forecasting

MDPI

Article

Projecting Climate Change Impacts on Channel Depletion in the Sacramento–San Joaquin Delta of California in the 21st Century

Sohrab Salehi [1], Seyed Ali Akbar Salehi Neyshabouri [1,*], Andrew Schwarz [2] and Minxue He [2,*]

[1] Department of Civil and Environmental Engineering, Tarbiat Modares University, Tehran P. O. Box 14115-111, Iran
[2] California Department of Water Resources, Sacramento, CA 95814, USA
* Correspondence: salehi@modares.ac.ir (S.A.A.S.N.); minxuehe@gmail.com (M.H.)

Abstract: The Sacramento–San Joaquin Delta (Delta) is a critical hub of California's statewide water distribution system. Located at the confluence of California's two largest rivers, the Sacramento River and the San Joaquin River, the Delta features a complex network of braided channels and over a hundred islands, most of which are located below sea level. The Delta's complex nature and low-lying topography make it a unique hydrological area pertinent to climate change studies. This paper aims to estimate and explore the potential effects of climate change on the hydrological features of the Delta, especially Net Channel Depletion (NCD), which is one of the main contributors to the Net Delta Outflow (NDO). Downscaled CMIP6 General Circulation Model outputs are used to generate plausible future climate data. The Delta Channel Depletion model (DCD) is used to simulate daily hydrological processes for 61 plausible future climate scenarios. Simulation models are applied to the historical period (1930–2014) and projected future periods (2016–2100). A thorough water balance is computed in the DCD simulation model, offering insights into various elements in the hydrological cycle. Key hydrological features such as crop evapotranspiration, seepage, drainage, and runoff are simulated. Potential changes in NCD, calculated as the sum of diversions and seepage minus drainage, are also examined. The study identified a wide range of increases in NCD across all scenarios in the future period relative to the average of the historical period. These increases are projected to vary from 0.3% up to 20%. Moreover, a spatial analysis conducted across diverse regions of the Delta highlights notable variations in depletion across these areas. The results of this research indicate an anticipated increased stress on water resources, necessitating the adoption of innovative strategies to manage extreme events effectively and ensure the sustainability and resilience of water resource management.

Keywords: Sacramento–San Joaquin delta; climate change; deep uncertainty; hydrological simulation; net channel depletion; CMIP6

Citation: Salehi, S.; Salehi Neyshabouri, S.A.A.; Schwarz, A.; He, M. Projecting Climate Change Impacts on Channel Depletion in the Sacramento–San Joaquin Delta of California in the 21st Century. *Forecasting* **2024**, *6*, 1098–1123. https://doi.org/10.3390/forecast6040055

Academic Editor: Ajay Kalra

Received: 24 October 2024
Revised: 17 November 2024
Accepted: 18 November 2024
Published: 21 November 2024

1. Introduction

California's water management primarily focuses on five key climatic stressors: increasing temperatures, diminishing snowpack, shorter but more intense wet seasons, more extreme rainfall events, and sea level rise [1]. Historical observations showed a notable increase in average temperatures over the past four decades. The warming climate has a multifaceted impact, including reducing the proportion of precipitation that falls as snow, triggering earlier snowmelt and increased winter runoff, elevating water temperatures, and exacerbating the severity of droughts and floods [2]. Severe droughts like the one experienced from 2012 to 2016 strain groundwater storage, while intense storms put pressure on surface reservoirs [3]. This makes it challenging to balance the need to store water for droughts, protect communities from damaging floods, and preserve freshwater ecosystems. Over the next 20 to 50 years, droughts and floods are expected to intensify, posing significantly higher risks [1,4]. The extensive and sophisticated water supply and distribution system in California, which includes nearly 1500 dams and reservoirs, has aged and become antiquated, as it was constructed over 50 years ago based on past hydrological patterns. Groundwater basins are becoming increasingly vital as drought reserves, yet their full potential remains underutilized due to limitations in management practices and infrastructure. The state's water system, which includes rivers and thousands of miles of canals and aqueducts, has lost some of its capability to transport water. Adapting to climate change will necessitate a more resilient and better-integrated water system [1].

The Sacramento–San Joaquin Delta (Delta), located around the confluence of the Sacramento and San Joaquin Rivers, is one of the most crucial estuarine environments in the western United States (Figure 1). Around 6000 years ago, during the last glaciation, the Delta was created as the rising sea levels submerged the confluence of the Sacramento and San Joaquin Rivers upstream of San Francisco Bay [5]. For thousands of years, sediments have been deposited in the Delta, the lowest point of the Central Valley, by river flows and tidal action. These sediments covered plants and formed thick organic peat soils. However, in the 19th century, the majority of the region was drained, diked, and developed for agriculture, leading to wind erosion and the oxidation of organic peat soils, causing a steady loss of surface elevation. The process of farming has caused peat-rich soils to oxidize and land to sink, with many islands currently positioned 10 to 25 feet below sea level [6]. Today, around 1100 miles of levees have converted about 283,000 ha of Delta tidal marsh into farming "islands" [7,8]. Under normal conditions, the low elevation of the land facilitates the efficient use of siphons to divert water for irrigation, minimizing energy consumption. To remove excess water from the crop root zone, these low-lying islands utilize pumps to return the water to nearby channels. Additionally, the hydrology of Delta islands is influenced by factors such as crop evapotranspiration, seepage through levees, and the interactions between local groundwater and the root zone of the crops [9]. Water from the Delta is pumped and conveyed through several aqueducts under the two main water supply programs, the Central Valley Project (CVP) and the State Water Project (SWP), to provide for the needs of approximately 30 million people and over 2.4 million ha of agricultural land. The timing and volume of these diversions are subject to strict regulatory oversight through state and federal administrative directives, aiming to ensure flow and water quality standards within the Delta while also upholding additional protective measures for threatened and endangered species [10].

The inflow of fresh water through the Delta is of utmost importance in mitigating the intrusion of saline waters from San Francisco Bay. From an ecological standpoint, this area stands out as one of the 25 critical biodiversity hotspots worldwide, earmarked as a top priority for international conservation efforts [11]. It serves as a direct habitat or support system for approximately 750 plant and animal species, some of which are on the verge of extinction [12]. Delta outflow, or the freshwater flow to the San Francisco Bay, is a crucial variable for decision-makers. The precise quantification of freshwater outflow to San Francisco Bay is crucial for the sustainable management of the water resources, supporting its diverse uses and improving the accuracy of simulations of hydrodynamic and water quality variations. This outflow is challenging to measure because of the channels' size and tidal interactions. Instead, outflow estimates are derived using a daily water balance evaluation that accounts for upstream inflows from the Delta, water exports, and consumption within the Delta. This calculation is known as the Net Delta Outflow Index (NDOI). The NDOI is computed as the total of the daily river inflows across the periphery of the Delta minus the water exports and depletions within the Delta channel [9].

Water diversions onto agricultural lands for irrigation are also challenging to measure because of the absence of meters and the utilization of siphons and pumps in Delta channels, which experience constantly changing water levels. These diversions are located at over 1800 sites within the Delta [13]. Seepage occurs from the neighboring channels in the Delta, particularly in the low-lying areas below the 5-foot mean sea level. While the seepage onto the islands in the Delta lowlands is not directly measured, it plays a role in the depletion of the channels. Estimates of Delta channel depletions are primarily based on crop water demands, specifically crop evapotranspiration (ET), and the corresponding water sources allocated to meet these demands. The leaching of salts from the root zone through extensive irrigation is also prevalent in the lowlands. Typically, the application of leach water occurs between October and December, with drainage occurring from January to April. Excess water, which includes irrigation water, leach water, and surface runoff from precipitation, is pumped from the Delta islands and returned into the channels [14].

1.1. Background of Analysis

Several studies have employed climate change datasets to examine the potential changes in California's hydroclimate and their consequences for managing the state's water resources. While many other Mediterranean climate regions are expected to be drier due to a decrease in the frequency of winter precipitation, projections of changes in annual precipitation for California remain inconsistent [15–17]. It has been common practice in various research studies to employ hydrological models, such as the Variable Infiltration Capacity (VIC) or Sacramento Soil Moisture Accounting (SAC-SMA) model, to capture the variability of the primary inflows into California's Central Valley water system in response to global warming [18–20]. Most of these studies reported increased vulnerability, environmental concerns, and decreased reliability and water supply deliveries for the 21st century compared to the historical period [18]. However, disagreement between models is also described [19,21]. Some studies have shown a significant reduction in snowfall and advancement in the timing of snowmelt within the Central Valley mountains, which has made water management more complex [22–25]. As the central hub for water distribution in California, the Delta has been extensively studied by water and climate researchers. While it is highly probable that there will be a temperature rise in this region during the 21st century, there is a lack of consensus among various models regarding the alterations in annual precipitation. Therefore, using averages or ensembles of climate models may not reveal significant changes in precipitation and could be misleading [10,26]. From a hydrological point of view, both the Sacramento and San Joaquin Rivers are already showing signs of declining late winter and spring flows [26]. In addition, there will be significant changes in the temporal distribution of precipitation [10]. These situations will make sustainable management much more difficult.

Calculating the water balance in the Delta is a matter of debate in several studies [14,27,28]. The following provides some of the main methods used during several past decades. One of the common methods for this purpose is a methodology called Dayflow, a computer program developed in 1978 that serves as an accounting tool for estimating the daily average outflow from the Delta [14]. It is computed annually, following the beginning of the new water year (1 October) [28]. The Delta Island Consumptive Use Model (DICU) was developed to enhance estimates of Delta channel depletion compared to DAYFLOW [13,29]. It aims to improve the modeling of Delta conditions by incorporating both spatial variations in Delta channel depletion and temporal patterns related to irrigation seasons. DICU conducts monthly estimations to determine the water inflow, outflow, and storage levels for each 142 Delta subareas. The factors considered in water monitoring are land use, plant rooting depths, seepage, soil moisture, irrigation season, evapotranspiration, and precipitation [13]. The University of California (UC) at Davis developed the first version of the Delta Evapotranspiration of Applied Water model (DETAW v1.0) in 2006 to improve the estimation of consumptive water demands in the Delta [30]. DETAW estimates for water consumption in 168 subareas of the Delta Service Area. Unlike DICU, DETAW operates on a daily time scale and thus relies on daily measurements of unit consumptive use and precipitation. DETAW, with its daily time step, can replicate both the volume and salinity response of large, sporadic runoff events, which is not possible with the DICU model [14,31,32]. An additional development was necessary to incorporate DETAW-based information into Delta modeling. The program was rewritten in Python script; seepage assumptions were updated; crop coefficients were calibrated based on satellite images of consumptive use; island diversions, seepages, and drainages were estimated to calculate net channel depletion; and model nodes were assigned island diversions, seepages, and returns. DETAW v2.0 results from combining these efforts [33].

The estimation of withdrawal from and drainage into the streams that flow between the islands of the Delta has been a matter of debate in several recent decades. A precise estimate of net channel depletion (NCD) is crucial to computing the NDOI, a critical benchmark for managers and policymakers when making decisions. Since there is no explicit NCD measurement, most previous studies have relied on indirect methods for calculating NCD. Many studies have shown substantial deviations in the Delta outflow and measured salinity when using the simplified hypothesis that Delta net depletion is equal to the crop evapotranspiration of the Delta islands [9,34]. Empirical studies conducted during the 1960s revealed a persistent discrepancy in the NDOI estimates [35], wherein it consistently underestimates the flow in summer and fall and overestimates it in winter and spring. These inaccuracies are attributed to the combination of evapotranspiration from the Delta islands and unmeasured water exchanges between the waterways and the islands.

1.2. Motivation and Scope

It is widely accepted that human activities have contributed significantly to the warming of the atmosphere, ocean, and land. The documented rise in greenhouse gas concentrations since approximately 1750 is very likely attributable to human actions. There is high confidence that extreme climate occurrences, including droughts and floods, are becoming more prevalent in the majority of terrestrial areas [36]. As the most populous state in the United States, California experiences a significant variability in the projected trends of key climatic variables, such as temperature and precipitation, as evidenced by a range of scholarly investigations [15,37–39]. The Delta, which serves as a pivotal point for California's water supply, will face various impacts from climate change. Rising sea levels and intensified droughts will elevate the salinity levels in the Delta, necessitating increased discharges from upstream reservoirs to maintain sufficiently fresh water for agricultural, urban, and export purposes within the Delta [40].

These variabilities are often exacerbated when integrating climatic variables into hydrological models. Consequently, this growing uncertainty presents substantial challenges for policymakers engaged in integrated water resource management, as it hampers their ability to make robust and sustainable decisions. The latest body of research has yielded conflicting results in light of the widely held belief that employing advanced global circulation models (GCMs) can alleviate uncertainty in climate projections. Despite what was expected, the research has indicated that the uncertainties related to these newer models, particularly CMIP6, have widened in certain areas, like the Central Valley of California [19,41]. This unexpected finding highlights the ongoing challenges inherent in climate modeling and underscores the need for continued research to improve our understanding of these uncertainties and their implications. Climate change may alter the hydrological processes in various ways. This research investigates how one of the world's most regulated Delta systems, the Sacramento–San Joaquin Delta, could be affected by climate change using the outputs of CMIP6 models.

The inflow of water into the Delta, stemming from its extensive catchment area incorporating a substantial portion of California, significantly outweighs the hydrological exchanges within the Delta region. Nonetheless, recognizing the ecological and strategic significance of the Delta area, the analysis of hydrological exchanges such as runoff, evaporation, transpiration, and interactions with subsurface water reservoirs has been a focal point of interest for natural science researchers in recent decades [5,42–44]. The unique water withdrawal and agricultural drainage techniques in this region, coupled with the islands' topography, engender a dual layer of complexity in simulating the Delta's hydrological processes. These simulations also serve as indispensable tools for the water resource planners of the Delta region and local farmers, facilitating the implementation of more efficient management practices by discerning the precise quantities of water withdrawal and drainage from each of the islands. As a result of increased competition for water, rising concerns about environmental consequences, and the changing climate, the reliability of sustainable water supplies from Delta is now decreasing. This requires a more precise accounting and modeling of the water cycle in the Delta and its watershed. This work focuses on an ungauged quantity known as channel depletions, which refers to the sum of diversions from Delta channels onto adjacent islands minus in-Delta return flows and precipitation.

This study addresses three primary research questions. First, we investigate how net Delta channel depletion may evolve over the remainder of the 21st century by leveraging CMIP6 datasets to project future changes. Second, we explore how climate change may impact different components of the total depletion. Finally, we examine how the depletion varies spatially across distinct regions within the Delta, identifying the spatial contributions to overall depletion patterns and supporting the development of localized adaptation strategies for sustainable water management. To summarize, this study aims to evaluate and analyze the potential alterations in several Delta hydrological variables in the shadow of climate uncertainty.

Following this Introduction, the paper proceeds as follows: Section 2 provides an in-depth examination of our study area, calculation procedures, simulation model, and assumptions. Subsequently, Section 3 presents the outcomes of our analysis. Finally, Sections 4 and 5 offers a reflection on these findings, explores the limitations of our study, and proposes directions for further investigation.

2. Materials and Methods

2.1. Study Area

The Sacramento–San Joaquin Delta, situated at the confluence of California's two primary rivers—the Sacramento and the San Joaquin—is depicted in Figure 1. The geographic positioning of the Delta, the San Francisco Bay, and California's two main rivers—the Sacramento River and the San Joaquin River—is illustrated in section A of Figure 1. Furthermore, Figure 1B details the 168 subdivisions within the Delta, often referred to as Delta islands, alongside the seven meteorological stations from where historical data are gathered. In the context of water resource management simulation models, grouping these islands into larger segments can enhance efficiency. For instance, the CalSim3 model consolidates the 168 Delta islands into seven distinct regions. The latest version of the California water resources system planning model, CalSim3, simulates how SWP and CVP might operate under various planning scenarios limited by legal limitations, such as permissible salinity levels at different Delta locations [45,46]. Section C of Figure 1 presents Google Earth imagery of the Delta region, superimposed with these seven subregions utilized as input parameters for the CalSim3 model. According to the historical precipitation data of 1916–2011, the Delta has an average annual precipitation of approximately 370 mm [10,47]. The long-term mean annual maximum temperature is approximately 23.1 °C, the average temperature is around 16.3 °C, and the minimum is about 9.4 °C [10]. The wet season (October–March) experiences a majority of precipitation owing to the Mediterranean climate of the Delta's location. The dry season (April–September) precipitation only accounts for 12–13% of the total annual precipitation across Delta subregions [10].

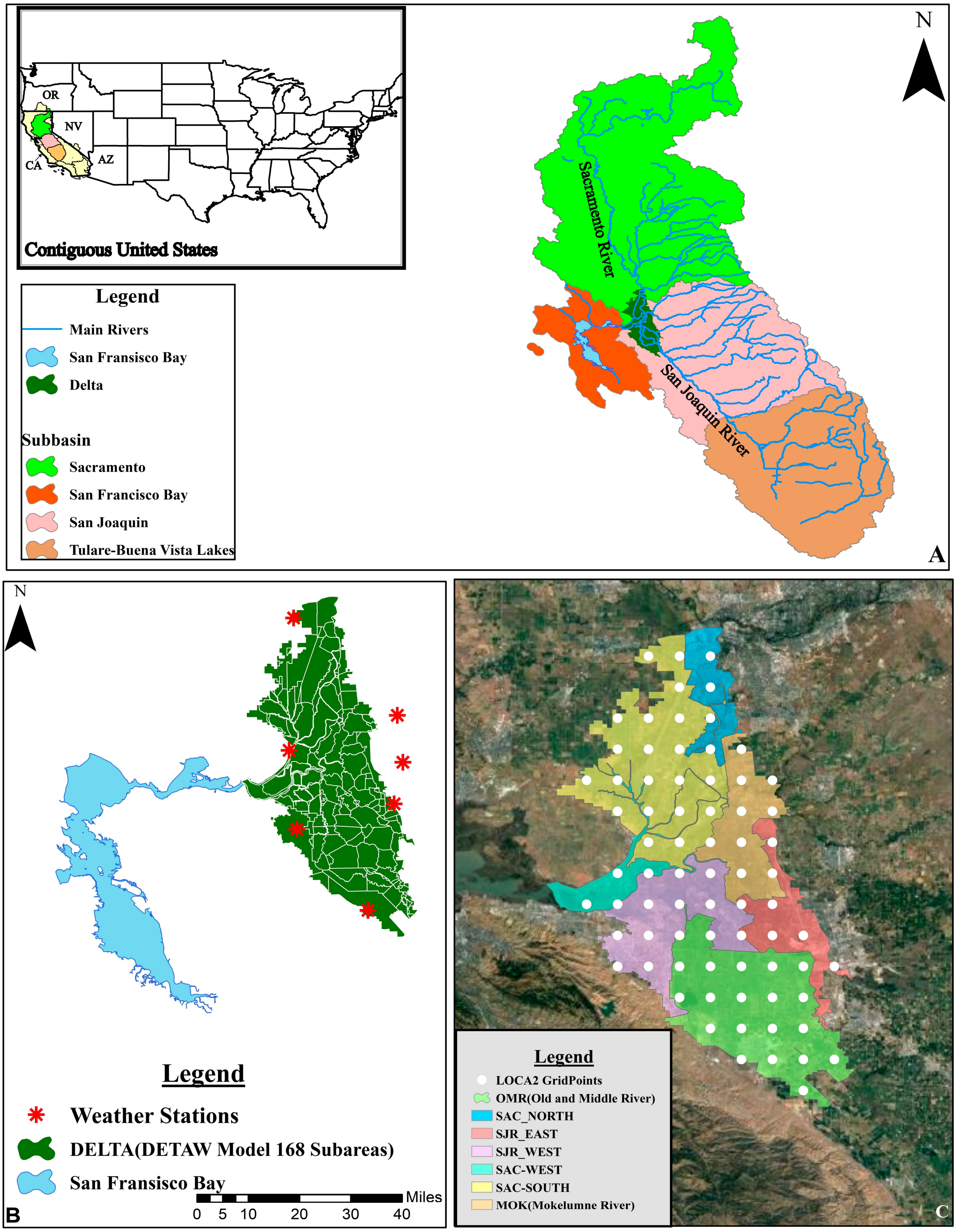

Figure 1. Delta dynamics: an integrated view of the Sacramento–San Joaquin's islands, weather stations, and CalSim3 subregions: (**A**) geographic positioning of the Delta, San Francisco Bay, and California's two primary rivers (Sacramento and San Joaquin); (**B**) 168 Delta subareas (islands); (**C**) aerial image of Delta region and seven subregions defined in the CalSim3 simulation model [48].

2.2. DCD Simulation Model

The Delta Channel Depletion (DCD) model enhances the functionality of its predecessor, known as DETAW. Using the root zone hydrological assessments conducted by DETAW, DCD provides a framework for calculating the daily water dynamics within the Delta, incorporating variables such as diversions, drainages, and infiltration across all 168 Delta islands. The model captures key water balance factors, including lowland and upland water sources, surface runoff, and agricultural activities, consistent with DETAW's foundational elements. DCD uses the algorithms and parameters derived from the Delta Island Consumptive Use (DICU) model. These elements are crucial for accounting for agricultural practices, evaluating irrigation efficiency, and supporting allocation decisions in hydrodynamic modeling of the islands (e.g., the DSM2 model).

In addition, DCD recognizes the significance of both regional groundwater in the Delta uplands and subsurface water in the Delta lowlands for meeting the water needs of the Delta ground surface [49]. Delta state-of-the-art hydrological models, DETAW v2.1 and DCD v1.2, the latest model versions, maintain all core parameters and algorithms from prior versions, with interface adjustments to support planning applications. In this paper, DCD and DETAW refer to these updated versions unless stated otherwise.

DCD employs five groups of inputs, with its primary input derived from the outputs of DETAW. DETAW estimates the daily actual evapotranspiration (ET) and the root zone water balance across 168 subareas within the Delta. For each subarea, the root zone water balance is derived from the combined effects of applied irrigation water, precipitation, seepage, and soil moisture variations, all contributing to meeting the water demand represented by ET [50]. The dataset encompasses daily evapotranspiration (ETc), total precipitation (PPT), effective seepage (S_E), daily drop of soil water content (Dsw), ET of applied water (ETaw), and effective rainfall (PPT_E). Other input categories include DICU parameters, leach application characteristics, leach drainage characteristics, and groundwater contribution rates, specific to each island and crop type.

DETAW, as a core of DCD, demands a broad input dataset that includes main control parameters, daily precipitation in 7 stations around the Delta (depicted in Figure 1B), daily maximum and minimum temperature at Lodi station, crop and soil parameters in critical and noncritical years, land use of 168 subareas and precipitation and evapotranspiration correction factors. The precipitation data are derived from seven stations, namely Brentwood, Davis, Galt, Lodi, Rio Vista, Stockton, and Tracy [50].

The water balance components of the current form of the Delta are shown in Figure 2. DCD formulates this cycle as indicated in Equations (1)–(5). DCD introduces a new coefficient, Sr, into the equations derived from DETAW. This term provides a method of accounting for the additional subsurface water in lowlands and groundwater contribution in uplands. The applied and drained leach water have also been revised. Except for Sr, LW_A, and LW_D, all terms in the equations remain unchanged from DETAW [34].

$$\text{Channel Depletion (CD)} = \text{Diversion (DIV)} - \text{Return Flow/Drainage (RET)} + \text{Seepage (S)} \quad (1)$$

$$V = (1 - S_r) \times \frac{I_{AN}}{\eta} + \mathrm{LW}_A \quad (2)$$

$$ET = RO + I_{AN} \times \frac{1-\eta}{\eta} + \mathrm{LW}_D + S_D \quad (3)$$

$$\begin{array}{ll} S = (1 - S_r) \times (S_E + S_D) & \text{(For Lowlands)} \\ \mathrm{S} = 0, \mathrm{S_E} = \mathrm{S_D} = 0 & \text{(For uplands)} \end{array} \quad (4)$$

$$O = (1 - DP) \times (\mathrm{PPT} - PPT_E) \quad (5)$$

where

I_{AN}: Irrigation calculated by DETAW;
S_r: Contribution rate of the subsurface water (in lowlands) or groundwater (in uplands);
η: Irrigation efficiency factor;
LW_A: Applied leach water;
RO: Runoff;
LW_D: Drained leach water;
S: Total seepage;
S_D: Drained seepage;
S_E: Effective seepage;
DP: Deep percolation rate;
PPT: Precipitation;
PPT_E: Effective precipitation;

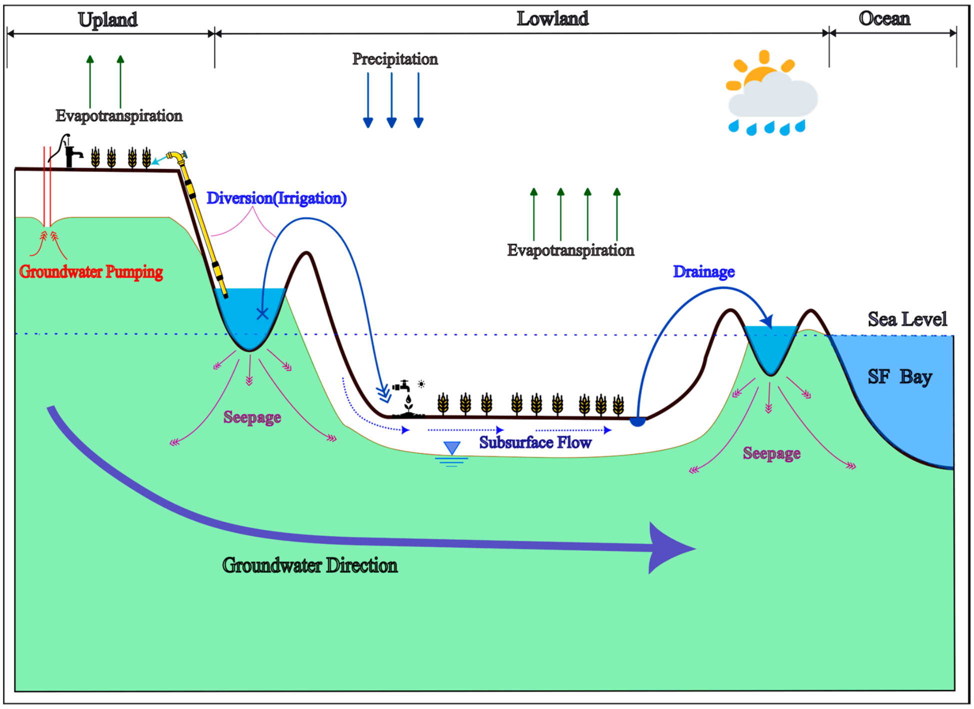

Figure 2. Water balance of a typical Delta island (adopted and revised from [34]).

The DCD model, in conjunction with the Delta Simulation Model 2 (DSM2), was calibrated and validated for historical hydrological conditions, using the integrated modeling approach outlined in [34]. DSM2 serves as a computational tool designed to analyze hydrodynamics and water quality within the Delta, with a particular focus on predicting salinity patterns [51]. By integrating river, estuarine, and terrestrial system models, DSM2 facilitates the estimation of water flows, surface water elevations, and flow velocity. Its application in this context extends to modeling salinity transport, which is influenced by Sacramento and San Joaquin River inflows and tidal dynamics from the San Francisco Bay [52]. The calibration of the integrated DCD and DSM2 models focused on the interaction between the Delta outflow and salinity in the western Delta, allowing reliable estimates of net Delta-wide channel depletion despite limited parameter data for each island. This process involved calibrating and validating the impacts of subsurface water and groundwater on both channel depletion and electrical conductivity (EC) over a 40-year period of observed data from six Delta sites. The results at the Sacramento–San Joaquin confluence showed that subsurface and groundwater contributions significantly influence Delta surface water conditions, validating the importance of these linkages for accurate salinity intrusion modeling [34]. Although this calibrated model underpins the current study, additional rigorous calibration using more diverse observed data is recommended for future studies to further improve model accuracy and robustness.

In the absence of observed data for key processes, DCD assumes full mixing of root zone water sources, including channel diversions, precipitation, seepage, and groundwater. The groundwater contribution rate in Delta uplands, a critical parameter, was estimated from the historical data on well numbers, as precise groundwater pumping data was unavailable. Well numbers increased from 2 in 1931 to approximately 450 in 2009, and a linear relationship was used to estimate groundwater contributions, assuming uniform well yields. For Delta lowlands, a previous study [53] identified significant discrepancies between drainage and inputs from precipitation and irrigation. To reflect these patterns, subsurface water rates (Sr) were calibrated to values of 0.25, 0.3, and 0.35, depending on island subsidence. The calibration of leachate volume and timing was also achieved using electrical conductivity (EC) observations [34].

2.3. Climate Change

To capture the most recent available knowledge, the 6th phase of the Coupled Model Intercomparison Project (CMIP) models was chosen [54]. This selection aligns with the determination of the uncertainty bounds of the climate variables involved in the DCD model, specifically daily precipitation and temperature. One of the recent advanced downscaling methods is the Localized Constructed Analogs (LOCA) method of statistical downscaling, which was used for the 4 the Fourth California State and Fourth United States National Climate Assessments [55,56]. Using a multiscale spatial matching scheme, the LOCA method selects suitable analog days from observations to produce downscaled estimates for hydrological simulations. Initially, a selection of potential analog days is determined by comparing the downscaled model field with observed days in the region that show a positive correlation with the point of interest. This ensures that the downscaling outcomes are inherently unaffected by the domain size. Then, it uses the single analog day with the best match in the local vicinity of the grid cell of interest as the downscaling source. In most cases, downscaled grid cells are assigned a single analog day chosen locally. However, when neighboring cells have different analog days, a weighted average of the center and neighboring analog days is employed to prevent edge discontinuities [57]. There are two versions of the LOCA method. LOCA1 was the method employed to downscale the CMIP5 data. Version 2 of LOCA uses an improved precipitation training data set [58,59], downscales more ensemble members per model, applies a more robust bias correction method for precipitation [60], and downscales more emissions scenarios than LOCA1. Using CMIP6, LOCA version 2 at 6 km was applied to the North American domain (covering roughly southern Canada to central Mexico) and was completed in late 2022. The downscaled dataset is among the sources of information used for the Fifth National Climate Assessment (NCA5). LOCA2 downscaled daily minimum and maximum temperature and precipitation, which are used in the current study, are gathered from [61]. The dataset has a spatial resolution of 6 km and covers the period from 1950 to 2100. To further elaborate on this, the central points of the grids situated within the Delta are illustrated as white dots in Figure 1C. The dataset comprises three Shared Socioeconomic Pathways (SSPs) that depict various scenarios of greenhouse gas emissions and socioeconomic development: SSP 245 (sustainability), SSP 370 (middle of the road), and SSP 585 (fossil-fueled development), but only if the original GCM ran those scenarios. Each SSP has up to 10 ensemble members from different GCMs. In this study, we used the most prominent variant, r1i1p1f1. Out of the 27 downscaled GCMs available, we selected 21 with the desired scenarios and listed them in Table A1 in the Appendix A. Daily minimum and maximum temperatures for the Lodi station point and daily precipitation for Brentwood, Davis, Galt, Lodi, Rio Vista, Stockton, and Tracy station points were derived from the dataset for each of the GCMs and scenarios. Two 84-year periods were chosen for comparison based on the available historical observed data. The historical period spans from October 1929 to September 2014 (WY1930-WY2014), while the future period covers October 2015 to September 2100 (WY2016-WY2100).

It is worth noting that this study is centered exclusively on exploring hydrological processes within the Delta region. The inflows from upstream basins, specifically the Sacramento and San Joaquin Rivers, as well as the outflow to the San Francisco Bay, are assumed to have no impact on the calculation of hydrological variables in this research. These variables include rainfall runoff, evapotranspiration, and exchanges with surface and groundwater currents. It is essential to highlight that, based on the regulations and criteria dictating the water flow in this region, the water inflow throughout all seasons exceeds the agricultural requirements of the Delta islands. Therefore, the simulations consistently assumed no restrictions on the withdrawal, distribution, or drainage of agricultural water within the Delta. Additionally, for future scenario simulations, we assumed that key agricultural practices—such as groundwater and subsurface contribution rates, land use, and crop patterns—remain fixed at their values from the final year of the historical simulation. To provide a clear overview of the research methodology, a technical roadmap is presented in Figure 3, outlining the key steps and processes involved in this study.

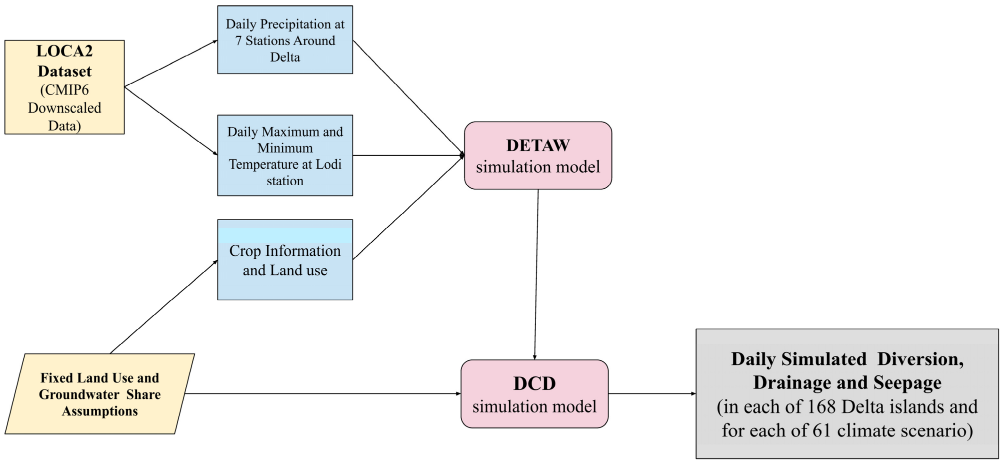

Figure 3. Technical roadmap illustrating the methodology for analyzing climate change impacts on channel depletion in the Sacramento–San Joaquin Delta.

3. Results

The hydrological features of the Delta were simulated for both the historical and all 61 GCM-scenario cases using the DCD model. For the historical period, simulations are conducted using the default input data in the model's latest version (version 1.2). To simulate the plausible future conditions, the daily precipitation for seven representative stations (explained in the methodology section) and the maximum and minimum air temperatures for the Lodi station were used as inputs to the simulation model.

To address the uncertainties associated with the climate scenarios considered in this study, box-and-whisker plots were created to show the projected average annual precipitation (Figure 4A), maximum air temperature (Figure 4B), and minimum air temperature (Figure 4C) for the Lodi station. These diagrams illustrate the uncertainty bounds for each variable, with red circles indicating the historical period averages. The results show that, while the direction of temperature changes follow a consistent upward trend, there is significant variability in precipitation projections. The lack of agreement regarding precipitation trends, including whether average rainfall will increase or decrease, highlights the greater uncertainty associated with this variable. In contrast, temperature projections display a clearer pattern, with changes in average minimum temperatures being particularly notable compared to maximum temperatures.

Regarding future land use in the Delta, we assumed that the land use of 168 subareas will remain fixed as it was in 2015. This assumption aligns with the method used in the planning part of DETAW v2.1. To optimize data transfer to CalSim 3, the DCD v1.2 planning model combines channel diversions, drainage, and seepage information from 168 subareas into seven Delta subregions, as shown in Figure 1C. These combined data serve as the input for the

CalSim 3 model. In this study, the total monthly diversion, seepage, and drainage for the entire Delta were obtained by summing the hydrological variables from these seven subregions.

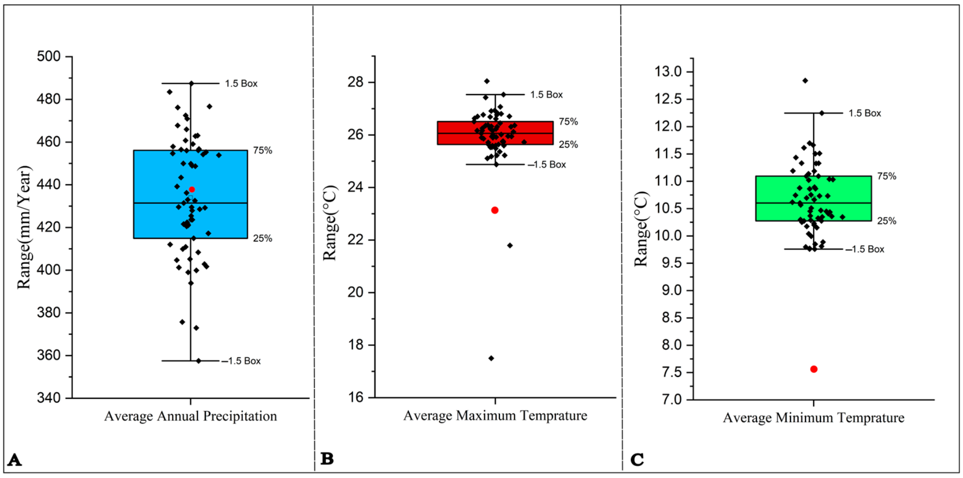

Figure 4. Box-and-whisker diagrams illustrating the projected uncertainty ranges for (**A**) average annual precipitation, (**B**) maximum air temperature, and (**C**) minimum air temperature at the Lodi station under various climate models and scenarios. Red circles denote the historical period averages for each variable.

3.1. Historical Baseline

Figure 5 presents the historical (1930–2014) outcomes for annual NCD, seepage, diversion, and drainage. To provide a comprehensive overview of the hydrological simulation outcomes for the historical period, Table 1 summarizes the descriptive statistics. Upon careful examination of the four principal variables—diversion, drainage, seepage, and NCD—it becomes evident that NCD exhibits the most significant variability. The values for NCD span a considerable range, from approximately 450 to 1420 million cubic meters (MCM) per year. This variance highlights the substantial fluctuations that characterize net channel depletion within the studied timeframe (84 years), underscoring its critical role and the complexities inherent in managing water resources in this context.

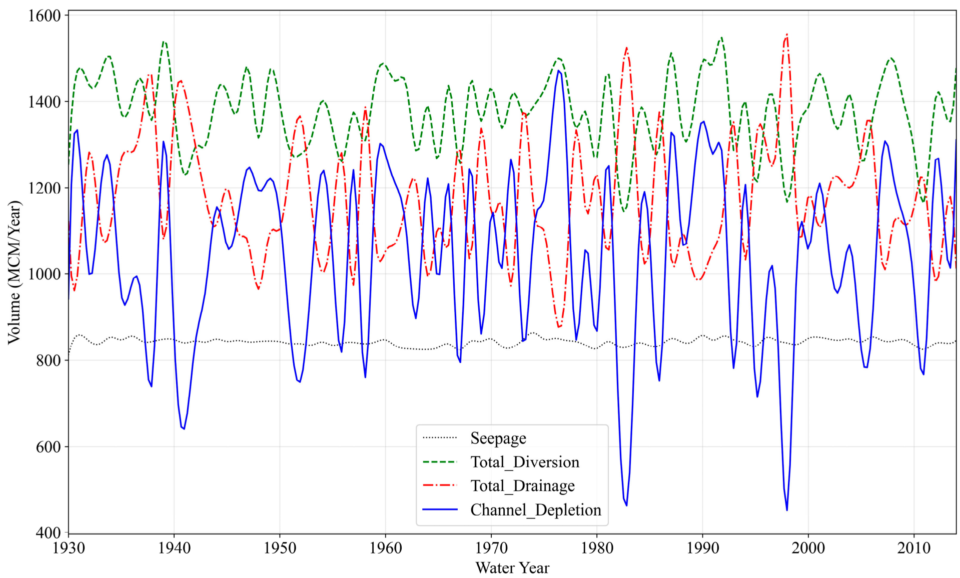

Figure 5. Historical simulated annual channel depletion, seepage, drainage, and diversion using historical meteorological data and simulation setup from [62].

Table 1. Descriptive statistics of historical simulation results (MCM/Year) using historical meteorological data and simulation setup from [62].

Variable \ Statistics	Average	Standard Deviation	Minimum	Median	Maximum
Net Channel Depletion	1045.7	205.4	452.8	1064.1	1418.3
Diversion	1374.4	87.2	1167.0	1380.3	1539.4
Drainage	1170.1	137.8	919.7	1141.3	1553.8
Seepage	841.4	8.9	811.1	842.9	863.2

3.2. Projected Changes

Modifications to the climatic inputs of the DCD model were made for all 61 GCM-Scenario cases, and the simulation was performed for the period of water years from 2016 to 2100. Figure 6 presents the average annual results using a box-and-whisker diagram, while Table 2 provides the corresponding descriptive statistics. The analysis of model projections relative to historical values suggests a range of percentage changes across four main variables. Regarding average annual drainage, the models suggest a maximum decrease of 0.7%, an average decrease of 3.4%, and a maximum increase of 9%. The projected changes are more pronounced for average annual Delta channel depletion, with a minimum increase of 0.3%, an average increase of 8%, and a maximum increase of 20%. In the case of average annual seepage, the changes are relatively moderate, with a minimum rise of 1.4%, an average increase of 2.6%, and a maximum increase of 4.3%. Finally, projections for diversion indicate a minimum hike of 3.2%, an average growth of 7.2%, and a maximum surge of 13.2%.

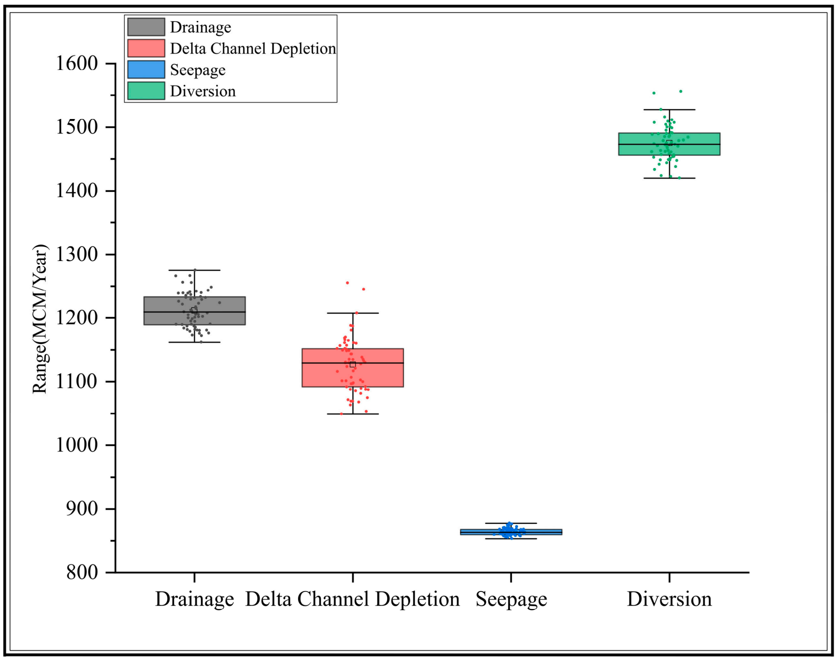

Figure 6. Box-and-whisker diagrams for annual hydrological variables resulted from 61 GCM-Scenario simulations.

Figure 7 showcases a graphical representation of monthly simulated data, highlighting the mean historical records of four key metrics—NCD, diversion, drainage, and seepage—denoted by red lines. Complementing these, the ensemble average derived from 61 distinct climate change projections is illustrated by a blue line, while the light blue shading surrounding this line demarcates the 99% confidence interval for these projections. Figure 7 demonstrates that the uncertainty range for NCD is notably wider during the winter and late autumn months, specifically from November to February. The further analysis of three additional factors—seepage, diversion, and drainage—reveals that the observed fluctuation in uncertainty during these colder months is primarily attributed to the drainage component. Additionally, the data indicate that the margin of uncertainty surrounding diversion rates increases during the summer, with June, July, and August being the key months. For drainage, uncertainty is more pronounced during the wet season, which typically extends from October to March. It is essential to highlight that negative NCD values are predominantly recorded in February, a phenomenon that can be traced back to high drainage volumes in this period, leading to a scenario where the combined total of diversion and seepage falls below that of drainage.

Table 2. Descriptive statistics of the GCM-Scenario simulation results (MCM/Year).

Statistics \ Variable	Drainage	Channel Depletion	Seepage	Diversion (Irrigation)
Maximum	1274.8	1255.1	877.6	1555.9
3rd quantile	1233.1	1151.9	867.9	1491.1
Median	1209.7	1129.6	863.5	1472.9
1st quantile	1189.5	1092.2	859.9	1456.3
Minimum	1161.7	1048.9	853.1	1419.6
Nr. of data points	61	61	61	61
Historical Annual Average	1170.1	1045.7	841.4	1374.4

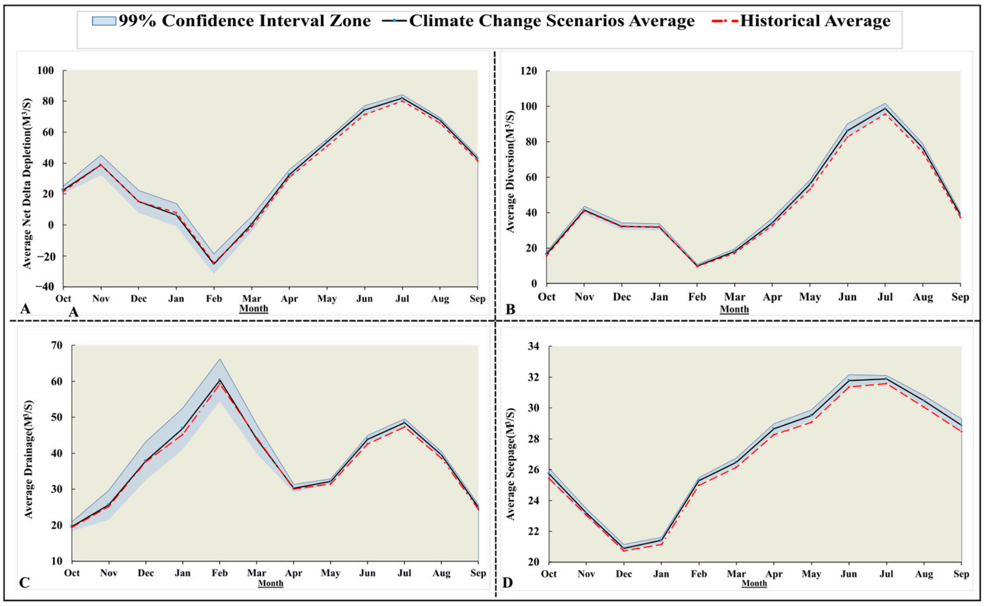

Figure 7. Monthly simulated (**A**) net channel depletion, (**B**) diversion, (**C**) drainage, and (**D**) seepage (historical average and climate change scenarios average).

Further details are depicted in the box-normal diagrams (Figure 8), which show the depletion of the Delta channels across 61 GCM-Scenario climate cases, along with an average case computed by determining the mean values of all 61 plausible climate scenarios. Box plot representations of yearly channel depletion also highlight variability across various scenarios. For example, GCM models such as ACCESS-ESM1-5 (Figure 8A), BCC-CSM2-MR (Figure 8A), INM-CM4.8 (Figure 8B), and MIROC6 (Figure 8C) illustrate more significant variability and the occurrence of more extreme events. This finding corroborates previous research showing that assuming equal weights when generating an ensemble can distort results, as it tends to obscure extreme conditions [63,64]. Equal weighting means each model contributes identically to the average, potentially diminishing the impact of outlier data.

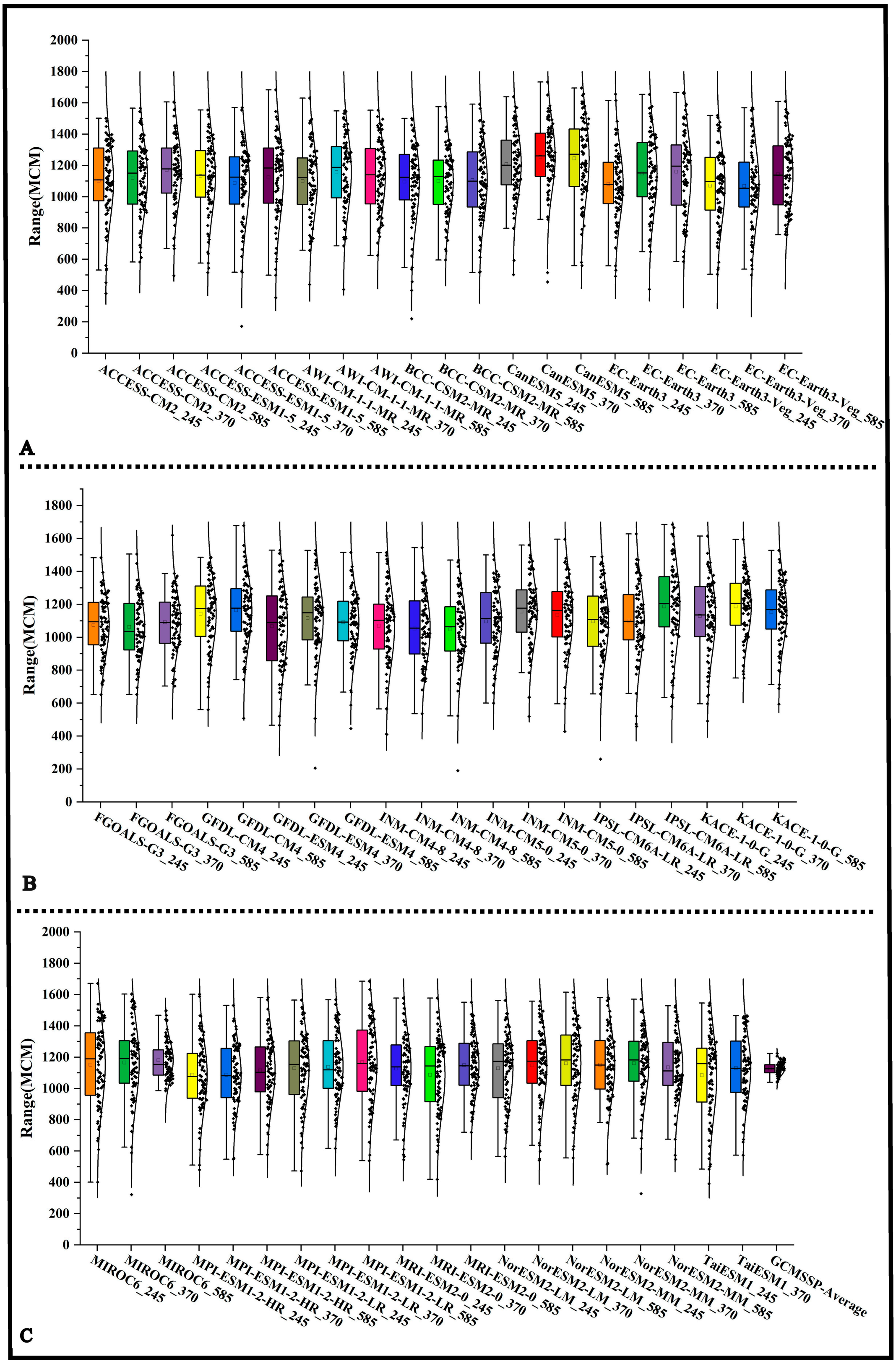

Figure 8. Box-normal diagrams for the net channel depletion resulted from different GCM-Scenarios (subfigures (**A**)–(**C**) are the same box-normal diagrams for different CMIP6 model and scenarios).

For a comprehensive overview of the results, Figure 9 presents yearly NCD for all climate scenarios. The primary aim of this figure is to demonstrate the plausible deviation of various climates resulting from GCM-Scenarios relative to the average value. The thick black line depicts the average value of all cases, showing minimal variability throughout the study period. Figure 9 demonstrates the extensive spectrum of Delta channel depletions across the 61 simulated climate scenarios, represented by shaded lines. The red and blue lines indicate the upper and lower 90% confidence intervals, respectively. However, this diversity is completely lost when considering at the mean scenario. Nevertheless, the upward trend is significant even in the average scenario. Figure A1 showcases diagrams that provide a more detailed interpretation and are easier to comprehend individually.

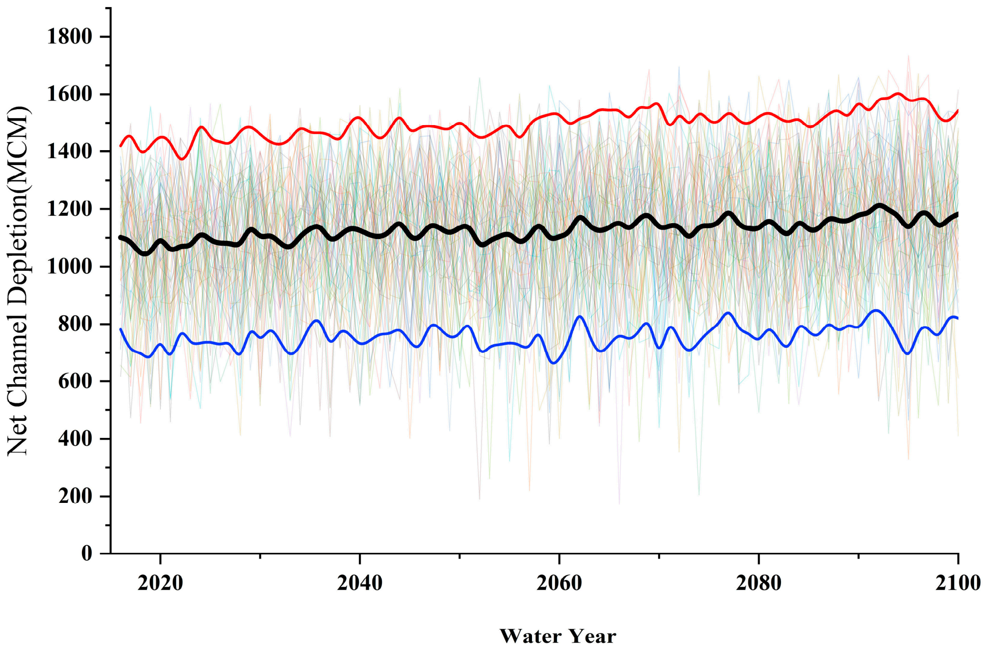

Figure 9. Net channel depletion for projected climate trends (black line depicts the average value of all scenarios, and red and blue lines indicate the upper and lower 90% confidence intervals, respectively).

3.3. Spatial Analysis

A comprehensive analysis of the regional contributions to the overall average depletion of the Delta, alongside seepage, diversion, and drainage values, was conducted over the historical simulation period. These findings are presented in Figure 10, highlighting the varying degrees of contribution among the seven subregions, distinguished by their respective areas and land use patterns. Notably, the South Sacramento subregion (SAC_South) emerges as the most significant contributor across all four variables examined throughout the Delta, while the North Sacramento subregion (SAC_North) registers the lowest level of involvement. This differential contribution underscores the heterogeneity of regional impacts on Delta water management metrics.

Using historical simulations and future climate scenarios results, we examined annual average variations in four key variables, comparing them to the baseline (historical) period. The results of this analysis for annual NCD are visually represented using box-and-whisker plots in Figure 11, where the vertical axis represents the percentage change of this variable during the future period relative to the average simulated during the baseline period. Across all seven subregions, the average changes in 61 climate scenarios demonstrate a consistent positive trend, ranging from 4.25% in the SAC_South subregion to 15.5% in the SJR_East subregion. Throughout all scenarios, the Old and Middle River (OMR), Sacramento River West (SAC_W), San Joaquin River East (SJR_E), and San Joaquin River West (SJR_W) subregions consistently show positive NCD changes. However, some minor decreases appear in other subregions, i.e., Mokelumne River (MOK) and Sacramento River

South (SAC_South). These simulated variations can be attributed to a combination of climatic conditions, geographical features, land use patterns, and cultivation practices. These multifaceted factors collectively contribute to the observed changes in the system.

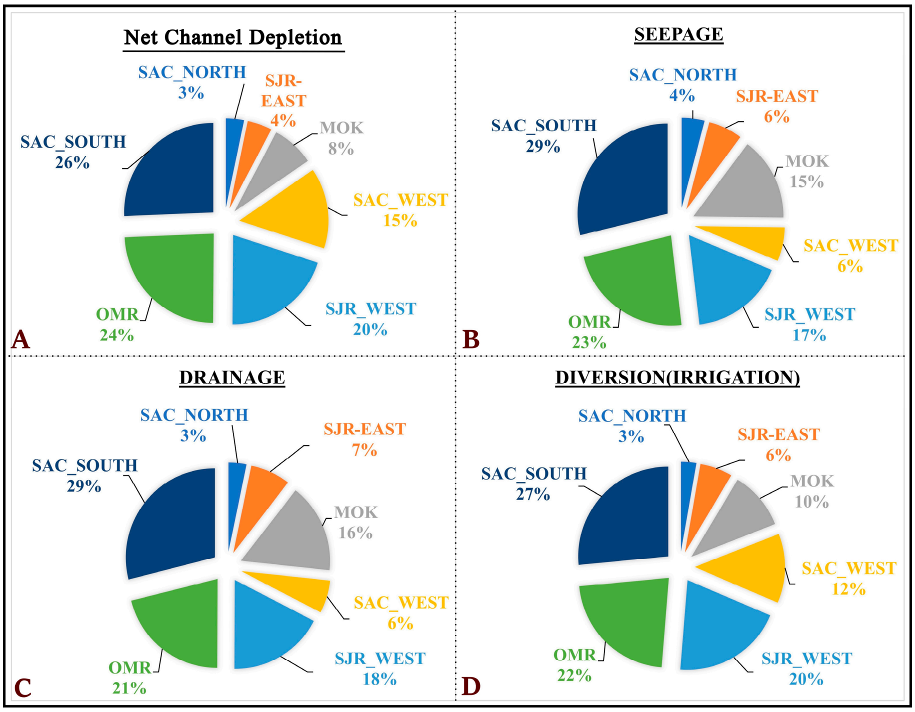

Figure 10. Annual (**A**) net channel depletion, (**B**) drainage, (**C**) diversion, and (**D**) seepage spatial distribution resulting from the historical simulation.

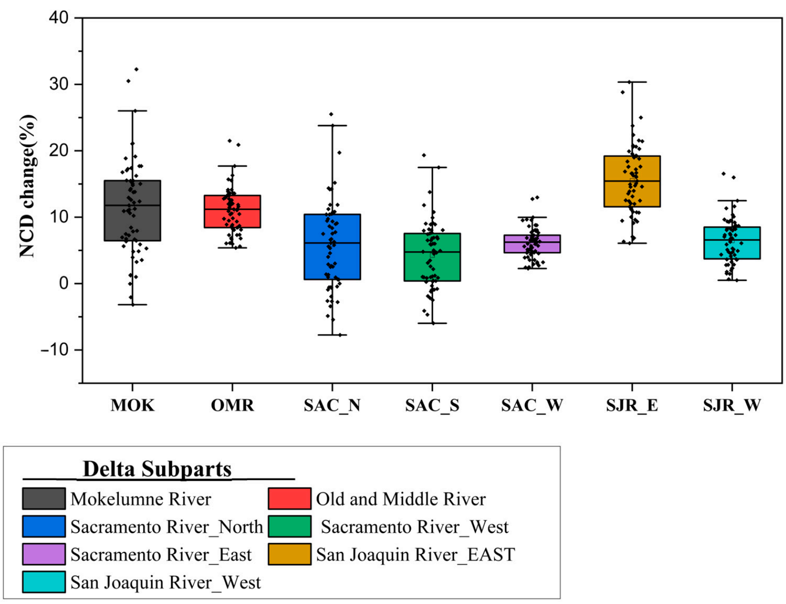

Figure 11. Box-and-whisker diagram for annual net channel depletion (NCD) resulting from 61 GCM-Scenario simulations.

4. Discussion

This research provides a comprehensive analysis of the potential changes in both average and extreme values of four main variables within the Sacramento–San Joaquin Delta area. The LOCA2 dataset was used to project potential future outcomes, incorporating the most recent advancements in downscaled General Circulation Models. These projections are based on an analysis of 61 possible future scenarios derived from 21 CMIP6

GCMs, under three distinct Shared Socioeconomic Pathways (SSPs). A comprehensive hydrologic simulation model, DCD v1.2, was used to simulate hydrological processes that contribute to the net depletion of the Delta islands and the channels that are widespread in the Delta. The results of this study align closely with previous findings in the broader Central Valley and other parts of California. One notable consensus across all General Circulation Models is the anticipation of significant warming in the Delta [10,19,65]. On the other hand, substantial uncertainties surround the anticipated outcomes of precipitation changes. Despite extensive attempts to ascertain them, uncertainty persists regarding the average annual precipitation change, whether a decline or an increase.

The study suggests that the method employed in this research results in an average increase in net channel depletion for the remainder of the current century, which implies that more water needs to be released from upstream reservoirs to comply with the existing environmental regulations. Moreover, with the anticipated rise in sea level [66], more water must be released to keep the Delta salinity safe and healthy. These factors, coupled with the likely increase in water demand in the Central Valley, may complicate the situation further. Such results could also be more influential and require managerial actions, especially in extreme drought conditions where the inflow to the Delta decreases drastically. An increase in Delta depletions serves as an alarming exacerbation of the extreme conditions, necessitating precise flow management to meet Delta outflow rules. This implies that, although the size of Delta depletions may appear minor in the total outflow balance of the Delta, it could become more influential under extreme conditions, which are expected to become more frequent and widespread due to climate change.

The methodology outlined in this study offers a framework that two primary groups can further utilize. First, water authorities and users could undertake studies to evaluate the impact of implementing non-structural adaptation strategies, such as farmland idling, water conservation, and relaxed regulatory requirements. These strategies were previously implemented during the mega-drought of 2012–2015 [3]. The assumptions and parameters of the DCD model utilized in this study could be adjusted to simulate each of these adaptation strategies while accounting for climatic uncertainties. Second, researchers exploring uncertainty can apply the uncertainty boundaries presented in this study's findings across different methodologies for studying deep uncertainties. These extreme boundaries can be estimated using the same methods applied in this study.

This study has illuminated critical hydrological processes and their potential changes under climate change conditions. However, it is important to acknowledge several limitations, and we recommend further investigation in these areas. The diverse landscape of GCMs presents both challenges and opportunities. While dozens of GCM variants exist, not all are accessible within the LOCA2 archive. We opted for the widely used r1i1p1f1 variant to balance computational constraints and data availability. Yet, this decision comes with trade-offs. We risk missing valuable insights from other models by relying solely on one variant. Future studies should explore alternative variants, but the inherent uncertainty remains a formidable obstacle. Our deliberate choice to maintain fixed land use and cultivation methods allowed us to isolate climate change effects on hydrological processes. However, a subsequent study could explore sensitivity to varying land management practices.

Incorporating additional scenario generation tools, such as weather generators, could significantly enhance decision-making processes under conditions of deep uncertainty [67]. Furthermore, integrating advanced decision-making techniques, such as the decision scaling method, can offer a more nuanced perspective for decision-makers, leading to more robust and resilient strategies [68]. Applying these methodologies to the Delta region and comparing the outcomes with those from the present study may yield valuable insights and deepen overall understanding. Such comparative analyses could reveal the potential benefits and limitations, thereby optimizing resource management and policy planning in similar contexts.

5. Conclusions

The study explored potential effects of climate change on various hydrological features of the Sacramento–San Joaquin Delta (Delta) of California, especially the Net Channel Depletion. The investigation revealed increases in annual Net Channel Depletion are projected across all future scenarios projected for the period from 2016 to 2100. These increases ranged from a modest minimum of 0.3% to a maximum surge of up to 20%. Additionally, annual seepage rates were found to rise between 1.4% and 4.3%, while diversion rates increased between 3.3% and 8.6%, relative to the historical period from 1930 to 2014. A spatial analysis conducted across various regions of the Delta further illustrated significant discrepancies in depletion patterns among these areas. These findings demonstrate that conventional top-down management approaches may not be suitable in developing management programs, particularly for the Delta, where climate projections exhibit considerable variability, especially regarding precipitation, with contradictory model predictions. Relying on average scenarios is also not advisable, as different models and scenarios can offset one another, potentially leading to a compression of uncertainty bounds and misleading conclusions in further analyses. The results of this study indicate that climatic uncertainties are profound and multifaceted. Therefore, employing decision-making strategies under deep uncertainty—such as bottom-up, risk-informed methods—could provide more reliable and practical frameworks for managers and decision-makers when preparing long-term plans for complex water systems like those in California [68–70].

In addition, we recommend coupling this model with broader Central Valley water management models to bridge the gap between scientific analysis and practical decision-making. Stakeholders such as water resource managers and policymakers require actionable information. Integrating our findings into a comprehensive framework would facilitate more informed and sustainable water management strategies. In the context of long-term predictions, this study focuses on hydrological processes in the Delta. However, it is essential to acknowledge that the role of sea level rise could significantly impact these processes. This aspect was not addressed in our study. Therefore, we recommend that future research investigate the potential effects of sea level rise on Delta hydrology. It is important to note that this study relied on two significant assumptions: One is that the land use of the Delta subregions has not changed over the 21st century and matches the 2015 land use. The second assumption is that the groundwater supply share in upland areas remains fixed at 0.4. The existence of these assumptions may lead to increased uncertainty in the outcomes of this research. In our subsequent study, we will strive to reduce the number of assumptions we employ.

Author Contributions: Conceptualization, S.S. and S.A.A.S.N.; methodology, S.S. and M.H.; software, S.S.; validation, S.S. and A.S.; formal analysis, S.S.; investigation, S.S.; resources, M.H.; data curation, S.S.; writing—original draft preparation, S.S. and A.N.; writing—review and editing, A.S. and M.H.; visualization, S.S. and M.H.; supervision, S.A.A.S.N. and A.S.; project administration, S.A.A.S.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The downscaled CMIP6 data used in this study were obtained from the LOCA (Localized Constructed Analogs) dataset, accessible at https://loca.ucsd.edu/ (accessed on 1 December 2023). All results generated during this study are available from the corresponding authors upon reasonable request.

Acknowledgments: The authors would like to thank the editors and reviewers for their thoughtful and insightful comments. The views expressed in this paper are those of the authors and not their employers.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

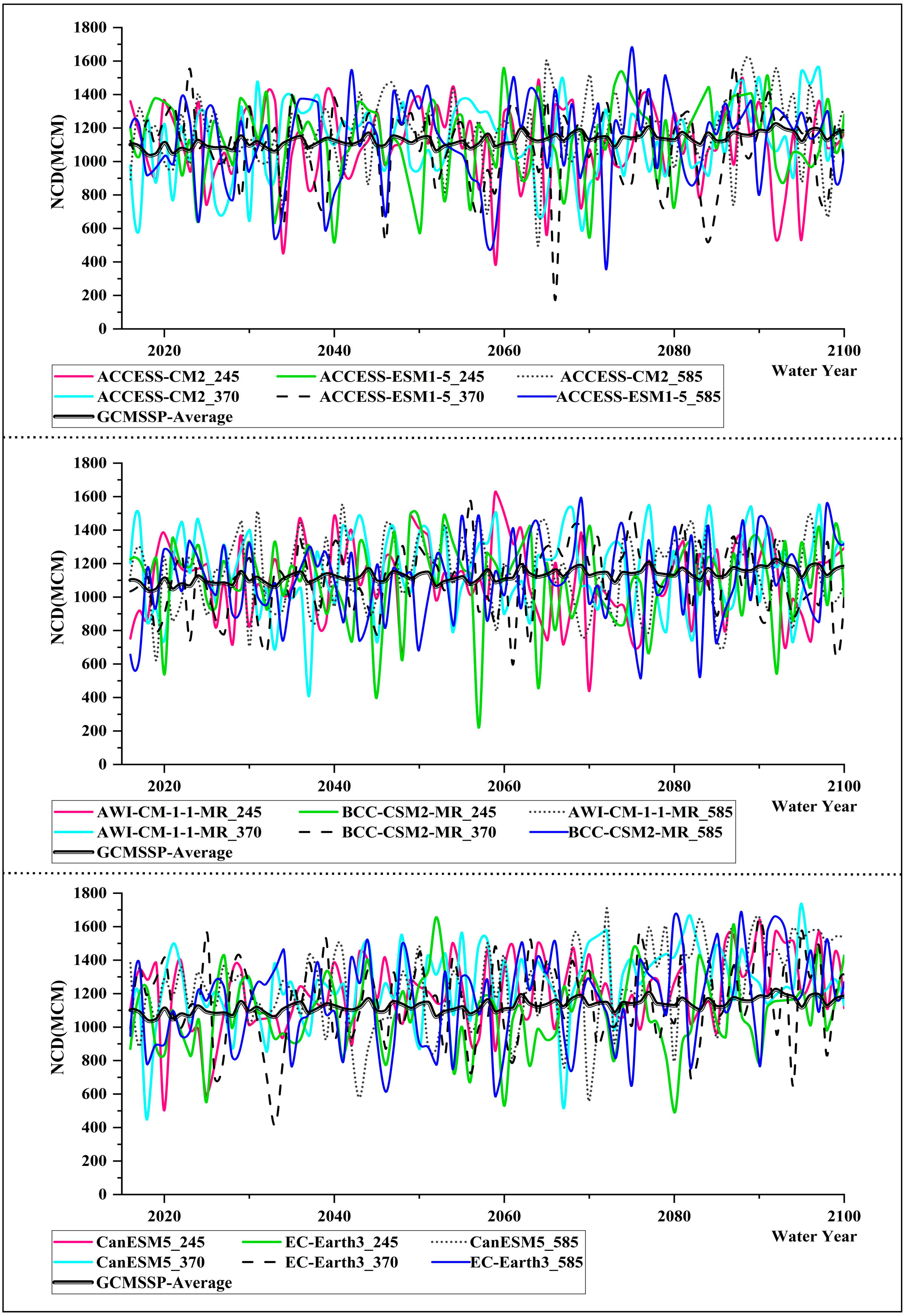

Figure A1. *Cont.*

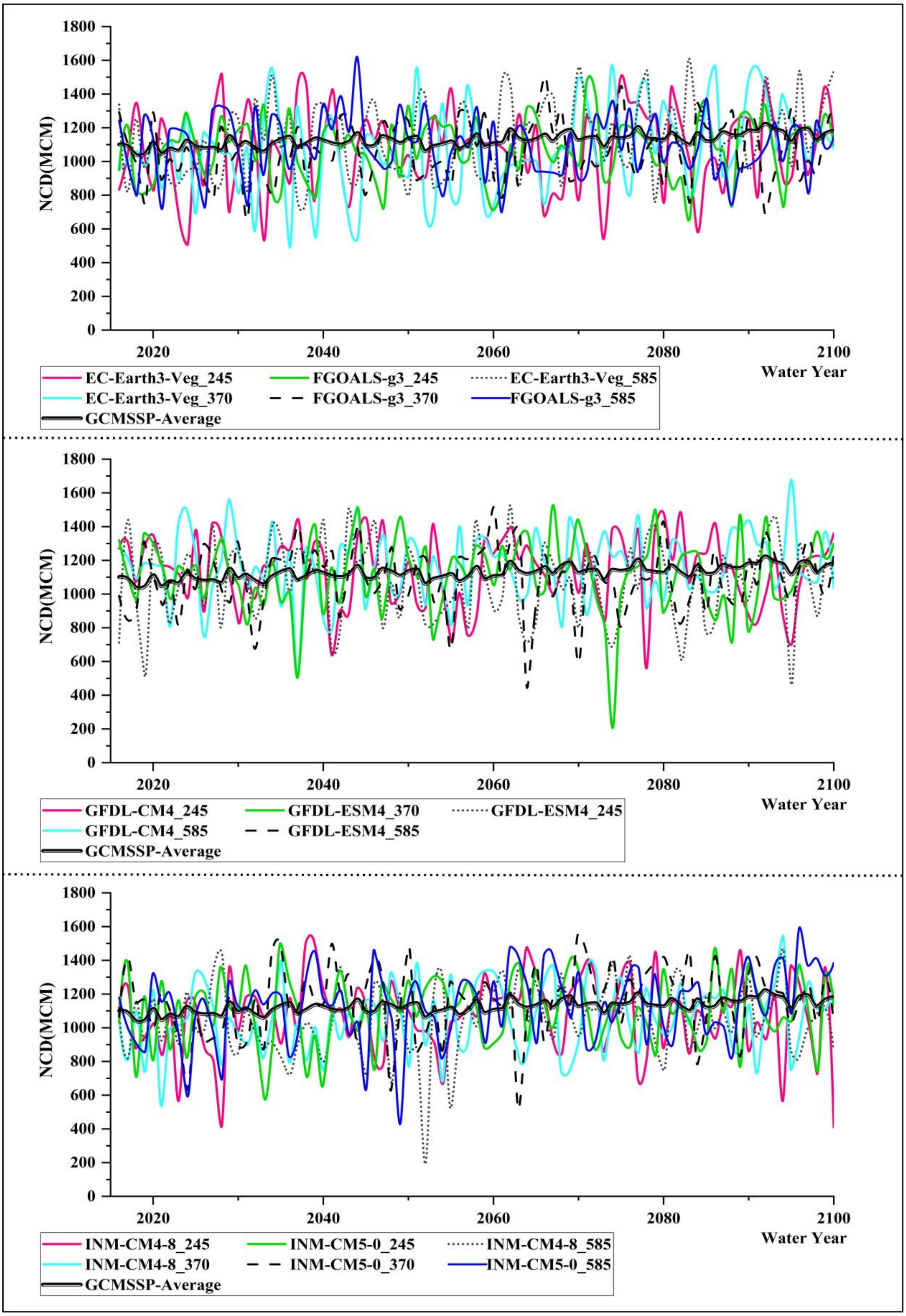

Figure A1. *Cont*.

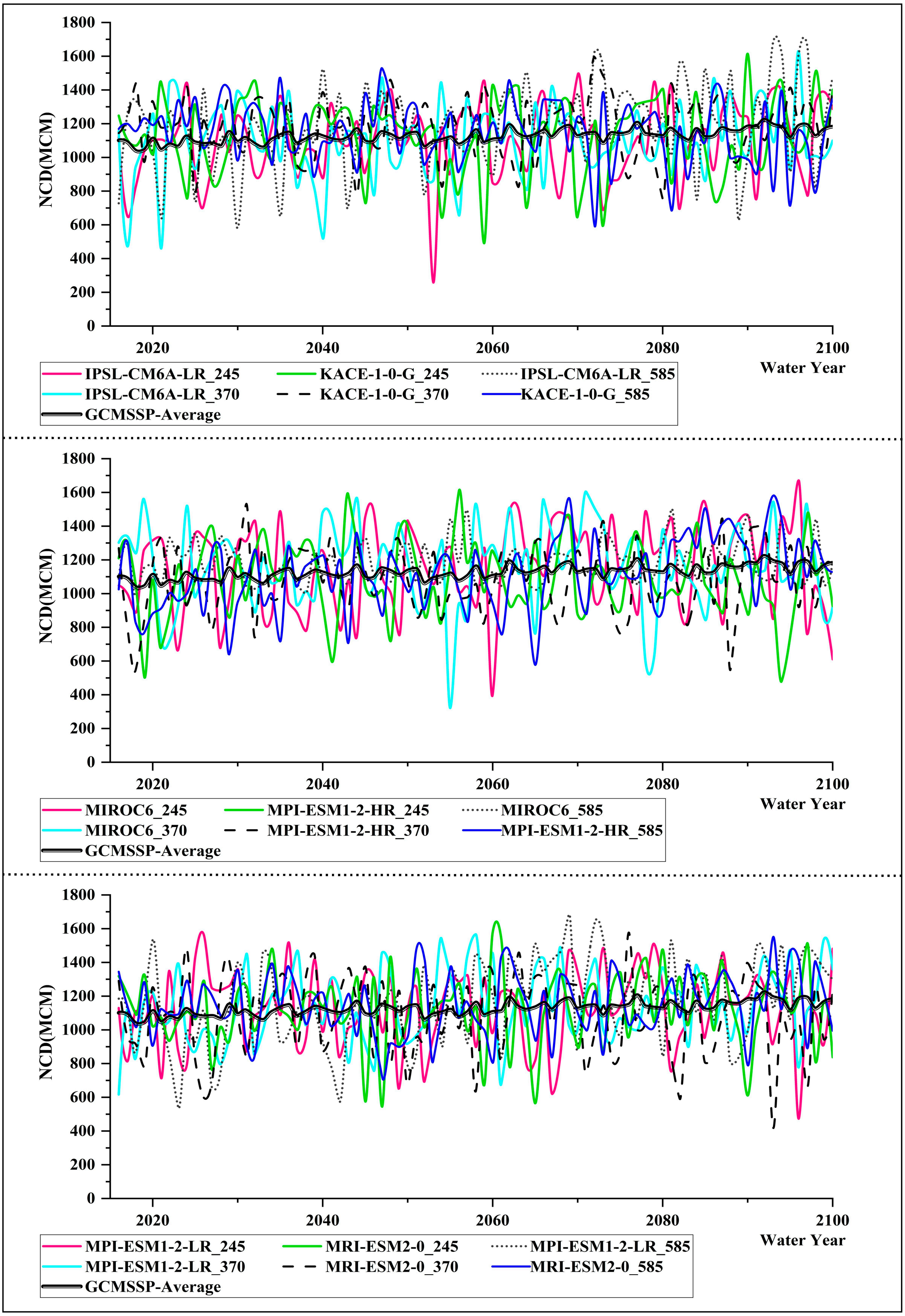

Figure A1. *Cont.*

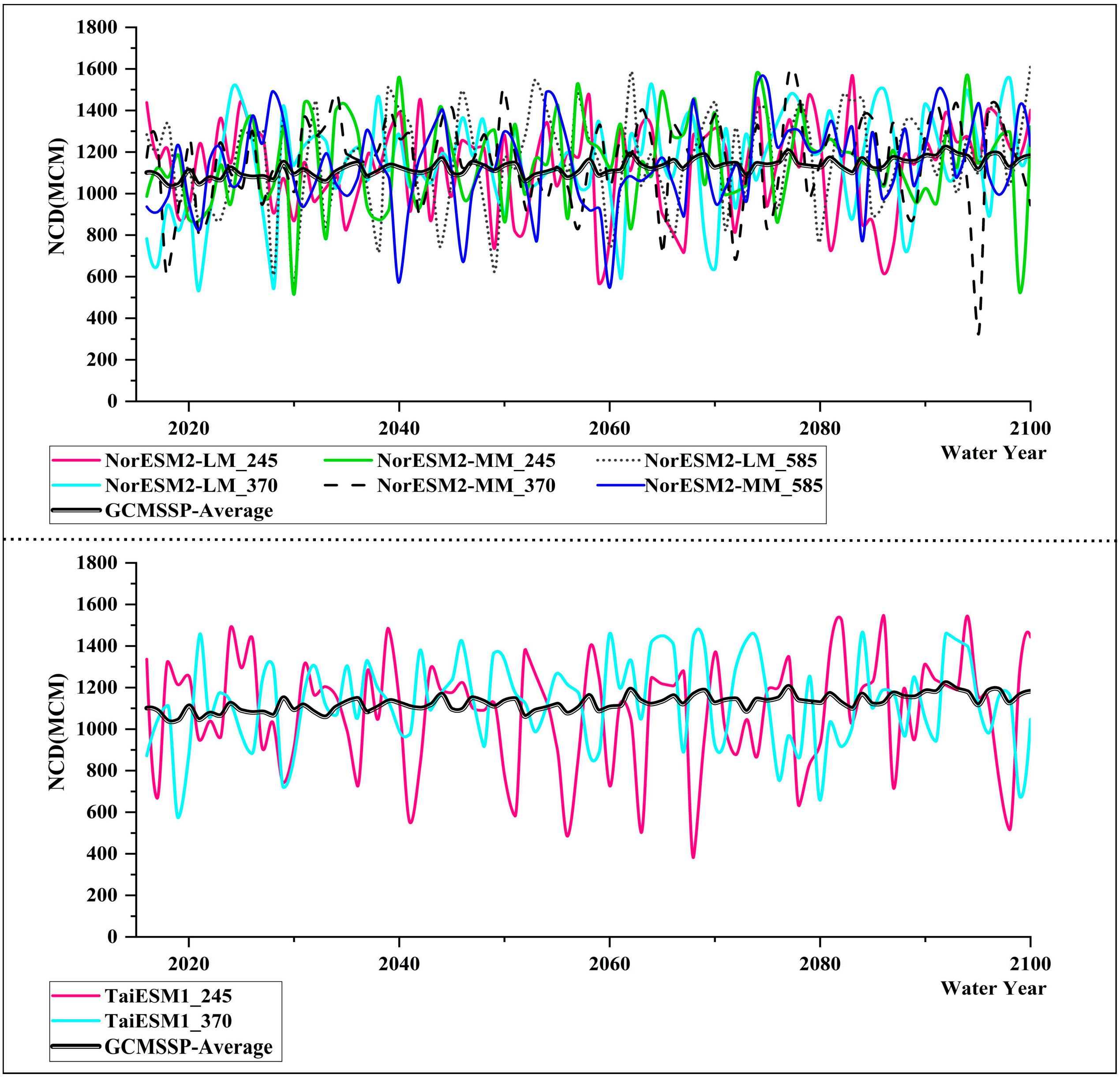

Figure A1. Net annual channel depletion projections.

Table A1. Selected GCMs for this study.

No.	GCM Name	Institution	Atmospheric Horizontal Resolution (Km) [71]
1	ACCESS-CM2	Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology, Australia	140
2	ACCESS-ESM1-5	Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology, Australia	140
3	AWI-CM-1-1-MR	Alfred Wegener Institute Climate Model (AWI-CM3)	80
4	BCC-CSM2-MR	Beijing Climate Center of China Meteorological Administration (BCC-CMA), China	100
5	CanESM5	Canadian Centre for Climate Modelling and Analysis (CCCMA), Canada	250
6	EC-Earth3	European Centre for Medium-Range Weather Forecasts (ECWMF), Europe	80
7	EC-Earth3-Veg	European Centre for Medium-Range Weather Forecasts (ECWMF), Europe	80
8	FGOALS-g3	Institute of Atmospheric Physics (IAP), China	190

Table A1. *Cont.*

No.	GCM Name	Institution	Atmospheric Horizontal Resolution (Km) [71]
9	GFDL-CM4	NOAA Geophysical Fluid Dynamics Laboratory (NOAA GFDL), USA	100
10	GFDL-ESM4	NOAA Geophysical Fluid Dynamics Laboratory (NOAA GFDL), USA	100
11	INM-CM4-8	Institute of Numerical Mathematics (INM) of the Russian Academy of Sciences, Russia	150
12	INM-CM5-0	Institute of Numerical Mathematics (INM) of the Russian Academy of Sciences, Russia	150
13	IPSL-CM6A-LR	Institute Pierre Simon Laplace (IPSL), France	160
14	KACE-1-0-G	National Institute of Meteorological Sciences/Korea	140
15	MIROC6	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute, National Institute for Environmental Studies (MIROC), Japan	120
16	MPI-ESM1-2-HR	Max Planck Institute for Meteorology, Germany	80
17	MPI-ESM1-2-LR	Max Planck Institute for Meteorology, Germany	170
18	MRI-ESM2-0	Meteorological Research Institute (MRI), Japan	100
19	NorESM2-LM	Norwegian Climate Centre (NCC), Norway	190
20	NorESM2-MM	Norwegian Climate Centre (NCC), Norway	100
21	TaiESM1	Research Center for Environmental Changes, Academia Sinica (Taiwan)	100

References

1. Jeffrey Mount, D.S.; Ullrich, U. Climate Change and California's Water. In *FACT SHEET*; Public Policy Institute of California: San Francisco, CA, USA, 2019.
2. Public Policy Institute of California. *Managing Drought in a Changing Climate: Four Essential Reforms*; Public Policy Institute of California: San Francisco, CA, USA, 2018.
3. Lund, J.; Medellin-Azuara, J.; Durand, J.; Stone, K. Lessons from California's 2012–2016 drought. *J. Water Resour. Plan. Manag.* **2018**, *144*, 04018067. [CrossRef]
4. Ullrich, P.; Xu, Z.; Rhoades, A.; Dettinger, M.; Mount, J.; Jones, A.; Vahmani, P. California's drought of the future: A midcentury recreation of the exceptional conditions of 2012–2017. *Earth's Future* **2018**, *6*, 1568–1587. [CrossRef] [PubMed]
5. Lund, J.R. California's agricultural and urban water supply reliability and the Sacramento–San Joaquin Delta. *San Fr. Estuary Watershed Sci.* **2016**, *14*. [CrossRef]
6. Ingebritsen, S.; Ikehara, M.E. Sacramento-San Joaquin Delta: The sinking heart of the state. *Land Subsid. United States. Circ.* **1999**, *1182*, 83–94.
7. Gartrell, G.; Mount, J.; Hanak, E.; Sencan, G. *Tracking Where Water Goes in a Changing Sacramento–San Joaquin Delta Technical Appendix: Methods and Detailed Results for 1980–2021*; Public Policy Institute of California: San Francisco, CA, USA, 2022.
8. Gartrell, G.; Mount, J.; Hanak, E. Policy Brief: Tracking Where Water Goes in a Changing Sacramento–San Joaquin Delta. Available online: https://www.ppic.org/publication/policy-brief-tracking-where-water-goes-in-a-changing-sacramento-san-joaquin-delta/ (accessed on 13 December 2023).
9. Hutton, P.H.; Rath, J.S.; Ateljevich, E.S.; Roy, S.B. Apparent Seasonal Bias in Delta Outflow Estimates as Revealed in the Historical Salinity Record of the San Francisco Estuary: Implications for Delta Net Channel Depletion Estimates. *San Fr. Estuary Watershed Sci.* **2021**, *19*. [CrossRef]
10. He, M. Assessing Changes in 21st Century Mean and Extreme Climate of the Sacramento–San Joaquin Delta in California. *Climate* **2022**, *10*, 16. [CrossRef]
11. Myers, N.; Mittermeier, R.A.; Mittermeier, C.G.; Da Fonseca, G.A.; Kent, J. Biodiversity hotspots for conservation priorities. *Nature* **2000**, *403*, 853–858. [CrossRef]
12. Moyle, P.B.; Brown, L.R.; Durand, J.R.; Hobbs, J.A. Delta smelt: Life history and decline of a once-abundant species in the San Francisco Estuary. *San Fr. Estuary Watershed Sci.* **2016**, *14*. [CrossRef]
13. California. Department of Water Resources. Division of Planning. *Estimation of Delta Island Diversions and Return Flows*; State of California, Department of Water Resources, Division of Planning: Sacramento, CA, USA, 1995.
14. Sandhu, N.; Suits, B.; Ateljevich, E.; Zhong, L.; Kadir, T. *On Estimating Net Delta Outflow (NDO) Approaches to estimating NDO in the Sacramento-San Joaquin Delta*; California Department of Water Resources: Sacramento, CA, USA, 2016.
15. Polade, S.D.; Gershunov, A.; Cayan, D.R.; Dettinger, M.D.; Pierce, D.W. Precipitation in a warming world: Assessing projected hydro-climate changes in California and other Mediterranean climate regions. *Sci. Rep.* **2017**, *7*, 10783. [CrossRef]
16. Mariotti, A.; Pan, Y.; Zeng, N.; Alessandri, A. Long-term climate change in the Mediterranean region in the midst of decadal variability. *Clim. Dyn.* **2015**, *44*, 1437–1456. [CrossRef]
17. Polade, S.D.; Pierce, D.W.; Cayan, D.R.; Gershunov, A.; Dettinger, M.D. The key role of dry days in changing regional climate and precipitation regimes. *Sci. Rep.* **2014**, *4*, 4364. [CrossRef] [PubMed]

18. Vicuna, S.; Maurer, E.P.; Joyce, B.; Dracup, J.A.; Purkey, D. The sensitivity of California water resources to climate change scenarios 1. *JAWRA J. Am. Water Resour. Assoc.* **2007**, *43*, 482–498. [CrossRef]
19. Schwarz, A.; Ray, P.; Wi, S.; Brown, C.; He, M.; Correa, M. Climate change risks faced by the California Central Valley water resource system. In *California's Fourth Climate Change Assessment*; Publication Number: CCCA4-EXT-2018-001; State o California: Sacramento, CA, USA, 2018.
20. Alam, S.; Gebremichael, M.; Li, R.; Dozier, J.; Lettenmaier, D.P. Climate change impacts on groundwater storage in the Central Valley, California. *Clim. Chang.* **2019**, *157*, 387–406. [CrossRef]
21. Mallakpour, I.; AghaKouchak, A.; Sadegh, M. Climate-induced changes in the risk of hydrological failure of major dams in California. *Geophys. Res. Lett.* **2019**, *46*, 2130–2139. [CrossRef]
22. Liu, Z.; Herman, J.D.; Huang, G.; Kadir, T.; Dahlke, H.E. Identifying climate change impacts on surface water supply in the southern Central Valley, California. *Sci. Total Environ.* **2021**, *759*, 143429. [CrossRef]
23. Ishida, K.; Ercan, A.; Trinh, T.; Kavvas, M.; Ohara, N.; Carr, K.; Anderson, M. Analysis of future climate change impacts on snow distribution over mountainous watersheds in Northern California by means of a physically-based snow distribution model. *Sci. Total Environ.* **2018**, *645*, 1065–1082. [CrossRef]
24. Li, D.; Wrzesien, M.L.; Durand, M.; Adam, J.; Lettenmaier, D.P. How much runoff originates as snow in the western United States, and how will that change in the future? *Geophys. Res. Lett.* **2017**, *44*, 6163–6172. [CrossRef]
25. Dettinger, M.D.; Anderson, M.L. Storage in California's reservoirs and snowpack in this time of drought. *San Fr. Estuary Watershed Sci.* **2015**, *13*. [CrossRef]
26. Dettinger, M.; Anderson, J.; Anderson, M.; Brown, L.R.; Cayan, D.; Maurer, E. Climate change and the Delta. *San Fr. Estuary Watershed Sci.* **2016**, *14*. [CrossRef]
27. Monismith, S.G. A note on Delta outflow. *San Fr. Estuary Watershed Sci.* **2016**, *14*. [CrossRef]
28. Dayflow. Available online: https://water.ca.gov/Programs/Integrated-Science-and-Engineering/Compliance-Monitoring-And-Assessment/Dayflow-Data (accessed on 20 December 2023).
29. Siegfried, L.J. *Physically Based Modeling of Delta Island Consumptive Use A Case Study of Fabian Tract and Staten Island*; University of California: Davis, CA, USA, 2012.
30. Medellín-Azuara, J.; Paw UK, T.; Jin, Y.; Jankowski, J.; Bell, A.; Kent, E.; Clay, J.; Wong, A.; Santos, N.; Badillo, J.; et al. *A Comparative Study for Estimating Crop Evapotranspiration in the Sacramento-San Joaquin Delta*; Center for Watershed Sciences, University of California: Davis, CA, USA, 2018.
31. Kadir, T. Estimates for consumptive water demands in the Delta using DETAW, methodology for flow and salinity estimates in the Sacramento–San Joaquin Delta and Suisun Marsh. In *27th Annual Progress Report to the CSWRCB*; California Department of Water Resources: Sacramento, CA, USA, 2006; Chapter 7.
32. Snyder, R.; Orang, M.; Matyac, J.; Sarreshteh, S.; Kadir, T. Delta Evapotranspiration of Applied Water–DETAW. *Calif. Water Plan Update 2009* **2009**, *4*, 489–501.
33. Liang, L.; Suits, B. *Implementing DETAW in Modeling Hydrodynamics and Water Quality in the Sacramento-San Joaquin Delta, Methodology for Flow and Salinity Estimates in the Sacramento-San Joaquin Delta and Suisun Marsh*; California Department of Water Resources: Sacramento, CA, USA, 2017.
34. Liang, L.; Suits, B. *Calibrating and Validating Delta Channel Depletion Estimates*; California Department of Water Resources Sacramento: Sacramento, CA, USA, 2018.
35. Owen, L.W.; Nance, D.H. *Hydrology of the Sacramento-San Joaquin Delta*; Department of Water Resources, Resources Agency of California: Sacramento, CA, USA, 1962.
36. Masson-Delmotte, V.; Zhai, P.; Pirani, S.; Connors, C.; Péan, S.; Berger, N.; Caud, Y.; Chen, L.; Goldfarb, M.; Scheel Monteiro, P.M. Ipcc, 2021: Summary for policymakers. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group i to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; 2021.
37. Swain, D.L.; Langenbrunner, B.; Neelin, J.D.; Hall, A. Increasing precipitation volatility in twenty-first-century California. *Nat. Clim. Change* **2018**, *8*, 427–433. [CrossRef]
38. Pathak, T.B.; Maskey, M.L.; Dahlberg, J.A.; Kearns, F.; Bali, K.M.; Zaccaria, D. Climate change trends and impacts on California agriculture: A detailed review. *Agronomy* **2018**, *8*, 25. [CrossRef]
39. Feldman, D.R.; Tadić, J.M.; Arnold, W.; Schwarz, A. Establishing a range of extreme precipitation estimates in California for planning in the face of climate change. *J. Water Resour. Plan. Manag.* **2021**, *147*, 04021056. [CrossRef]
40. Gartrell, G.; Mount, J.; Hanak, E.; Gray, B. *A New Approach to Accounting for Environmental Water*; Public Policy Institute of California: San Francisco, CA, USA, 2017.
41. Zhang, S.; Chen, J. Uncertainty in projection of climate extremes: A comparison of CMIP5 and CMIP6. *J. Meteorol. Res.* **2021**, *35*, 646–662. [CrossRef]
42. MacVean, L.J.; Thompson, S.; Hutton, P.; Sivapalan, M. Reconstructing early hydrologic change in the California Delta and its watersheds. *Water Resour. Res.* **2018**, *54*, 7767–7790. [CrossRef]
43. Monsen, N.E.; Cloern, J.E.; Burau, J.R. Effects of flow diversions on water and habitat quality: Examples from California's highly manipulated Sacramento–San Joaquin Delta. *San Fr. Estuary Watershed Sci.* **2007**, *5*. [CrossRef]
44. Orang, M.; Snyder, R.L.; Sarreshteh, S. Historical Estimates of Agricultural and Wetland Water Use in the San Joaquin Sacramento River Delta. *CA Water Plan Update 2009* **2009**, *4*.

45. Qi, S.; He, M.; Bai, Z.; Ding, Z.; Sandhu, P.; Chung, F.; Namadi, P.; Zhou, Y.; Hoang, R.; Tom, B.; et al. Novel Salinity Modeling Using Deep Learning for the Sacramento–San Joaquin Delta of California. *Water* **2022**, *14*, 3628. [CrossRef]
46. Chen, Z.E.D.; Hillaire, T.; Lui, M.; Polsinelli, J.; Reyes, E.; Wang, J.; Yin, H.; Zhong, L.; Sumer, D.; Parker, N.; et al. *CalSim 3 Report: A Water Resources System Planning Model for State Water Project & Central Valley Project*; California Department of Water Resources: Sacramento, CA, USA, 2022.
47. Livneh, B.; Rosenberg, E.A.; Lin, C.; Nijssen, B.; Mishra, V.; Andreadis, K.M.; Maurer, E.P.; Lettenmaier, D.P. A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States: Update and extensions. *J. Clim.* **2013**, *26*, 9384–9392. [CrossRef]
48. GoogleEarth, Sacramento-San joaquin Delta. Google, 2024. Available online: https://www.google.com/earth (accessed on 20 December 2023).
49. *Delta Channel Depletion Model (DCD) User Guide*; California Department of Water Resources: Sacramento, CA, USA. Available online: https://water.ca.gov/Library/Modeling-and-Analysis/Bay-Delta-Region-models-and-tools/DCD (accessed on 22 October 2024).
50. Liang, L.B.S.A.N.S. Delta Evapotranspiration of Applied Water (DETAW v2.1)-User's Manual; 2020. Available online: https://water.ca.gov/Library/Modeling-and-Analysis/Bay-Delta-Region-models-and-tools/DETAW (accessed on 22 October 2024).
51. Jayasundara, N.C.; Seneviratne, S.A.; Reyes, E.; Chung, F.I. Artificial neural network for Sacramento–San Joaquin Delta flow–salinity relationship for CalSim 3.0. *J. Water Resour. Plan. Manag.* **2020**, *146*, 04020015. [CrossRef]
52. DSM2: Delta Simulation Model II. Available online: https://water.ca.gov/Library/Modeling-and-Analysis/Bay-Delta-Region-models-and-tools/Delta-Simulation-Model-II (accessed on 2 June 2024).
53. Kabakov, S. *Investigation of the Sacramento-San Joaquin Delta, Report No. 4, Quantity and Quality of Waters Applied to and Drained from the Delta Lowlands*; California Department of Water Resources: Sacramento, CA, USA, 1956.
54. Eyring, V.; Bony, S.; Meehl, G.A.; Senior, C.A.; Stevens, B.; Stouffer, R.J.; Taylor, K.E. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.* **2016**, *9*, 1937–1958. [CrossRef]
55. Hayhoe, K.; Edmonds, J.; Kopp, R.; LeGrande, A.; Sanderson, B.; Wehner, M.; Wuebbles, D. *Fourth National Climate Assessment-Chapter 4: Climate Models, Scenarios, and Projections*; U.S. Global Change Research Program: Washington, DC, USA, 2017.
56. Pierce, D.W.; Cayan, D.R.; Dehann, L. *Creating Climate Projections to Support the 4th California Climate Assessment*; University of California at San Diego, Scripps Institution of Oceanography: La Jolla, CA, USA, 2016.
57. Pierce, D.W.; Cayan, D.R.; Thrasher, B.L. Statistical downscaling using localized constructed analogs (LOCA). *J. Hydrometeorol.* **2014**, *15*, 2558–2585. [CrossRef]
58. Livneh, B.; Bohn, T.J.; Pierce, D.W.; Munoz-Arriola, F.; Nijssen, B.; Vose, R.; Cayan, D.R.; Brekke, L. A spatially comprehensive, hydrometeorological data set for Mexico, the US, and Southern Canada 1950–2013. *Sci. Data* **2015**, *2*, 150042. [CrossRef]
59. Pierce, D.W.; Su, L.; Cayan, D.R.; Risser, M.D.; Livneh, B.; Lettenmaier, D.P. An extreme-preserving long-term gridded daily precipitation dataset for the conterminous United States. *J. Hydrometeorol.* **2021**, *22*, 1883–1895.
60. Pierce, D.W.; Cayan, D.R.; Feldman, D.R.; Risser, M.D. Future Increases in North American Extreme Precipitation in CMIP6 Downscaled with LOCA. *J. Hydrometeorol.* **2023**, *24*, 951–975. [CrossRef]
61. Pierce, D.W. (Ed.) *LOCA Version 2 for North America*, Available online: https://loca.ucsd.edu/loca-version-2-for-north-america-ca-jan-2023/ (accessed on 1 December 2023).
62. Yu, M. *Delta Channel Depletion (DCD) and Suisun Marsh Channel Depletion (SMCD) Models*; California Department of Water Resources: Sacramento, CA, USA; California Natural Resources Agency Open Data: Sacramento, CA, USA, 2021.
63. Knutti, R. The end of model democracy? An editorial comment. *Clim. Chang.* **2010**, *102*, 395–404. [CrossRef]
64. Hausfather, Z.; Marvel, K.; Schmidt, G.A.; Nielsen-Gammon, J.W.; Zelinka, M. Climate simulations: Recognize the 'hot model'problem. *Nature* **2022**, *605*, 26–29. [CrossRef]
65. Salehi, S.; Neyshabouri, S.A.A.S. Extreme Climate Trends in California Central Valley: Insights from CMIP6. *Authorea Preprints* **2024**, *11*.
66. Griggs, G.; Cayan, D.; Tebaldi, C.; Amanda Fricker, H.; Arvai, J.; DeConto, R.; Knopp, R.E.; Whiteman, L.; Moser, S.; Fox, J. *Rising Seas in California-An Update on Sea-Level Rise Science*; California Ocean Science Trust, 2017. Available online: https://www.opc.ca.gov/webmaster/ftp/pdf/docs/rising-seas-in-california-an-update-on-sea-level-rise-science.pdf (accessed on 22 October 2024).
67. Najibi, N.; Perez, A.J.; Arnold, W.; Schwarz, A.; Maendly, R.; Steinschneider, S. A statewide, weather-regime based stochastic weather generator for process-based bottom-up climate risk assessments in California–Part I: Model evaluation. *Clim. Serv.* **2024**, *34*, 100489. [CrossRef]
68. Ray, P.; Wi, S.; Schwarz, A.; Correa, M.; He, M.; Brown, C. Vulnerability and risk: Climate change and water supply from California's Central Valley water system. *Clim. Chang.* **2020**, *161*, 177–199. [CrossRef]
69. Marchau, V.A.; Walker, W.E.; Bloemen, P.J.; Popper, S.W. *Decision Making Under Deep Uncertainty: From Theory to Practice*; Springer Nature: Cham, Switzerland, 2019.

70. Shipman, P.; Rayej, M. *From Climate Traces to Climate Insights:Future Scenarios Analysis for the California Central Valley*; California Department of Water Resources: Sacramento, CA, USA, 2023.
71. Masson-Delmotte, V.; Zhai, P.; Pirani, A.; Connors, S.L.; Péan, C.; Berger, S.; Caud, N.; Chen, Y.; Goldfarb, L.; Gomis, M. Climate change 2021: The physical science basis. In *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Intergovernmental Panel on Climate Change, 2021; Volume 2, Available online: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_FrontMatter.pdf (accessed on 22 October 2024).