California's Water Crisis in the Context of Global Warming: Water Resources Future Trends, and Countermeasures

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Abstract: Since the advent of the Second Industrial Revolution, the accelerated development of science, technology, and industry has precipitated an unprecedented rate of resource consumption, particularly of Earth's natural reserves. This industrial activity has significantly contributed to greenhouse gas emissions, predominantly carbon dioxide, thereby exacerbating global warming. The repercussions of these environmental changes are profound, affecting ecosystems and various natural resources, with water resources being notably impacted. This study focuses on the water crisis in California, highlighting the dual challenges of pollution and excessive water resource consumption. By examining the past two decades, this paper analyzed the interplay between groundwater depletion, climate change, and the increasing aridity of California's landscapes. This analysis is crucial for the long-term management of water resources, offering data and insights to address current water challenges, ensure future water sustainability, and inform the development of effective policies and strategies.

1 INTRODUCTION

Global warming is a major issue in the world in the 21st century. Since the mid-20th century, the Earth's land and ocean surface temperatures have continued to rise, and this phenomenon is mainly due to the emission of large amounts of greenhouse gases, including carbon dioxide, methane and nitrogen oxides. Greenhouse gases accumulate near the atmosphere and allow the sun's short-wave radiation to pass through, but the long-wave radiation emitted by the earth is blocked and absorbed, causing the earth's surface and atmosphere to increase in temperature, forming the greenhouse effect. Since the Industrial Revolution, industry has developed rapidly and the use of fossil fuels has been increasing, resulting in rising anthropogenic greenhouse gas emissions. According to a report published by the IPCC in 2023, global greenhouse gas emissions increased by an average of 1.5% per year from 2009 to 2018 (Yang et al., 2023). In 2022, global CO_2 emissions reached 36.1±0.3 Gt, an increase of 1.5% compared to 2021 (Liu et al., 2023). From 1850 to 2020, the global surface temperature has risen by about 1.1℃, which will lead to sea level rise and increase the frequency of extreme weather events such as heat waves, heavy precipitation, and droughts, which will affect millions of human habitats in the future.

As the third largest state in the United States in terms of area and the largest state in terms of total production in the United States, California has diverse characteristics in terms of geography, landform, products, and population composition. California's economy is dominated by agriculture, which is more than twice the size of its second-largest industry, along with aviation, entertainment, and light industry (Helbling and Meierrieks, 2023 & Pedersen et al., 2022). However, California's industrial development makes it more susceptible to climate change due to its climatic diversity and rich landform features (coastal, inland, and alpine regions). During the 2007–2009 and 2012–2016 periods, California experienced two periods of extreme drought, with the Central Valley, for example, losing groundwater reserves by 19 and 28 cubic kilometers, respectively. In the two post-drought recovery periods of 2010–2011 and 2017–2019, the recovery rate of groundwater was very low, with only 34% and 19% restored (Alam et al., 2021). Nearly two decades of successive droughts have also led to significant impacts on California's water resources and ecosystems, including years of below-average precipitation, high temperatures, and extreme droughts that have led to significant reductions in

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river flows and groundwater reserves (which have also led to a decline in soil moisture and the effects of drought on a large number of plants, including wild plants and agricultural crops, especially in inland forest areas, with increased vegetation mortality). In a recent study climate change in California has led to an increase in the frequency and intensity of droughts, especially in the interior, which will lead to the early depletion of soil moisture resources, and the vegetation of grassland ecosystems will remain in a state of drought for a long time and die rapidly, increasing the risk of wildfires and even leading to desertification in parts of California (Warter et al., 2021).

The purpose of this paper is to study the water resources situation in California in the context of climate change in the past two decades, identify the problems of the water crisis, analyses and predict the future global greenhouse gas emissions and water use management trends in California, and put forward suggestions for policy-making, industrial, urban and agricultural water use, etc., in order to alleviate the water crisis in California in the next decade.

2 CURRENT STATUS AND FUTURE TRENDS OF CALIFORNIA'S WATER RESOURCES UNDER GLOBAL WARMING

2.1 California Water Resources Status

Over the past two decades, average annual temperatures in California have risen by more than 1 °F (about 0.56 °C), with some areas experiencing increases of more than 2 °F (about 1.1°C). According to forecasts, average daily maximum temperatures will rise by 4.4–5.8°F(about 2.4–3.2°C) by the middle of this century, and by the end of the century, this increase may reach 5.6°F to 8.8 °F(about 3.1– 4.9°C). California has been grappling with increasing water demands and emerging water conflicts brought about by population growth, agricultural demands, and increasingly severe climate change. Previous studies have shown that California mainly relies on surface water and groundwater to supply urban and agricultural water, but the supply of surface water is decreasing due to drought and climate variability (Dahlke et al., 2018 & Moyers et al., 2024). At the same time, over-exploitation of groundwater has led to problems such as well depletion and land subsidence, and water stress continues to increase despite water conservation measures. To this end, California enacted the Sustainable Groundwater Management Act in 2014 to ensure the long-term availability of groundwater. In addition, water resources projects, including the State Water Project and the Central Valley Project, facilitate the replenishment of surface water from water-rich Northern California to arid areas such as Southern California and the Central Valley.

Despite the above significant progress in water management, California continues to attempt to adopt multifaceted strategies to comprehensively address the water crisis (Table 1). These initiatives cover water resources planning, conservation, development of alternative water sources (such as desalination and recycled water use), sustainable groundwater management, and measures to combat climate change. In addition, the state is actively responding to the impacts of climate change by strengthening infrastructure and promoting green infrastructure solutions.

Table 1: California Water Management Plans

Purpose	Corresponding policies	Policy content
Water resources planning and utilization	California Water Plan	California' s long-term water management strategy, updated every five years, is designed to ensure sustainable use of water resources across the state. The plan includes improving water use efficiency, developing alternative water sources, improving water supply infrastructure, etc.
	Integrated Regional Water Management (IRWM)	Through regional collaboration, the IRWM program promotes water management across sectors and regions to increase efficiency and flexibility
	Urban Water Management Plans	Require city water suppliers to submit detailed water use plans every five years, including water conservation measures and contingency plans

Alternative Water Resources Development	Desalination Project	Promote the construction and operation of desalination plants to increase drinking water supplies, such as the Carlsbad Desalination Plant
	Reclaimed Water Utilization Water Recycling and Reuse	Promote wastewater treatment and reuse technologies to use recycled water for purposes such as agricultural irrigation, industrial cooling and landscape irrigation
Sustainable Groundwater Management	Sustainable Groundwater Management Act (SGMA)	Require local governments and water management agencies to develop and implement sustainable groundwater management plans to prevent over-exploitation of groundwater and land subsidence
Tackling Climate Change	California Climate Adaptation Strategy	Includes improving water infrastructure, increasing reservoir reserve capacity and advancing green infrastructure to increase resilience to droughts and extreme weather events caused by climate change

2.2 Future Trends of California's Water Resources Under Different RCP Backgrounds

Through extensive reading of literature and annual reports of major organizations, different RCP scenarios were considered in the analysis of global greenhouse gas emissions and California water resources trends in the next ten years (IPPC adopted it in the fifth assessment report released in 2014). Under three different RCP scenarios, global greenhouse gas emissions have the following development trends:

(1) Under the RCP 2.6 scenario (ideal case), by developing renewable energy and clean technologies and reducing non-carbon dioxide emissions, global carbon emissions will peak in 2040 and decline rapidly, and global warming will be controlled within 2℃.

(2) RCP 4.5 and 6.0 scenario (moderate): Under this scenario, a more moderate emission reduction plan will be adopted in the future; that is, according to the United Nations Environment Program (UNEP), the current climate change under the Paris Agreement will be fully implemented. It is promised that the global surface temperature will rise by 2.1–2.6℃ by the end of this century.

(3) Under the RCP 8.5 scenario (high dependence on fossil fuels and no control), greenhouse gas emissions continue to grow and if more radical measures are not taken, global emissions will increase sharply and global surface temperatures will rise by 4.3℃ by the end of this century. or even higher, leading to severe climate change impacts.

These scenarios will impact California's water resources, potentially leading to more extreme precipitation patterns, including droughts and flooding events, and increasing the frequency of "climate whiplash" events.by 50–100% (Dahlke et al., 2018 & Ghasemizade et al., 2019). In the next ten years, as the population increases, the demand for water in cities and agriculture will inevitably increase, and competition for water resources will become more intense. But according to the latest California Water Resources Plan, urban water use will be controlled through water management and water conservation measures to keep urban water demand relatively stable until 2035 (Liu et al., 2022).

Based on the California Water Plan, this paper predicts and maps the water resources in California in the next ten years (based on the Climate Model and Historical Data) as follows (shown in Figure1), agricultural water is still the main consumer of water resources in California, with slight fluctuations with the proportion of crops planted each year (Dahlke et al., 2018 & Ghasemizade et al., 2019); The average annual precipitation decreases significantly during the dry period, and gradually rises during the wet period, and so on. Urban water use is increasing year by year due to the rise of California's population, but due to better water-saving measures, annual urban water use will only increase slightly year by year; The efficiency of groundwater restoration is low, but the amount of groundwater used has been reduced, and there are a large number of water-using projects and construction, and groundwater is restored year by year with a stable amount.

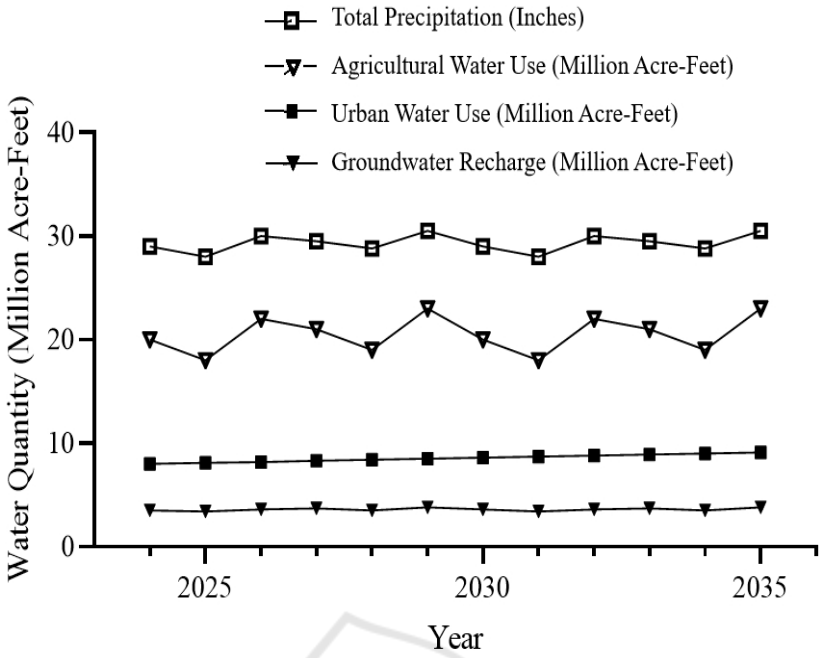

Figure 1: Forecast chart based on California Water Resources Plan.

3 CARBON EMISSIONS AND WATER MANAGEMENT RECOMMENDATIONS TO ADDRESS WATER SCARCITY IN CALIFORNIA

California has made some progress in reducing greenhouse gas emissions, but it still faces some inherent problems, such as industrial emissions, agricultural emissions and water use, and urban living emissions and water conservation. These issues are analyzed in Table 2 and recommendations are made.

Table 2: Countermeasures and suggestions for California emissions

Types	Existing Issues	Plans	Suggested measures
Industrial Emissions	Industry and manufacturing are accounting for about 24% of total emissions.	Carbon Capture and Storage, (CCS)	Invest in carbon capture technologies and promote related demonstration projects
	Industrial terminals emit many emissions	End-of-line treatment technology for treatment at the first time of waste generation	Timely treatment of pollution incidents or wastes that have occurred can significantly improve environmental quality and citizens' health
Emissions from Urban Life and Water Waste	Transportation accounting for about 40% of the state's emissions.	Zero Emission Vehicle Program, (ZEV)	Subsidies for purchases, construction of charging and refueling infrastructure
	Natural gas power generation accounting for about 15% of total emissions	Utilities are required with 50% of electricity coming from renewable sources by 2030	Promoting renewable energy sources to reduce dependence on fossil fuels (Gov-tech)

	Energy use in buildings, including heating, cooling, and electricity consumption accounting for 12% of total emissions	Enforce the California Title 24 Building Energy Efficiency Standard, which requires high energy efficiency in building design and construction	Replace high-efficiency windows, add insulation, upgrade HVAC systems, install solar panels and geothermal energy systems to provide clean energy for buildings, etc
	Methane and other greenhouse gases from landfills and wastewater treatment facilities account for about 2% of total emissions	California Integrated Waste Management Act	Promote waste sorting and resource recycling, carry out waste reduction publicity and education, and support composting projects and recycling technologies
Emissions from agricultural activities and water use	Water conservation in agriculture	Promote drip irrigation and micro-sprinkler irrigation techniques	Delivers water directly to plant roots, reducing water evaporation and soil moisture loss
	Agricultural activities, including livestock farming and the use of chemical fertilizers accounting for about 8% of total emissions	Reduce greenhouse gas emissions by accurately monitoring and managing farmland and optimizing fertilizer and water use.	Use sensors and drone technology to monitor soil moisture, nutrient content, and crop health for precise fertilization and irrigation.

4 CONCLUSION

The California water crisis underscores the critical need for effective water management amidst global warming. Historically, California has struggled with a disparity between water supply and demand, a situation aggravated by climate change. The increasing global greenhouse gas emissions have led to rising temperatures, exacerbating the state's water issues, including declining surface water reserves, over exploitation of groundwater, and land subsidence. As a major agricultural hub in the United States, California's water resources are vital to produce fruits, vegetables, and nuts. Prolonged droughts necessitate the study of water resources to optimize agricultural irrigation, enhance water use efficiency, and ensure sustainable agricultural development.

Moreover, population growth, urbanization, and economic expansion have intensified the demand for water, complicating its management. The future presents even greater challenges due to the unpredictability induced by climate change, complicating forecasts of water supply and demand. Recognizing the urgency, the California government and private sector have undertaken initiatives to address these issues. Efforts include promoting water-saving technologies, improving agricultural irrigation systems, and enhancing water infrastructure. There is a growing societal focus on water resource protection and management, with increased public participation in relevant initiatives.

California must develop a long-term water management strategy and collaborate with neighbouring states and countries to tackle water challenges collectively. This involves sharing expertise and technology and co-developing and implementing water management strategies. Strengthening water resource policies and regulations, raising public awareness of water conservation, and encouraging public participation in water management are crucial. Education and publicity efforts can enhance residents' understanding of water conservation and environmental protection, promoting the rational use of water resources.

Future water management will heavily rely on technological innovations, such as precision agriculture, intelligent irrigation systems, advanced sewage treatment technologies, and comprehensive water monitoring systems. These innovations will significantly improve water efficiency and reduce waste. Despite the challenges, California can mitigate some of the adverse effects of global warming through comprehensive policy measures, innovative technological applications, and active public engagement. Achieving the sustainable use of water resources and minimizing the impacts of the water crisis in California will require a multifaceted approach that integrates policy, technology, and public involvement.

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