2019.

> modest, net economic effect for Alaska as a whole obscures large regional disparities, as rural communities face large projected costs while more southerly urban residents experience net gains.[27]

The research did not consider "nonuse" impacts, such as on culture, subsistence harvests, or other nonmarket values, as well as additional sectors, such as military installations, housing, and others.

Another study estimating the effects of climate change on Alaskan infrastructure found "cumulative estimated expenses from climate-related damage to infrastructure without adaptation measures (hereafter damages) from 2015 to 2099 totaled $5.5 billion (2015 dollars, 3% discount) for RCP8.5 [a high climate scenario] and $4.2 billion for RCP4.5 [a moderate climate scenario], suggesting that reducing greenhouse gas emissions could lessen damages by $1.3 billion this century."[28] Costs were mostly due to road flooding and permafrost instability, and mostly in the interior and southcentral Alaska. It also concluded that adaptation measures could mostly reduce or entirely avoid the estimated economic losses for this land-based infrastructure.

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[27] Berman, Matthew, and Jennifer I. Schmidt, "Economic Effects of Climate Change in Alaska." Weather, Climate, and Society 11, no. 2 (April 1, 2019): 245–58, https://doi.org/10.1175/WCAS-D-18-0056.1. The five effects evaluated were change in value added in Alaska (value of shipments less cost of inputs purchased from outside Alaska) for specific industries; change in household cost of living; change in purchased input costs for businesses and governments; change in nonwage benefit flows to households, including subsistence benefits; and change in value of buildings and infrastructure.

[28] Melvin, April M., Peter Larsen, Brent Boehlert, James E. Neumann, Paul Chinowsky, Xavier Espinet, Jeremy Martinich, et al., "Climate Change Damages to Alaska Public Infrastructure and the Economics of Proactive Adaptation," Proceedings of the National Academy of Sciences 114, no. 2 (January 10, 2017): E122–31, https://doi.org/ 10.1073/pnas.1611056113.

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