Department of Economics and Finance

Major in Finance

Course of Mathematical Finance

Understanding Water Derivatives: Analysis of the Californian Water Market and Valuation Models for NQH2O Futures

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1 Introduction

1.1 Overview of sustainable finance in the USA

During the last decade, interest in environmental, social and governance issues has been continuously on the rise.

At the end of 2021 (Q4) ESG assets under management in the US accounted for a total of $357 billion.[1]

While the US still lags behind Europe in asset volume, the variety of ESG investment possibilities is increasing at an increasing pace.

Furthermore, the worsening, the increasing relevance, and the mediatic exposure of the climate crisis have posed the premises for the development of new financial instruments and derivatives to cope with tightening ESG laws and to deal with emissions and sustainability goals sought by the government.

In the United States, we can find different investment solutions, which can be summed up into four categories: climate or green bonds; YieldCos, instruments created appositely to finance renewable energy projects directly, these instruments are exchange-traded and therefore are available to all interested renewable energy investors; aligned intermediary is an initiative aimed at channeling significant amounts of institutional capital into resource innovation investments in energy, agriculture, waste, and water; lastly, conservation finance which provides the medium to invest into an ecosystem either through an intermediary or directly, these investments aim to conserve the values of an ecosystem in a long-term perspective.[2] (Orobello and Cirella, 2021)

The role of sustainable finance is nowadays essential for developed and efficient markets, it provides the tools to cope with climatic risks and gives the tools for hedging against increasingly unpredictable climate changes.

1.2 Sustainable derivatives

In the last 30 years, the introduction of ESG derivatives have provided a wide variety of sustainable choices for the public to invest in. Notably, it is now normal to invest in sustainable derivatives.

The CME (Chicago Mercantile Exchange), one of the world's biggest and most important financial services companies, as well as the world's largest operator of financial derivatives exchanges, offers

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[1] Source: Morningstar ESG data & metrics

[2] See Orobello and Cirella, 2021, *Financialization of water: conceptual analysis of the California water crisis*

nowadays a significant number of sustainable financial derivatives in different sectors including bioenergy such as ethanol futures and options on different markets globally (Rotterdam, New York) and biodiesel futures; renewable feedstocks offering corn futures and options, palm oil futures, options, and swaps, and soybean oil futures as well as the newly added used cooking oil futures; batteries offering cobalt and lithium futures; recyclable metals marketing crap steel futures; and weather offering a range of hedging instruments against the unpredictable nature of weather which are now exchanged globally (USA, Europe, and Asia).[3]

1.3 CME Water Futures (NQH2O)

Among the aforementioned instruments, CME has started also offering water futures based on the indexed spot price given by the Nasdaq Veles California water index (NQH2O). The index began on October 31, 2018, and track the spot price of water transfer contracts in the state of California.

Fredrick Kaufman[4] understood as early as 2012 that the new financial frontier would involve water derivatives.

The widely accepted and demonstrated assumption that water scarcity will be a major concern of the next century brought water to the center of the financial world's attention.

The main ethical constraint with the financialization of water resides in its characteristics: water is to this day rightfully classified not just as a storable commodity but also as a common good[5], which makes speculations over its price morally not recommendable.

Another problem is establishing a generally accepted spot price for water.

Speculations over usage rights for water could result in a market-wide "run for water" which would lead to a general rise in prices which would worsen not only the general public but also agriculture and economic activity related to water consumption such as farming and breeding.

Water being a common good cannot be bought or sold by itself, what you can get is the right to usage of a body of water both overground and underground.

These contracts come at different prices, but no physical place exists where rights of usage over water are exchanged, resulting in an almost impossible market-size price discovery.

The solution has been found through the analysis of different prices coming from different water suppliers which resulted in the creation of an index of California water market spot prices.

Spot prices indexed in the Nasdaq Veles California water index (NQH2O) are the basis upon which the futures contracts offered by CME are built upon.

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[3] Source: CME Group: sustainable products

[4] See Kauffman, 2012, *Wall street's thirst for water*

[5] See UN 2023 water conference

The futures are then exchange-traded and over the NQH2O index, the price of a 6-month future then at maturity coincides with the spot price of the above-mentioned index.

The purpose of this dissertation is threefold: to analyze the conditions that have led to the development of water futures.

To analyze the water market in California, its regulation and the search for efficient water management.

To analyze the functioning of the NQH2O index by attempting to deconstruct its components and, finally, to analyze the futures contracts offered and to determine the possibilities offered by these instruments for hedging risks.

2 Climatic risk in California

2.1 Overview of the climate challenges faced by California

The state of California's economic and social well-being are inextricably linked to the challenges posed by the climate crisis and rising temperatures.

California is currently facing five major climate risks: rising temperatures and extreme heat waves, worsening and increasing wildfires, more frequent and stronger droughts, the risk of flooding in the north due to extreme precipitation, and coastal erosion due to sea level rise.[6]

The causal chain of climate-related damage is based on rising temperatures and the increasing frequency of catastrophic events, resulting mainly in prolonged droughts and bigger wildfires.

The Californian temperature level calculated in the RCP 4.5[7] scenario predicts an increase in average temperature of up to +7.2º (4 C°) Fahrenheit (depending on the geographical area and topography of the regions), and the presence of snow-prone mountain areas in the state of California increases the risk of flooding in the event of a drastic increase in temperature.[8]

Given the level of economic and social stress already present in the State of California and caused by climatic agents, the need for regulations, policies and efficient management aimed at reducing exposure to these risks is increasingly necessary.

The impact of the worsening conditions described above has several consequences for citizens.

There are several harms to the citizenry that result in enormous negative externalities to the state's economy.

2.2 Drought risk

There are three types of droughts, as defined by the USGS: meteorological drought, which is due to a lack of rainfall; agricultural drought, which is due to a lack of soil moisture; and hydrological drought, which is a direct consequence of a decrease in both surface and groundwater flow.[9]

It is important to emphasize that the predominance of one typology does not preclude the coexistence of the three, although one of them may have a greater impact.

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[6] See Brown R. and Petek S., *Climate Change Impacts Across California Health*

[7] RCP 4.5 (medium emissions scenario): a mitigation scenario where GHGs (Greenhouse gasses) emissions peak by 2040 and then decline. In California, annual average temperatures under this scenario are projected to increase 2°C - 4°C by the end of this century, depending on the location.

[8] Source: Cal-Adapt database

[9] See USGS (United States Geological Survey), California drought

To better understand and analyze the risk of drought in California, it is essential to specify the hydrological constitution of the state and so to understand the difference between surface water and groundwater and their distribution.

Surface water comprises streams, lakes, rivers, and reservoirs and provides important resources for irrigation, public supply, wetlands, and wildlife.

To better measure the availability of surface water is fundamental to introduce the concept of runoff which is the amount of rain and snowmelt drainage left after the demands of nature, such as evaporation from land and transpiration from vegetation have been supplied.[10]

The runoff gives a measure of unusable and unavailable water. So, it can be a good predictor for drought periods.[11] About 75 percent of California's surface water supply originates in the northern third of the state, but around 80 percent of water demand occurs in the southern two-thirds of the state. The demand for water is highest during the dry summer months when there is little natural precipitation or snowmelt.[12]

A common trend can be seen from *Figure 1(See appendix 2.2)* above showing the monthly runoff data in California over the last 10 years (using as a benchmark for dryness the year 1977 and for a wet year 1983) which supports the increase in demand mentioned above.

In fact, runoff, measured in inches, has a seasonal trend regardless of the level of wetness in the year under consideration.

From the average calculated over the 30-year levels, it can be stated that the level of runoff tends to decrease from May onwards, reaching a minimum between September and October.

Reservoir levels are also an important variable to consider in analyzing the general water system stress.

Figure 2 and 3 (See appendix 2.2) both map the reservoirs over the state of California and measure a daily average storage availability.

The two maps were chosen to highlight in the same week over different weeks the difference between a period of normal rainfall (2024) and a period of drought (2016), as was the case in 2012-2016.

Groundwater, which is found in aquifers below the surface of the earth, is one of the state's most important natural resources. It provides drinking water for a large portion of the nation's population, supplies business and industries, and is used extensively for irrigation.

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[10] Source: USGS

[11] Herman et al., 2023, *Seasonal Forecast of the California Water Price Index*

[12] Source: Water Education Foundation

Source Figure 1: USGS Water Watch database

Groundwater can also contribute to surface water supplies. Some groundwater contributes to rivers and lakes and can flow to the surface as springs.[13]

The water level in an aquifer that supplies water to a well does not always remain the same.

Droughts, seasonal variations in rainfall and pumping all affect the level of the groundwater. If water is pumped faster than an aquifer is replenished by rainfall or other sources of recharge, the water level can drop. This can happen during droughts when there is an extreme lack of rainfall.

Indeed, the analysis of temperature, rainfall and snowpack are the most important factors for predicting a period of drought, as these phenomena act as warning signals if they fall below or deviate from normal levels.[14]

This is because their absence would lead to a chain of events that would cause groundwater levels to drop significantly, resulting in reduced surface water runoff, leading to a water crisis.

Figure 4 shows the total water storage (comprising 160 reservoirs) per year in California graphically compared to the yearly level of snowpack as of April 1 each year.

The figure shows the correlation between the two variables and how, in times of drought, the snowpack level goes hand-by-hand with the total water storage in the state, suggesting once more snowpack water content as a key element to assess the probability of drought. *Figure 5* records the hydrological conditions based on precipitations in the state of California over the same period as *Figure 4* (1970-2015), so that the two graphs can be compared.

The graph records the degree of drought for a percentage of the state's territory on a scale from D0 to D4 and does the same for “wetness” on a scale from W0 to W4. (The scale uses the standardised precipitation index as a benchmark)[15].

A comparison of the two graphs above shows that snow and precipitation are critical elements in predicting possible droughts, as well as assessing the severity of an extremely dry period.

These variables are necessary to predict possible periods of stress on the Californian water system and are also central to the logic of water pricing.

California is currently (2023-2024) drought-free thanks to frequent rainfall and winter snowfall, but the general and continuous rise in temperatures puts this at risk and highlights the need for efficient water management.

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[13] Id at 9.

[14] Milanes et al., 2022, Indicators of Climate change in California, PPIC

[15] The Standardized Precipitation Index, or SPI, is a drought index that captures how observed precipitation deviates from the climatological average over a given time period.

3 California’s water network, regulations, and market

3.1 Overview of California’s water network

California's water network is complex, encompassing diverse hydric resources throughout the state and beyond extending to Nevada and Oregon, as well as Arizona.

The network consists of surface water and groundwater resources, which form the backbone of the state's water supply for agricultural, industrial, urban, and environmental uses.

To better understand California's water network, it is fundamental to divide California into three geographic regions, as each region is topographically different from the others: Northern California, Central California, and Southern California.

The proposed geographic division (as seen in *Figure 6, see appendix 3.1*) is useful mainly to explain the process of supply and demand through the state and how California's water network tries to cope with differences in supply and demand.

To better analyze the Californian water network, it is necessary to keep in mind the difference between surface water and groundwater, their geographical distribution and their importance in the network.

California’s surface water network mostly stretches in the northern and central parts of the state and it is composed of both natural resources and man-made reservoirs and canals.[16]

Among the state's natural water resources, the San Joaquin River (central California's main waterway and the main river in California's agricultural areas) and the Sacramento River (California's longest waterway, flowing only in northern California), along with their tributaries, are fundamental in accounting the water supply of the California water system. In addition, the two rivers flow into the Sacramento Delta, which is a major water resource.

The Delta provides drinking water for a total of 27 million citizens and contributing to the supply of water for irrigation; furthermore, it is the intersection point to the state's two major water delivery projects, the State Water Project (SWP) and the Central Valley Project (CVP).[17]

California's surface water also includes natural lakes, the largest of which is Lake Tahoe, and 228 reservoirs in the state and beyond.

These reservoirs are an important part of the state's water supply for industrial, agricultural and urban uses.

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[16] Id at 9

[17] Source: California Water Impact Network

The largest reservoir in the state is Shasta Lake, which is fed by the Sacramento River and has a total capacity of 4,552,000 AF (acre-feet), while the total capacity of the reservoir system in the state of California is 38,102,000 AF. [18]

While surface water is important to California's water system, groundwater is an important source of water stored in the earth, deep beneath our feet, in what are called aquifers.

Aquifers are the collective saturated spaces between many layers of sand, soil and gravel (called alluvial aquifers), or the interconnected fractures in bedrock or volcanic deposits (called fractured rock aquifers).

Layers of alluvial aquifers make up a groundwater basin. In an average year, California's 515 groundwater basins and subbasins contribute about 41 percent of the state's total water supply. In dry years, groundwater contributes up to 60 percent (or more) of the statewide annual supply and serves as a critical buffer against the impacts of drought and climate change. About 83 per cent of Californians rely on groundwater for some of their water supply, and many communities are 100% dependent on groundwater for their water needs.[19]

In the management of these resources two projects are worth citing (as mentioned above) for their importance in the water network: the State Water Project (SWR) and the Central Valley Project (CVP).

3.1.1 The State Water Project

The former (SWP), extending for 701.5 miles and stretching from north to south (*Figure 7, see appendix 3.1.1*), is a multi-purpose water storage and delivery system constituted by a series of man-made canals, pipelines, reservoirs and hydroelectric power facilities. SWP delivers water to 30 million Californian, as well as supplying clean water to 750,000 acres of farmland, and businesses throughout the state.[20]

Planned, built, operated and maintained by the state’s department of water resources (DWR), The SWP is the nation’s largest state-owned water, power generator and user-financed water system.

Together with the DWR, 29 public agencies and local water districts form the SWP water contractors, these agencies signed long-term water supply contracts ending in 2035 and specifying the maximum amount of SWP water a contractor may request annually.

To ensure the adequate water supplies are available under various conditions and legal conditions, the project is managed directly by the DWR granting efficiency and operational flexibility.

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[18] Source: California Data Exchange Center

[19] Source: California DWR (Department of Water Resources)

[20] Source: State Water Project, DWR

Source *Figure 7*: California Department of Water Resources

The project has an annual water yield of 2,400,000 AF to its contractors.[21]

3.1.2 The Central Valley Project

The latter, the Central Valley Project features a combined storage capacity of 13,000,000 AF distributed among 20 reservoirs, in addition it generates 2,254 MW (Mega-Watt) thanks to the operations of 11 power plants along the project.[22]

On the San Joaquin Valley's east side, the CVP's Friant Division serves about 15,000 farms on more than 1.5 million acres of land and supplies several cities, including the Fresno County area.

In an average year, the CVP delivers more than 7,000,000 AF of water to farms, cities and the environment. About 75 percent of CVP water is devoted to agricultural use (mainly irrigation), as a matter of fact the project supports seven of California's top 10 agricultural counties.

While the SWP is state-owned and managed, the CVP is federally managed by the Bureau of Reclamation.

Figure 7 and 8 (see appendix 3.1.2) show the size of the two projects and their geographical location in order to better highlight the similarities and differences between the two.

The Californian water system is also made up of small private contractors, but to simplify the analysis of the system itself, only the state's largest water supply projects have been included.

3.2 Regional supply and demand

As described in the previous section, the distribution of water in California is unbalanced, with most of the state's natural supply concentrated in the northern part of the state and most of the demand concentrated in southern California, where the largest cities (Los Angeles and San Diego) are located, and central California, where agriculture is concentrated.

While the aforementioned projects aim to make the distribution of water between north and south more efficient, differences in geography, topography, climate and demographics make this process very complex.

Northern California, in particular the north coast and the Sierra Nevada region, is subject to significant amounts of rainfall and snowfall, which contributes to a robust and constant natural water supply.

However, this region is sparsely populated, which increases the surplus of water resources.

By contrast, Southern California, including major urban areas such as Los Angeles and San Diego, has a semi-arid to arid climate with limited natural water availability.

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[21] See *California State Water Project at a Glance,* 2013, DWR

[22] See *Central Valley Project*, USBR, 2011, USBR (United States Bureau of Reclamation)

Along with Southern California, the Central Valley area, which is an agricultural hub, has the highest demand for water in the state.

The Central Valley, known for its extensive agricultural activities, consumes a large portion of the state's water for irrigation purposes.[23]

The agricultural sector alone accounts for nearly 80% of the state's water use, in addition the trend for water use in this sector remains steady and constant through the years, highlighting the urgent need for efficient water management practices in this region.[24]

California relies on the two aforementioned major projects, the State Water Project (SWP) and the Central Valley Project (CVP), to address this demand and supply imbalance.

This delivery network is complemented by a variety of water rights and trading systems.

California's water market, the largest in the United States, facilitates the exchange of water rights through short-term, long-term and permanent transfers.

Spot market (short-term transfers) transactions are typically short-term contracts which provide for the immediate transfer of water to meet emergencies, e.g. peak demand and unanticipated droughts.

Long-term leases, which are often used by municipalities and industrial users to secure water for future development, provide a more stable solution for entities that require a sustained supply of water over several years. (e.g. SWP contractors)

Permanent sales, by contrast, involve the outright transfer of water rights from one owner to another, potentially changing the state's water use and availability.

This flexible and adaptable market structure allows to mitigate the economic impact of droughts and to adapt to shifts in water demand caused by economic change and population growth.[25]

Water trading has become an essential tool for managing water scarcity, allowing users to buy and sell water rights to meet their specific needs.

For example, during droughts, agricultural users which hold most water usage rights in the State[26] can sell water rights to urban areas, receiving financial compensation ensuring that water needs are met.

One of the most important and new features of the California water market is the role of water banking. These public-private institutions act as intermediaries, storing water during wet periods and making it available during dry periods.

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[23] See Peterson C. et al., 2023, *Water Use in California's Agriculture,* PPIC (Public Policy Institute of California)

[24] See Cooley H., 2015, *Urban and Agricultural Water Use in California 1960-2015,* Pacific institute

[25] Id at 11

[26] Id at 23

The Kern Water Bank is a key example, in which water is recharged into an underground aquifer during times of abundance and withdrawn during times of shortage.

This banking mechanism increases the flexibility and reliability of water supplies by acting as a buffer against fluctuations in water availability.[27]

To ensure that water transfers do not harm third parties or the environment, the regulatory framework for water transfers in California is designed accordingly.

These deals are monitored directly by California's Department of Water Resources as well as the State Water Resources Control Board, which set strict standards to prevent negative externalities.

Transactions require review and approval by these agencies, which assess factors such as the potential to deplete aquifers, impacts on flows and water quality, and downstream user rights.[28] (SWRCB, 2021).

This oversight ensures that while the water market remains dynamic and efficient.

Another important, already mentioned, aspect of the Californian water market is the distinction between surface and groundwater transfers.

Surface transfers tend to be more straightforward and involve physically moving water using existing infrastructure such as canals and pipelines.

Groundwater transfers, however, involve more complex considerations due to the interconnected nature of aquifers and the potential for over-abstraction to cause land subsidence and reduce the availability of water. The Sustainable Groundwater Management Act (SGMA) of 2014 introduced significant reforms to groundwater management, requiring local agencies to develop and implement groundwater sustainability plans, improving groundwater use and recharge. These plans include provisions for transferring groundwater rights to ensure that such trading is consistent with long-term sustainability goals (California Department of Water Resources, 2022).

Water trading in California also includes innovative approaches to conservation and efficiency. The implementation of advanced irrigation technologies, such as drip irrigation, helps reduce agricultural water use by delivering water directly to plant roots, minimizing evaporation and runoff.

Advanced metering infrastructure (AMI) enables accurate monitoring of water use, allowing users to adjust their consumption patterns based on real-time data. These technologies not only conserve water, but also make water trading more efficient by providing accurate information on water availability and use.[29]

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[27] Hanak and Stryjewski, 2012, *California's Water Market by the Numbers,* PPIC

[28] Source: SWRCB (State Water Resources Control Board)

[29] Source: DWR

3.3 California's water rights system

California's water rights system is a intricate structure constituted by a mix of riparian, appropriative, and correlative rights.

Riparian rights are tied to land ownership along a watercourse, granting landowners the right to reasonably use water if it does not harm downstream users.

These rights are included into the land property rights and thus do not require a permit.

Appropriative rights, established by historical use, allow for the diversion of water for beneficial use, irrespective of land ownership.

These rights are based on a "first in time, first in right" principle, where older rights have priority over newer ones during times of scarcity.

Correlative rights pertain to groundwater and require sharing water resources among landowners above a common aquifer. These rights mandate that each landowner has an equal right to use groundwater, but the use must be reasonable and beneficial.[30]

The state's water rights are further complicated by the co-existence of federal and state projects that distribute water across vast distances.

The SWP and CVP extensive networks influence the allocation and use of water throughout California. These projects operate under long-term contracts with various water districts, ensuring a regulated distribution of water while maintaining operational flexibility to address changing conditions.

The contracts specify the amount of water allocated to each district, which can be adaptable based on annual water availability and other factors.

The California Water Code and the federal legal frameworks allow for temporary and permanent transfers of water rights as described previously.

These transfers must meet stringent criteria to ensure that they do not negatively impact third parties or the environment. The legal and regulatory environment thus plays a crucial role in balancing the needs of different water users while promoting efficient water use and sustainability.

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[30] Littleworth A. and Garner E., 2019, *California water*

4 The Nasdaq Veles California Water index

4.1 Introduction to the Nasdaq Veles California Water Index (NQH2O)

The Nasdaq Veles California Water Index (NQH2O) is a pioneering financial instrument which tracks the spot price of water rights in California.

The index was launched on 31 October 2018. It was developed in response to the growing recognition of water as a critical, yet scarce resource in the state. It helps stakeholders manage the financial risks associated with water scarcity by providing a transparent and standardised benchmark for water prices.[31]

The creation of the Nasdaq Veles index was a response to the inefficiency of the water market. Scarce water, aggravated by climate change and population growth, has become a valuable commodity. The NQH2O enables more efficient allocation of water resources and encourages sustainable use and conservation efforts by providing a benchmark spot price for water.

The index reflects the reality of water as an essential resource for agriculture, industry and urban areas, and through the futures contracts offered by CME serves as a tool for hedging and efficiently transfer risk in the Californian water market.[32]

The development of NQH2O is rooted in the recognition of water as a critical component of economic stability.

It has serious implications for agricultural productivity, industrial activity and urban living, and may disrupt the economy.

The index quotes water prices in US$-AF (acre-feet) and price data reflect the commodity value since they do not include additional costs associated with losses and transportation, since the index spot price reflects water rights transfer prices and not physical exchange prices.

Water spot price on the NQH2O is the result of the aggregation of 5 major water market prices[33] sourced weekly from Waterlitix[34].

The index spot price is then updated on weekly basis.

Nasdaq states that the index is adaptive to demand and supply variations within the underlying physical markets, given that NQH2O is completely reflective of the conditions of the physical water markets.

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[31] Source: Nasdaq, NQH2O

[32] Id at 31

[33] These Markets are Surface Water; Central Basin; Chino Basin; Main Basin; Mojave Basin – Alto Subarea

[34] Waterlitix™ is the country's largest and most comprehensive pricing source for water transactions. Its proprietary database of water right sales and leases cover the past two decades.

Furthermore, the Index is responsive to the hydrological conditions: In periods of dry hydrological conditions and limited supply of water, the index responds to the upward pressure on price. The same relationship holds true in periods of wet hydrological conditions and excess supply of water.

Because the index is a composite of different water trading markets, there are always slight differences between the actual price paid for water in any given physical trade and the index price.[35]

4.2 Benchmarking

The Nasdaq Veles California Water Index development was driven by the need of transparency.

This was one of the main underlying principles that motivated its design.

Due to the public disclosure of the index's data sources, market players may gain a comprehensive knowledge of the process involved in creating and maintaining the index.

The transparency of the index not only enhances both price discovery of water rights, boosting confidence among its diverse user base, which includes agricultural producers, municipal water suppliers, and financial investors, but it also fosters trust among these users.

A crucial element of the NQH2O is the integration of benchmarking metrics, which is an essential component. The NQH2O index serves as a crucial benchmark for assessing and selling water-related services.

Furthermore, it signifies a significant accomplishment in its respective industry. This is the first occurrence of such a nature.

The objective of this project is to develop a benchmark by which other financial products and contracts related to water may be evaluated. The function is crucial for the establishment of a robust and efficient water market as it acts as a standard for determining prices and assessing performance. This feature contributes to market stability and facilitates decision-making by providing precise information[36] (Nasdaq, 2018).

Moreover, the openness of the index not only enhances confidence in the system's capacity to adhere to legal obligations, but it also enhances the effectiveness of market surveillance. The NQH2O contributes by offering readily available and fully understandable information on the cost of water and the exchange of water services. The purpose of this is to aid regulators in monitoring market activity and ensuring that trading processes are equitable and unbiased. Transparency, as stated by Nasdaq (2018), enables the straightforward identification and prevention of unethical actions like market manipulation and other unethical conduct. Therefore, ensuring the integrity of the water market helps avoid unethical activities.

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[35] See Kammeyer C., 2021, *California Water Futures Market*

[36] Id at 31

However, the index as of today, comprising 5 major markets is not yet a universal benchmark to understand California's spot market for water the proprietary database covers only a part of the available spot exchanges in the state's water market

The benchmarking capabilities of the NQH2O play a crucial role in establishing a suitable market price for readily accessible water.

While the water market may see occasional fragmentation into smaller segments, it lcks the same level of liquidity as more established commodities markets, as of today the market faces a serious problem of illiquidity.[37]

Anyway, The NQH2O addresses this problem by offering a price benchmark. Water users and policymakers can apply this reference to make more informed decisions.

This criterion can become essential for determining water tariffs, facilitating water transfers, and budgeting long-term expenses for water management infrastructure, if the liquidity of the market improves as well as its reflectiveness to the physical exchange spot prices.

When it comes to water management, each of these roles is vital.

4.3 Challenges in the development of the Index

Creating the Nasdaq Veles California Water Index posed several challenges involving the complexities of the water market and the unique characteristics of water as a commodity.

One of the primary challenges was the variability and inconsistency of water pricing data, as well as the volume of the dataset itself and the absence of a centralized exchange for water rights.

Unlike traditional commodities, water prices are particularly susceptible to location, season, and specific terms of the transaction.

Furthermore, to create a well-functioning index, the historical and current database of the transactions must be accurate so that it is possible provide a more precise and reality-reflecting spot price.

To sort out this challenge, Nasdaq partnered with West Water and Veles Water which professionally captured transaction-level data in the California Water markets.[38]

This variability required the development of sophisticated algorithms and methodologies to aggregate and standardize the data, ensuring that the index accurately reflects the true market value of water.[39]

Another significant challenge was the regulatory environment.

Water rights and trading are governed (as described previously) by a multi-layered web of federal, state, and local regulations, which can impact the availability and pricing of water.

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[37] See Wang et al., 2022, *Why is Water Illiquid: The NQH2O Water Index Futures*

[38] Source: West water, Waterlitix™

[39] Id at 31

Navigating this regulatory landscape and ensuring compliance with all relevant laws was essential for the index's development.

This involved close collaboration with regulatory bodies and continuous monitoring of policy changes that could affect the water market.[40]

The environmental impacts of water trading also presented a challenge. Ensuring that the index promotes sustainable water use and does not incentivize harmful practices was a critical consideration. This required integrating environmental factors into the index's methodology and working with environmental organizations to develop guidelines and best practices for sustainable water trading.[41]

Additionally, the fragmented nature of the water market posed logistical challenges in gathering consistent and comprehensive data.

Unlike more centralized markets, water trading in California involves numerous local entities, each with its own pricing mechanisms and reporting standards.

Coordinating with these diverse stakeholders to collect and standardize data required significant effort and collaboration.

4.4 Composition of the Index

The Nasdaq Veles California Water Index mathematical development involves collecting and analyzing transaction data from water rights sales across key water (See footnote 33) markets in California.

The index is calculated using a volume-weighted average[42] price of water transactions from the aforementioned market sources.

This approach as shown in a simplified version in equation (1) (where the transaction volume acts as the weight for the transaction price) ensures that the index accurately reflects the market value of water, providing a reliable benchmark for traders and investors.

The composition of the index includes various types of water transactions, such as spot market sales, long-term leases, and permanent transfers. Each transaction is weighted based on its volume and price, ensuring that the index represents a comprehensive picture of the water market.

$$S_t = \frac{\sum_{i=1}^{n}(p_i V_i)}{\sum_{i=1}^{n}(V_i)} \tag{1}$$

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[40] Source: DWR

[41] Id at 31

[42] Id at 31

By incorporating a diverse range of transactions, the NQH2O captures the dynamic nature of water trading and the varying conditions across different regions and seasons (Nasdaq, 2018).

The data sources for the index include publicly available information from water districts, regulatory filings, and market reports.

While data sources are publicly shared the database is not, Nasdaq states that data is rigorously vetted and processed to ensure accuracy and consistency.

The methodology also involves regular updates and adjustments to account for changes in market conditions, regulatory policies, and environmental factors, maintaining the index's relevance and reliability.

The inclusion of long-term leases and permanent transfers alongside spot market sales helps to smooth out short-term fluctuations and provides a more stable representation of water prices over time (California Department of Water Resources, 2022).

The methodology also takes into account the geographic diversity of water markets in California. Different regions have varying supply and demand dynamics, influenced by factors such as climate, agricultural patterns, and urban development. By including data from multiple regions, the index provides a more comprehensive and balanced view of the overall water market. This regional diversity helps to ensure that the index is not overly influenced by localized conditions and remains representative of broader market trends.[43]

Unfortunately, information regarding the inclusion choice over which climatic factors are considered in the index is proprietary to NASDAQ and is not publicly available, so in order to better understand the nature of the index and its possible climatic components, an econometric model has been utilized to better understand the correlation between different climatic variables and the NQH2O spot price.[44]

The aim of this analysis is to study, on a logarithmic basis, the variation of the price in relation to the variation of different variables, selected based on their geographical characteristics and their relevance to the Californian water system.

The goal that this analysis pursues is not to find the correlations between the different variables chosen, but to better frame the components of the NQH2O index, to then build a pricing model for the NQH2O futures contracts.

As explained above, in order to simplify the model, four types of variables are studied: reservoir storage, precipitation, snowpack water content and temperature.

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[43] See *Understanding The Water Futures Markets,* 2021, CME

[44] See Herman J., 2023, *Seasonal Forecast of the California Water Price Index*

For the purpose of carrying out the data collection, the database of the California Water Department was utilized. This database is responsible for collecting data on rainfall, snow water content, temperatures, and reservoir storage from a vast number of meteorological stations placed all over the state's territory.[45]

For each variable (rainfall, snow water content, temperatures, and reservoir storage) the data stations were chosen following the following rules: one station for each geographical area (north, central 1, central 2, and south)[46], and one station for each altitude range spanning from 0 to 5000 feet and from 5000 to 10000 feet. These criteria were utilized to select the stations that were available.

Invariably, the stations that were chosen for testing were determined in part by the comprehensiveness of the data across the given period, which was an additional criterion that played a role in the selection process.

The time range that has been chosen for the purpose of selecting data and creating a regression model is the period commencing on January 1 of the current year and ending on April 30 of the following year, 2024. This time frame has been chosen since it is the most convenient for both of these purposes (2024 being a standardly wet year).[47]

Daily data is provided both for climatic variables and spot prices (data was gathered and employed in the model in the same manner that CME does when it gathers the data and makes it accessible in its historical prices database).

In the case of the NQH2O index, the spot price is updated on a weekly basis; hence, the data does not change on a daily basis until the next update is performed.

Because the model combines data with a variety of units, all of which are use the imperial unit system, it was developed on a logarithmic basis in order to study the influence that the fluctuation in each of the variables has on the spot price.

This was done in order to determine how the spot price is affected by the variation in each of the variables.

The simplified model includes the following variables with the connected estimates for the betas:

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[45] Data source: California Data Exchange Center (DWR)

[46] In the data collection process 4 regions were identified to collect data from. The distinction between Central 1 and Central 2 is made to highlight the difference between the central valley area and the coastal area (San Francisco Bay).

[47] It is inferred that the model would be more significant if the wetness of the year took in analysis would be standard and not extremely wet or dry which leads to peak prices and market stress.

Term	**Estimate**	**Std. Error**	**Statistic**	**P.value**
(Intercept) **(β_0)**	36,50141801	3,631667411	10,05087027	2,73319E-17
log_statewide_reservoir_storage (**β_1)**	1,358632262	0,159058356	8,541722008	7,88126E-14
log_precipitation_ORK_north **(β_2)**	0,357202867	0,088966143	4,015042732	0,000108349
log_precipitation_SFN_central1 **(β_3)**	0,006503577	0,077498399	0,083918852	0,933272111
log_precipitation_WSD_central2 **(β_4)**	0,023918426	0,038620436	0,619320438	0,536974383
log_precipitation_SDG_south **(β_5)**	0,003240346	0,018551445	0,174668118	0,861658615
log_snowpackwatercontent_ADM_north **(β_6)**	0,000955575	0,001196737	-0,79848397	0,426294798
log_snowpackwatercontent_BLS_central **(β_7)**	0,030241122	0,013850057	2,183465494	0,03110656
log_snowpackwatercontent_BSH_south **(β_8)**	0,047145144	0,02230151	2,113988862	0,036755501
log_maxtemperature_WRS **(β_9)**	0,000972279	0,010758352	0,090374313	0,928152647

Table 1

For a matter of simplicity from now on following the order presented in *Table 1* the different variables will be renamed and mentioned $\{X1, X2, \dots, X9\}$. So that the model can assume the following implicit equation form (where $S(t)\ (spot\ price)\ =\ Y$):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \beta_8 X_8 + \beta_9 X_9 + \varepsilon \tag{2}$$[48]

Which with our model translates to:

$$\begin{aligned} Y = 36{,}50141801 - 1{,}358632262X_1 + 0{,}357202867X_2 + 0{,}006503577X_3 \\ + 0{,}023918426X_4 + 0{,}003240346X_5 + 0{,}000955575X_6 \\ + 0{,}030241122X_7 + 0{,}047145144X_8 + 0{,}000972279X_9 + \varepsilon \end{aligned} \tag{3}$$

The purpose of this model is not the numerical correlations analysis between the variables and the spot price. Instead, it aims to find empirical evidence of the relevance of these climatic variables.

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[48] The model proposed here is a simplified model.

This evidence will then be used to develop a mathematical model for the futures contract based on the NQH2O. Therefore, the true objective of the model is to analyze the significance of the model itself.

The presented information in *Table 2* highlights the statistical results of the regression analysis that linked NQH2O pricing to nine factors related to snowfall, reservoir storage, rainfall, and temperature. Here's a thorough analysis on the statistics:

R^2	*Adj. R^2*	*Sigma*	*P-value*	*d.f.*	*Deviance*	*d.f. residual*	*N° obs*
0,64441937	0,615588513	0,025092361	3,33944E-21	9	0,069888551	111	121

Table 2

R-squared statistic shows that the model's nine predictor variables account for about 64.44% of the variability in NQH2O pricing.

This highlights a reasonably strong association between the predictors and the dependent variable.

Adjusted R-squared considers the number of predictors in the model, giving a more accurate estimate of model fit when numerous variables are included, at 61.56%, it is somewhat lower than the R-squared value, indicating a balance between model complexity and explanation power.

Sigma is the regression's standard error, which quantifies the normal divergence between observed and anticipated NQH2O prices. The value of Sigma suggests that the model is better fitted to the data.

The extremely low p-value (nearly zero) implies that the model is statistically significant, allowing the null hypothesis (all regression coefficients are zero) to be rejected.

It is possible to conclude then that, overall, the regression model appears to be significant and well-fitted, explaining a considerable percentage of the variability in NQH2O pricing using the nine factors related to snowfall, reservoir storage, rainfall, and temperature.

Furthermore, from the Q-Q plot (*Figure 9, see appendix 4.4)* it is possible to state that most residuals follow a normal distribution confirming the intrinsic assumption of the model for which residuals must be normally distributed.

The Q-Q plot (*Figure 9, see appendix 4.4)* suggests that the normality assumption in this model is largely met, confirming the reliability of the model.

Concluding, it appears that the NQH2O index includes in its weighed average algorithm these climatic variables, making these variables important also when forecasting prices.

4.5 Understanding the components of the Index

The Nasdaq Veles California Water Index as it has been analyzed is composed of several key components that together provide a comprehensive but not complete picture of the water market.

These components include the volume-weighted average price of water transactions, the types of water rights traded, and the regions where transactions occur.

Each component is carefully selected and weighted to ensure that the index accurately reflects market conditions and provides a reliable benchmark for trading and investment.

The volume-weighted average price is a critical component, as it balances the impact of large and small

transactions, providing a more accurate representation of market trends.

By weighting transactions based on their volume, the index mitigates the impact of outliers and ensures that the prices reflect typical market conditions (Nasdaq, 2018).

The geographic distribution of transactions is another vital component. Water prices vary significantly across different regions due to factors such as local supply and demand conditions, regulatory policies, and environmental factors. By incorporating transactions from various regions, the index provides a more balanced and accurate picture of the overall market.[49]

Furthermore, the regressive model (*See Table 1*) and its significance suggests other variables are incorporated in the index, such as the state wide reservoir storage to which the price appears to be most susceptible.

The components then must be accurately considered both for calculating the spot price and understand its possible future trends.

Understanding these components is, then, crucial for interpreting the index and making informed trading and investment decisions.

Each component plays a role in capturing the complexity and dynamics of the water market, providing a detailed and accurate reflection of market conditions. This comprehensive approach ensures that the NQH2O is a reliable and valuable tool for all stakeholders involved in water trading and management.[50]

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[49] Id at 31

[50] See Coogan et al., 2024, *Veles Water Weekly Report*

5 NQH2O futures

5.1 Introduction to NQH2O futures

The NQH2O futures contracts, introduced by the CME Group on 7 December 2020, represent a significant innovation in the realm of commodity trading.

These contracts are based on the Nasdaq Veles California Water Index (NQH2O), which tracks the spot price of water rights in California.

The primary purpose of these futures contracts is to provide a financial tool for water users, such as agricultural producers, municipalities, and industrial users, to hedge against price volatility and manage risk more effectively.

Unlike traditional commodity futures that involve the physical delivery of the underlying asset, NQH2O futures are settled in cash, thus eliminating the logistical complexities associated with the transportation of water.[51]

The introduction of water futures was driven by the increasing scarcity and variability of water supplies, particularly in regions like California that are heavily dependent on consistent water availability. By offering a transparent and standardized mechanism for price discovery and risk management, NQH2O futures enable market participants to secure more predictable water costs and mitigate financial risks associated with water scarcity.

These derivatives present a cost-effective means of risk transferring to manage water price risks.

5.2 Contract specifications

NQH2O futures contracts are designed to be both flexible and accessible, catering to a wide range of market participants.

Each contract is valued at 10 acre-feet times the value of Nasdaq Veles California Water Index (NQH2O), a unit that aligns with common usage in water management.

The Exchange (CME) determines the trading schedule for the contract such as time for delivery.

The contracts are traded on CME Globex, which operates nearly continuously from Sunday evening to Friday evening, reflecting the global demand for water resources.

The contracts have quarterly expirations (March, June, September, December) and include the two nearest non-quarterly months. The minimum price fluctuation is $1 per acre-foot for outright positions and $0.25 per acre-foot for calendar spreads. This structure allows traders to make precise

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[51] Source: CME group

adjustments to their positions. Settlement occurs on the third Wednesday of the contract month, unless it is not a business day, in which case it is the next business day. This standardized process ensures predictability and efficiency in trading and settlement.[52]

5.3 Cash settlement mechanism

The NQH2O futures contracts employ a cash settlement mechanism, which simplifies the trading process and enhances liquidity.

Upon contract expiration, the final settlement price is based on the value of the NQH2O index, which is derived from transaction data in California's water market, including both surface and groundwater transactions[53]. This method ensures that the futures contract value at expiration aligns with the actual market price of water, providing an accurate benchmark for financial transactions[54] (Hedging Effectiveness of Commodity Futures Contracts, 2021).

The cash settlement process involves the exchange of money rather than the physical delivery of water, which is advantageous for traders who seek to manage financial exposure without dealing with the logistics of water transport.

This mechanism also ties the futures market closely to the physical water market, ensuring that the futures prices reflect real-world conditions and transactions.

5.4 Valuation models for NQH2O futures

The true goal of this dissertation is to understand how these contracts would be modelized mathematically. Since the price model for such derivatives is proprietary to CME, the proposed model will be based on the observations analyzed by the regression model and based on similar cases such as electricity futures including a revised framework to better capture the characteristics of the commodity underlying the contracts, in this case water.

To develop these models, we must introduce and define water as a commodity because of its physical nature.

Commodities are mostly traded through forward and futures contracts as explained in the introduction these derivatives are usually exchanged by the CME which offers a large set of contracts underlying commodities.

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[52] See CME Rulebook: Nasdaq Veles California Water Index Futures

[53] Id at 31

[54] See Penone C. et al., 2021, *Hedging effectiveness of commodity futures contracts*

There will be two models proposed in this dissertation, that is because one will have the assumption of the future price coinciding to a hypothetical forward price on water which is not currently traded by CME.

The models comprise a revised model of the proposed model for electricity forward pricing presented by Carmona and Coulon, 2010[55].

The reason for which it is possible to revise the model on electricity futures/forwards is the similarities shared between these two commodities: both water and electricity are essential services for daily life activities, they require significant infrastructure for a supply network, they are continuously flowing through such networks[56], the commodities are storable and have a similar supply chain with a cost of treatment and transmission, furthermore both the commodities are subject to scarcity, both commodities have also a strong seasonal and weather-related risk as both water and electricity are sensitive to extreme weather condition.

The assumptions to be made to develop this model are mainly that there is no marketing to market during the period of the future contract, the model is arbitrage free and the interest rate is deterministic.

This assumption implies:

$$F^{fut}(t,T) = F^{fwd}(t,T) \tag{4}$$

From now on the notation $F(t,T)$ will be used to describe the value at time t of the forward (futures) contract with maturity T, while $S(t)$ or S_t indicates the spot price at time $t.$ ($F(t,T)$ this notation implies the delivery date to be coincident with the maturity date, which in the case of NQH2O is not realistic as delivery does not happen in these contracts, thus the maturity date coincides with the cash settlement).

Let's also define r as a deterministic interest over the $(T-t)$ period.

The model would be based on a simple arbitrage-free pricing model that relates the forward (futures) and spot as:

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[55] See Carmona R. and Coulon M., 2010, *A survey of commodity markets and structural models for electricity*

[56] See Aïd R., 2014, *Electricity derivatives*

$$F(t,T) = S_t e^{r(T-t)} \tag{5}$$

And under a risk-neutral measure ($\mathbb{Q}$) can be written as the expectation conditioned by the all the information available at time t ($\mathcal{F}_t$):

$$F(t,T) = \mathbb{E}_{\mathbb{Q}}[S(t) \mid \mathcal{F}_t] \tag{6}$$

The above equalities are however too simple to be used to model water futures pricing.

Since we defined water as a commodity it is necessary to take in consideration the case in which opposed to enter in futures contracts, the commodity is held physically.

Holding water physically can be really favorable during shock periods such as droughts but it involves storage costs and maintenance expenses. These costs can be modeled using a convenience yield δ. The introduction of a convenience yield helps to avoid backwardation, so the case in which the difference between forward and spot prices is less than the cost of carry c.

That is why we model the convenience yield as:

$$\delta = \delta_1 - c \tag{7}$$

With the condition:

$$\delta \geq 0 \tag{8}$$

Including the convenience yield in the spot-future relationship for commodities:

$$F(t,T) = S_t e^{(r-\delta)(T-t)} \tag{9}$$

$$F(t,T) = S_t e^{(r-\delta_1+c)(T-t)} \tag{10}$$

Given the price sensitivity to variations in climatic variables a risk premium related to the possibility of a drought period is included to better account for the risks underlying the contract.

This choice derives from the regression analysis explained above and from the predictability of drought periods.

Moreover, the unique characteristics of water such as scarcity and seasonal demand, sensitivity to regulation, and uncertainty in weather conditions.

A proposal no investigated further in this dissertation due to market incompleteness is adding a risk premium for drought risk D_t could be modelized as a mean-reverting process.

Including a connected parameter defining the sensitivity of drought risk λ, such that:

$$F(t,T) = S_t e^{(r+\lambda D_t-\delta_1+c)(T-t)} \tag{11}$$

5.4.1 One-factor mean-reverting model:

The first model develops from the spot-forward relation described by equation (5).

This model includes only one factor and revolves around the concept of mean-reversion, the assumption for which a commodity price tends to revert to its mean price.

This mean-reverting assumption works well for water prices.

The model proposed here is built from the model proposed by Schwartz, 1997.[57]

It is built to price futures contracts and assumes a mean reverting price of the Ornstein-Uhlenbeck type.

To develop the model, it is necessary to assume that the spot price follows the following stochastic process:

$$dS_t = \kappa(\mu - \ln S_t)S_t dt + \sigma S_t dW_t \tag{12}$$

Where μ is a constant mean reversion level, κ speed of mean-reversion, σ is volatility of the spot price and W is the standard Brownian motion.[58]

Defining:

$$X = \ln S_t \tag{13}$$

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[57] See Schwartz E., 1997, *The Stochastic Behavior of Commodity Prices: Implications for Valuation and Hedging*

[58] See Ladokhin et al., 2021, *Three-factor commodity forward curve model and its joint P and Q dynamics*

Applying Ito's lemma, the log-price can be characterized by a Ornstein-Uhlenbeck process in the form:

$$dX = \kappa(\alpha - X)dt + \sigma dW \tag{14}$$

$$\alpha = \mu - \frac{\sigma^2}{2\kappa} \tag{15}$$

$\kappa > 0$ is the measure of the degree of mean-reversion to the long-run mean log-price, $\alpha.$ σ is volatility of the process and W is the standard Brownian motion.

Under a risk-neutral measure, the dynamics of equation (14) can be rewritten including $\alpha^* = \alpha - \lambda$, where λ is the market price of risk (assumed in this model to be constant); and including dW^* the standard Brownian motion under the risk-neutral measure.

$$dX = \kappa(\alpha^* - X)dt + \sigma dW^* \tag{16}$$

The conditional distribution of X at time T, under the risk-neutral measure, has mean and variance:

$$E_0[X(T)] = e^{-\kappa T}X(0) + (1 - e^{-\kappa T})\alpha^* \tag{17}$$

$$Var_0[X(T)] = \frac{\sigma^2}{2\kappa}(1 - e^{-2\kappa T}) \tag{18}$$

The Ornstein-Uhlenbeck process, given an initial value $X(0)$ at time 0, the value of $X(T), T > 0$ is normally distributed.

So the expected price of a futures using this model follows the properties of the log normal distribution:

$$F(t,T) = \exp(\, E_0[X(T)] + \frac{1}{2}Var_0[X(T)]) \tag{19}$$

$$F(t,T) = \exp\left[e^{-\kappa T} \ln S_t + (1 - e^{-\kappa T})\alpha^* + \frac{\sigma^2}{4\kappa}(1 - e^{-2\kappa T}) \right] \tag{21}$$

Which translates in the logarithmic form to:

$$\ln F(t,T) = e^{-\kappa T} \ln S_t + (1 - e^{-\kappa T})\alpha^* + \frac{\sigma^2}{4\kappa}(1 - e^{-2\kappa T}) \tag{22}$$

5.4.2 Gibson-Schwartz two-factor model

In this model the risk premium will not be considered as it will be developed based on two-factors: the commodity spot price S_t and the convenience yield δ_t, following the classic Gibson-Schwartz model.

The model will be developed upon the spot-future relationship found at (9), (10).

The state variables then are in the following from Gibson and Schwartz, 1990[59]:

$$\begin{cases} dS_t = (r - \delta_t)S_t dt + \sigma_S S_t dW_S \\ d\delta_t = [\kappa(r - \delta_t)]\delta_t dt + \sigma_\delta dW_\delta \end{cases} \tag{23}$$

We revise the model following the model proposed by Ribeiro D.R. and Hodges S.D., 2004 in which the convenience yield using a Cox-Ingersoll-Ross (CIR) process to substitute the Ornstein-Uhlenbeck process so that the model is arbitrage-free.[60] So that:

$$\begin{cases} dS_t = (\mu - \delta_t)S_t dt + \sigma_S \sqrt{\delta_t} dW_S \\ d\delta_t = [\kappa(m - \delta_t)]dt + \sigma_\delta \sqrt{\delta_t} dW_\delta \end{cases} \tag{24}$$

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[59] See Gibson R. and Schwartz E.S., 1990, *Stochastic convenience yield and the pricing of oil contingent claims*

[60] See Ribeiro D.R. and Hodges S.D., 2004, *A Two-Factor Model for Commodity Prices and Futures Valuation*

The joint dynamics of the model take into consideration the case where volatility σ is also proportional to the square root of the convenience yield current level δ_t this allows to ensure non-negativity and better describes volatility itself.

μ is the total expected return on the spot commodity price; κ is the instantaneous convenience yield's speed of mean reversion, and m is the level to which δ_t reverts as t goes to infinity. (the long-run convenience yield mean)

These factors can be estimated using historical data.

$W_S \: and \: W_\delta$ are standard wiener processes correlated as:

$$dW_S \, dW_\delta = \rho dt \tag{25}$$

The probability density of the convenience yield at time t conditional on its value at current time t is a non-central chi-square.[61]

Under the risk-neutral measure the stochastic processes become, starting from equation (10):

$$\begin{cases} dS_t = (r + c - \delta_1)S_t dt + \sigma_S \sqrt{\delta_t} dW_S^* \\ d\delta_t = [\kappa(m - \delta) - \lambda]dt + \sigma_\delta \sqrt{\delta_t} dW_\delta^* \end{cases} \tag{26}$$

Where c is the constant storage cost expressed as a proportion of the spot price.

In the joint dynamics (24) since the convenience yield is non-traded, λ is introduced which is the market price of risk assumed to be constant.[62]

Furthermore W_S^*, W_δ^* are standard wiener processes adjusted for the risk-neutral measure. And correlated following: (where ρ is the same as before)

$$dW_S^* \, dW_\delta^* = \rho dt \tag{27}$$

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[61] See Cox et al., 1985, *A theory of the term structure of interest rates*

[62] See Schwartz, 1997

Applying Ito’s lemma and defining $x = \ln S_t$, the process for the log price is defined as:

$$dx = \left(r + c - \left(1 + \frac{1}{2}\sigma_S^2\right)\delta_1\right)dt + \sigma_s\sqrt{\delta_t}dW_S^* \tag{28}$$

Defining:

$$T - t = \tau \tag{29}$$

So that τ represents time to maturity.

This model has an exponential affine solution in the form:

$$F(t,T) = F(S_t, \delta, \tau) = S_t e^{A(\tau) - B(\tau)\delta} \tag{30}$$

With initial conditions:

$$A(0) = 0,\ B(0) = 0.$$

For a time to maturity τ, then:[63]

$$B(\tau) = \frac{2(1 - e^{-\kappa_1 \tau})}{k_1 + k_2(k_1 - k_2)e^{-\kappa_1 \tau}} \tag{31}$$

$$A(\tau) = (r + c)\tau + (\lambda - \alpha m)\int_t^T \frac{2(1 - e^{-\kappa_1 \tau})}{k_1 + k_2(k_1 - k_2)e^{-\kappa_1 \tau}} \tag{32}$$

So that:

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[63] Id at 60

$$A(\tau) = (r + c)\tau + (\lambda - \alpha m) \int_{t}^{T} B(\tau) \tag{33}$$

With:[64]

$$k_1 = \sqrt{k_2^2 + 2\sigma_\delta^2} \tag{34}$$

$$k_2 = (\alpha - \rho\sigma_s\sigma_\delta) \tag{35}$$

5.5 Rationale for the models

The valuation models proposed above have been chosen for their adaptability to the characteristics of the commodity analyzed. one-factor mean-reverting model is well-suited for NQH2O water futures due to the inherent seasonal and cyclical nature of water prices.

Water demand and supply, but also spot prices as empirically shown before, are strongly influenced by seasonal factors such as rainfall, snowmelt, and agricultural cycles. This results in price fluctuations that tend to revert to a long-term average over time.

Furthermore, water prices are highly persistent, and mean-reversion is found in a number of examples implying that in these cases shocks are of transitory nature and prices will return to their original long trend projections.[65]

The mean-reverting model captures this tendency by assuming that the price of water will fluctuate around a long-term mean, reflecting periods of excess supply and scarcity typical of water markets.

This model has been successfully applied to other commodities with similar cyclical patterns, such as electricity, crude oil and agricultural products.

These commodities, like water, are subject to seasonal variations and long-term trends, making the mean-reverting framework an efficient tool for modeling their prices.

Then, the well-recognized historical success of this model in other commodity markets supports its application to NQH2O water futures.

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[64] Id at 60

[65] See Monge M. and Gil-Alana L.A., 2020

Furthermore, the one-factor mean-reverting model proposed is simple and practical to implement, which makes it attractive for markets where data might be limited or where simplicity is preferred.

Given that water futures are a relatively new financial instrument, and the market for these derivatives is incomplete, a simpler model that captures the dynamics of price movements can be beneficial for initial market participants who are looking to hedge risks without dealing with complex modeling requirements.

On the other hand, the (revised)[66] Gibson-Schwartz model incorporates the convenience yield, which is the benefit of holding physical water reserves to avoid future shortages. (e.g. Water Banks, see Chapter 3)

This condition is particularly relevant for water, as having immediate access to water during a drought or high-demand period can be significantly more valuable than holding a futures contract.

The two-factor model accounts for this by including the convenience yield as a state variable, making it more aligned with the real-world economics of water storage and usage.

The two-factor model, thus, offers greater flexibility in capturing the complex dynamics of the water market. Water prices are influenced by both the current spot price and the convenience yield, which reflects the market's expectations about future water availability and scarcity. This dual-factor approach allows for a more nuanced understanding of price movements, especially in response to unexpected events such as droughts or regulatory changes.

By modeling both the spot price and convenience yield, the Gibson-Schwartz model provides a more comprehensive framework for pricing NQH2O futures.

Empirical evidence and applications in similar markets, such as electricity and other storable commodities, have demonstrated the efficiency of the Gibson-Schwartz model.

Furthermore, the adaptability of this model to different market conditions and its ability to incorporate key features of the physical nature of underlying commodity (like storage costs and convenience yield) make it particularly suitable for NQH2O water futures.

Additionally, the model's ability to handle volatility and mean reversion in both the spot price and convenience yield aligns well with the observed behavior of water prices, which are subject to significant short-term volatility and long-term mean reversion.

5.6 Hedging and speculation strategies

NQH2O futures provide powerful tools for both hedging and speculation in the water market.

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[66] Id at 60

For hedging purposes, agricultural producers, municipalities, and industrial users can take positions in the futures market to protect themselves against adverse price movements.

For example, an agricultural producer anticipating higher water costs can buy futures contracts to lock in current prices, offsetting potential future increases in water costs.

Moreover, NQH2O futures can be integrated into broader financial strategies to manage comprehensive risk exposures.

Companies involved in water-intensive industries can use these futures alongside other commodity futures to create a diversified risk management portfolio, enhancing their financial stability and resilience in the face of environmental uncertainties.

In Schwartz, 1997 a hedging strategy for the one-factor mean reversion valuation model is obtained by discounting the future price.

This hedging strategy investigates the possibility of hedging long-term forwards commitments with the existing short-term futures contracts.

The number of long positions w_i in future contract with maturity t_i required to hedge a forward commitment to deliver one unit of a commodity at time T is obtained by solving the equations:

$$w_1 F_t(t, t_i) = e^{-rT} F_t(t, T) \tag{36}$$

To find numerically the number of futures contracts w_i it is necessary to estimate the future price using historical data.

The hedging strategy described above is proposed here to understand what an effective hedging strategy in the one-factor model would be.

However, it is not realistic for the case of the NQH2O futures contracts.

6 Conclusion

6.1 Conclusive insights from valuing NQH2O Water Futures

The aim of this dissertation was to determine valuation models suitable for NQH2O water futures.

The valuation models proposed above, specifically the one-factor mean-reverting model and the revised Gibson-Schwartz two-factor model, offer a framework for understanding and predicting NQH2O water futures prices.

The one-factor mean-reverting model effectively captures the cyclical nature of water prices influenced by seasonal and climatic factors through its assumption of price reversion to a long-term mean. This model suits commodities like water, where supply-demand imbalances drive price fluctuations. Meanwhile, the Gibson-Schwartz two-factor model incorporates the convenience yield, adding depth to the understanding of market dynamics, particularly in situations where immediate access to water is crucial. Empirical evidence from similar markets like natural gas and crude oil supports these models' applicability to water futures, enhancing their relevance.

Furthermore, the regression analysis carried out in to analyze the NQH2O spot price identified significant variables, including climatic conditions, reservoir levels, and historical price trends, both confirming the mean-reverting behavior of water prices and validating the need for a two-factor model to comprehensively capture short-term price fluctuations.

Key findings from the regression analysis revealed that water prices are highly sensitive to seasonal changes and climatic events, such as droughts and heavy rainfall, which directly impact reservoir levels and water availability.

The inclusion of the convenience yield in the two-factor model provides realistic prediction of water prices, accounting for the immediate benefits of holding physical water reserves.

Despite the challenges posed by market incompleteness, such as limited historical data, lack of standardization in water contracts, water markets, and regulatory uncertainties, these valuation models provide essential tools for price prediction and risk management.

Market incompleteness can lead to inefficiencies and increased volatility, making accurate pricing and effective risk management more difficult.

The study underscores the importance of improved data collection, standardized reporting, and enhanced regulatory frameworks to address market inefficiencies. Accurate and comprehensive data collection is critical for refining model parameters and improving prediction accuracy. Additionally, regulatory clarity and the development of standardized water contracts can foster greater market participation and liquidity, reducing volatility and enhancing market stability. By integrating these models with ongoing efforts to improve market completeness, participants can better navigate and capitalize on the emerging water futures market.

This comprehensive framework for understanding water price dynamics offers practical solutions for hedging risks and exploiting opportunities in this evolving market.

The combination of robust valuation models, enhanced data practices, and supportive regulatory environments will be key to the successful development of a stable and efficient water futures market.

Appendix:

2.2 Drought risk

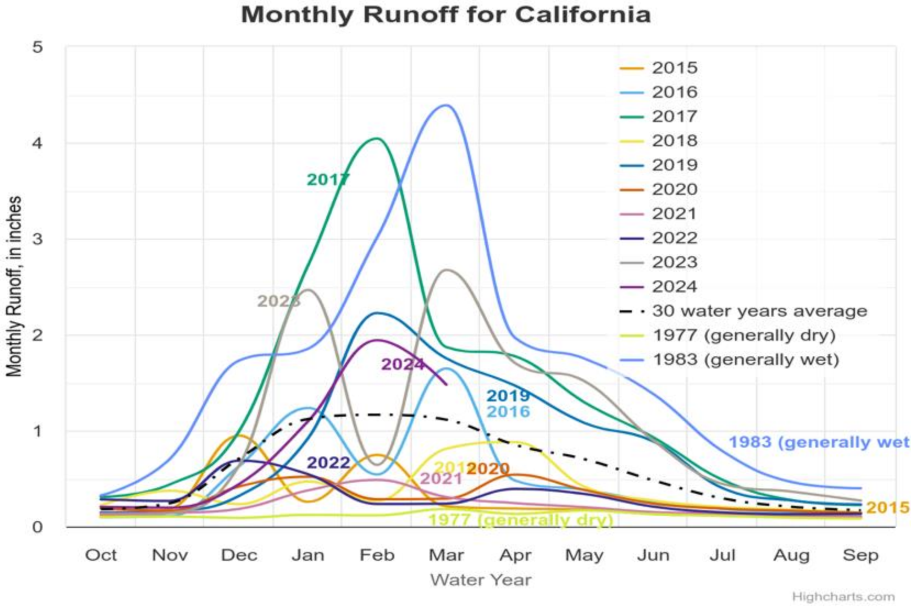

Figure 1 *(source: USGS Water Watch database)*

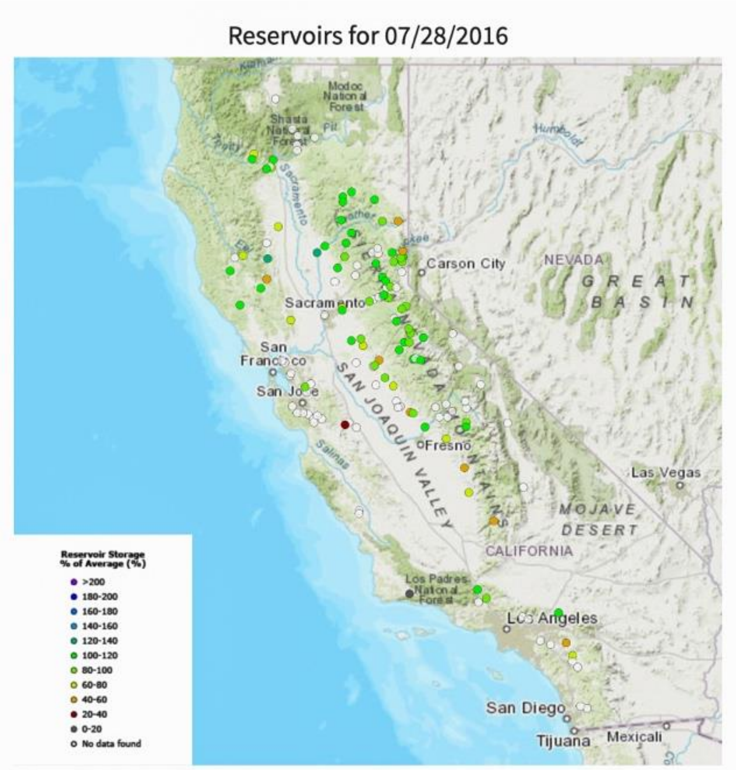

Figure 2 *(Source: Reservoir data shown here are for a subset of those DWR (Department of Water Resources) California Data Exchange Center reservoirs that have daily water level or storage data available.)*

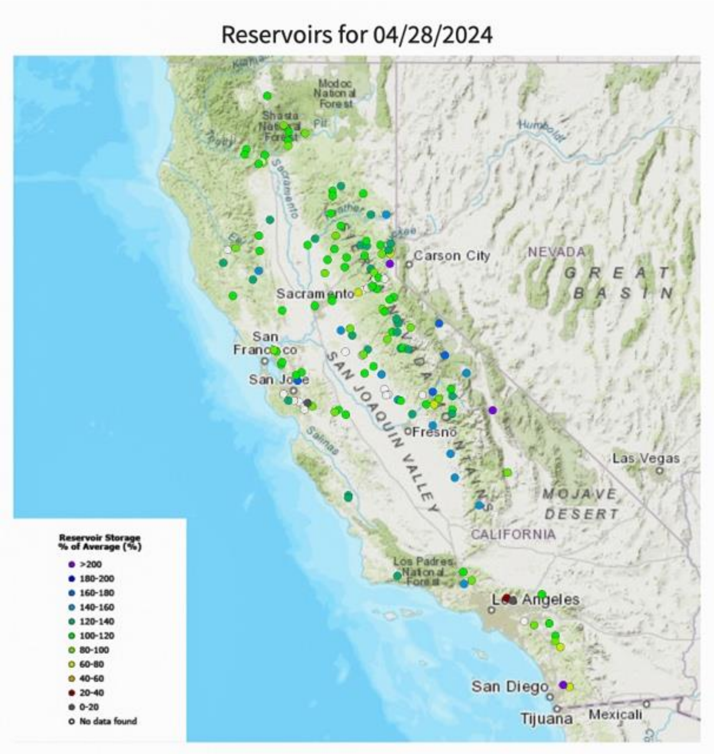

Figure 3 (Source: Reservoir data shown here are for a subset of those DWR (Department of Water Resources) California Data Exchange Center reservoirs that have daily water level or storage data available.)

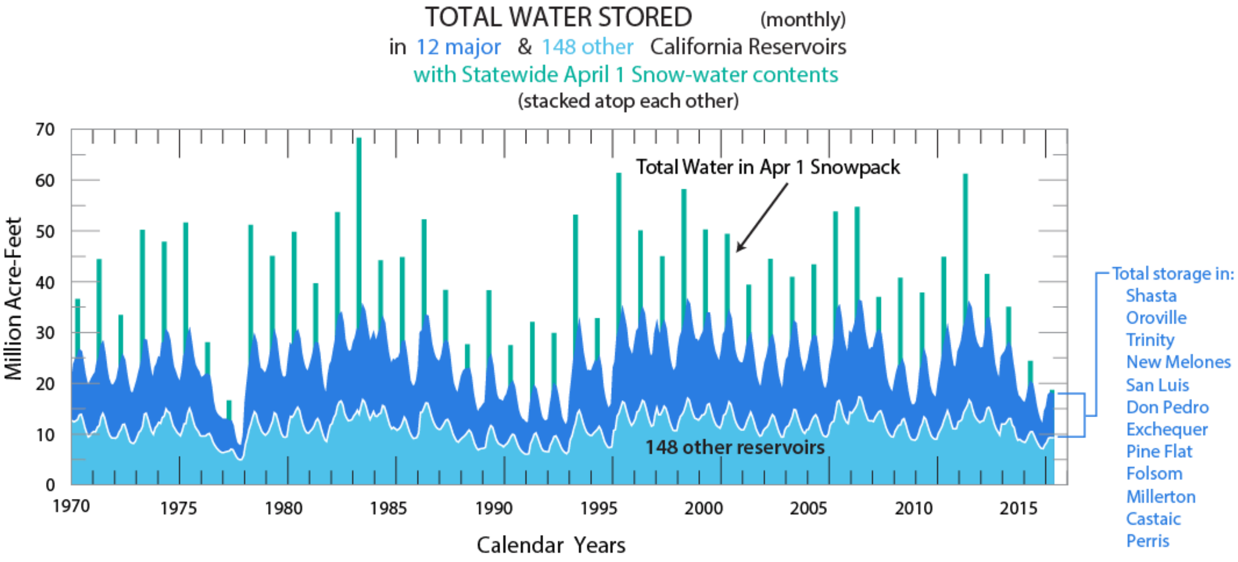

Figure 4: (Source: USGS Water Watch)

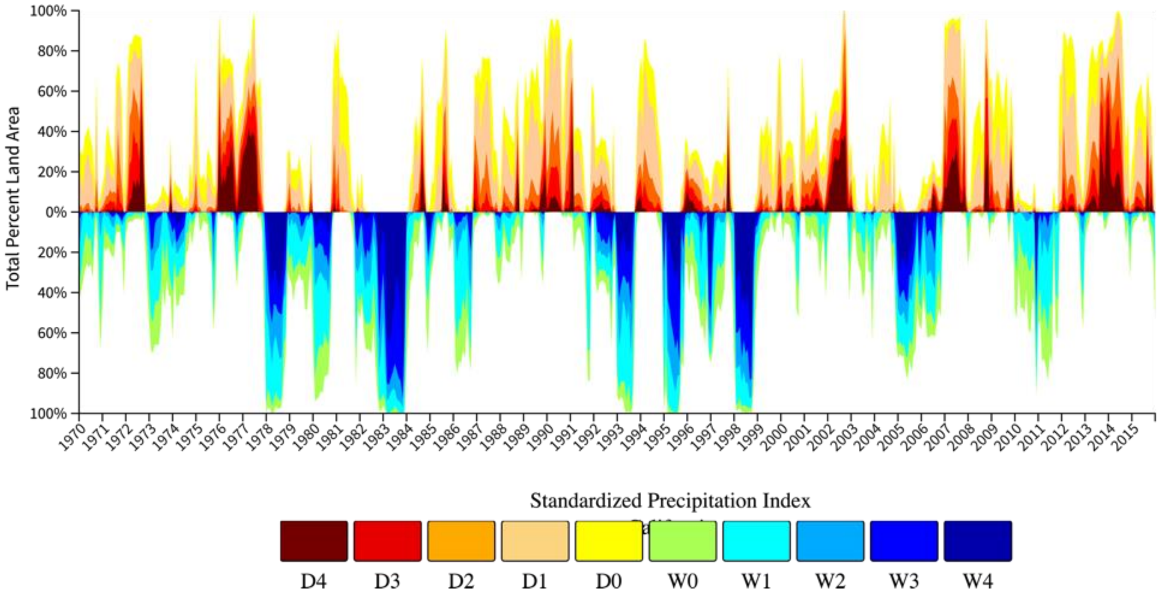

***Figure 5**: (Source: NIDIS (National Integrated Drought Information System))*

3.1 Overview of California's water network

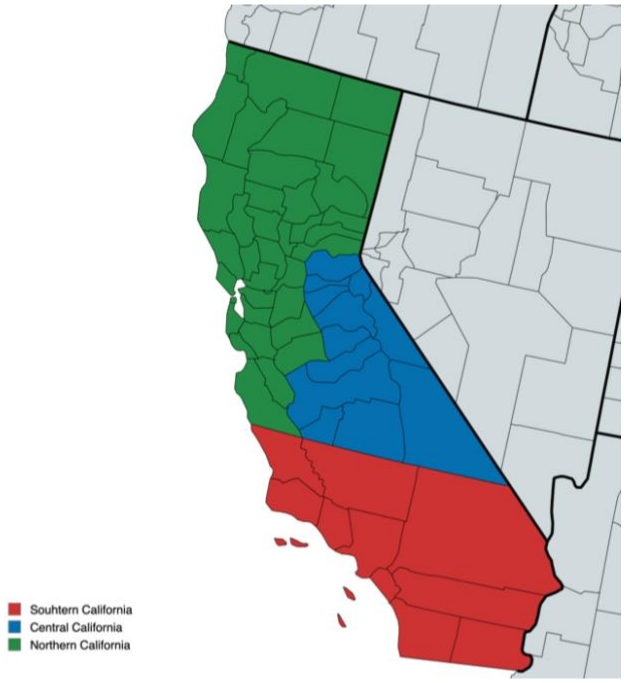

Figure 6

3.1.1 The State Water Project

Figure 7: (Source: California Department of Water Resources)

3.1.2 The Central Valley Project

Figure 8: (Source: United States Geological Survey)

4.4 Composition of the Index

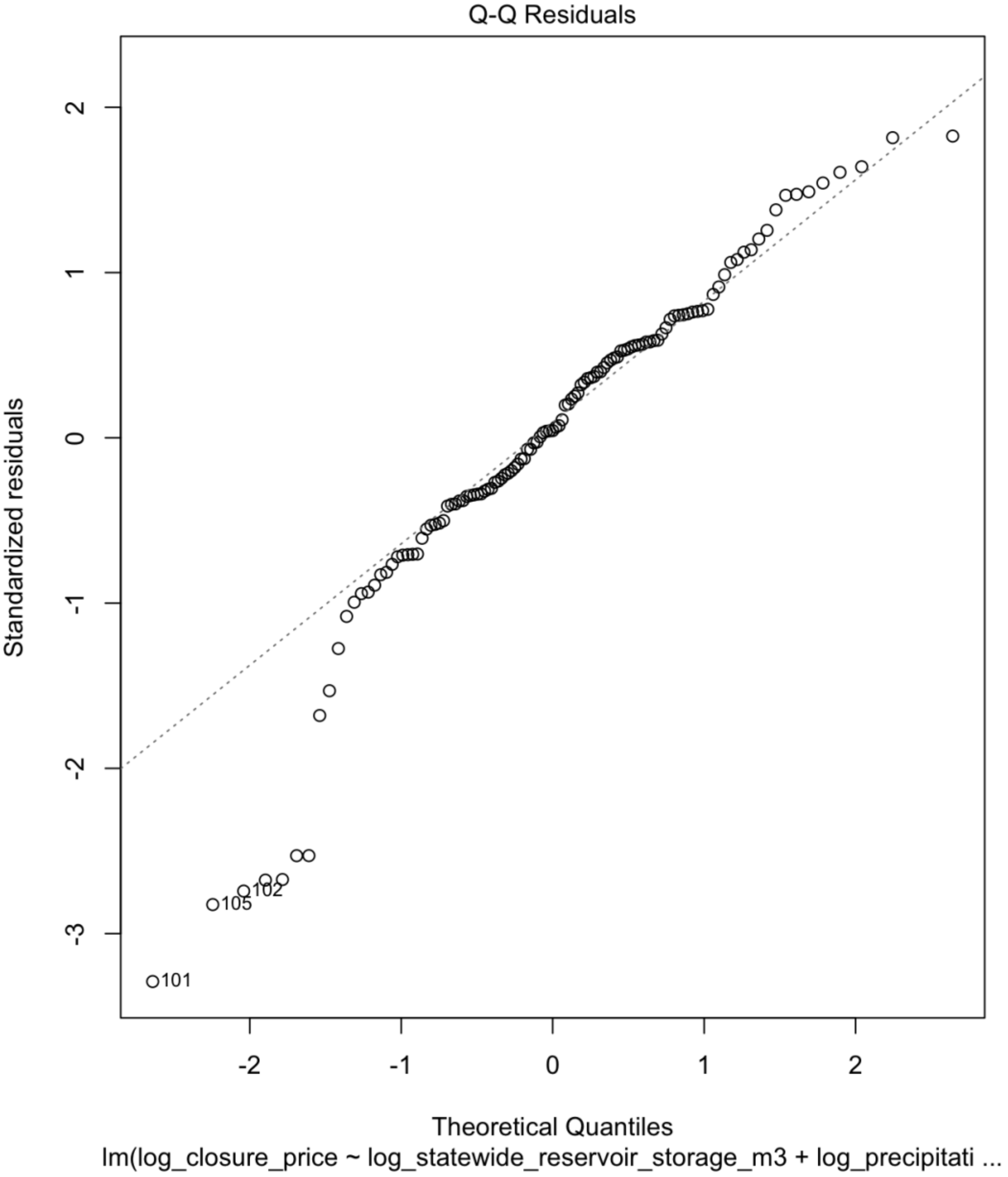

Figure 9: *(Source: data from regression analysis)*

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