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EDITED BY
Naser Valizadeh,
Shiraz University, Iran

REVIEWED BY
Cuthbert Taguta,
University of KwaZulu-Natal, South Africa
Latif Haji,
Shiraz University, Iran
Muhammad Kha,
Dalian University, China

*CORRESPONDENCE
Bethany O'Shea
✉ bethoshea@sandiego.edu

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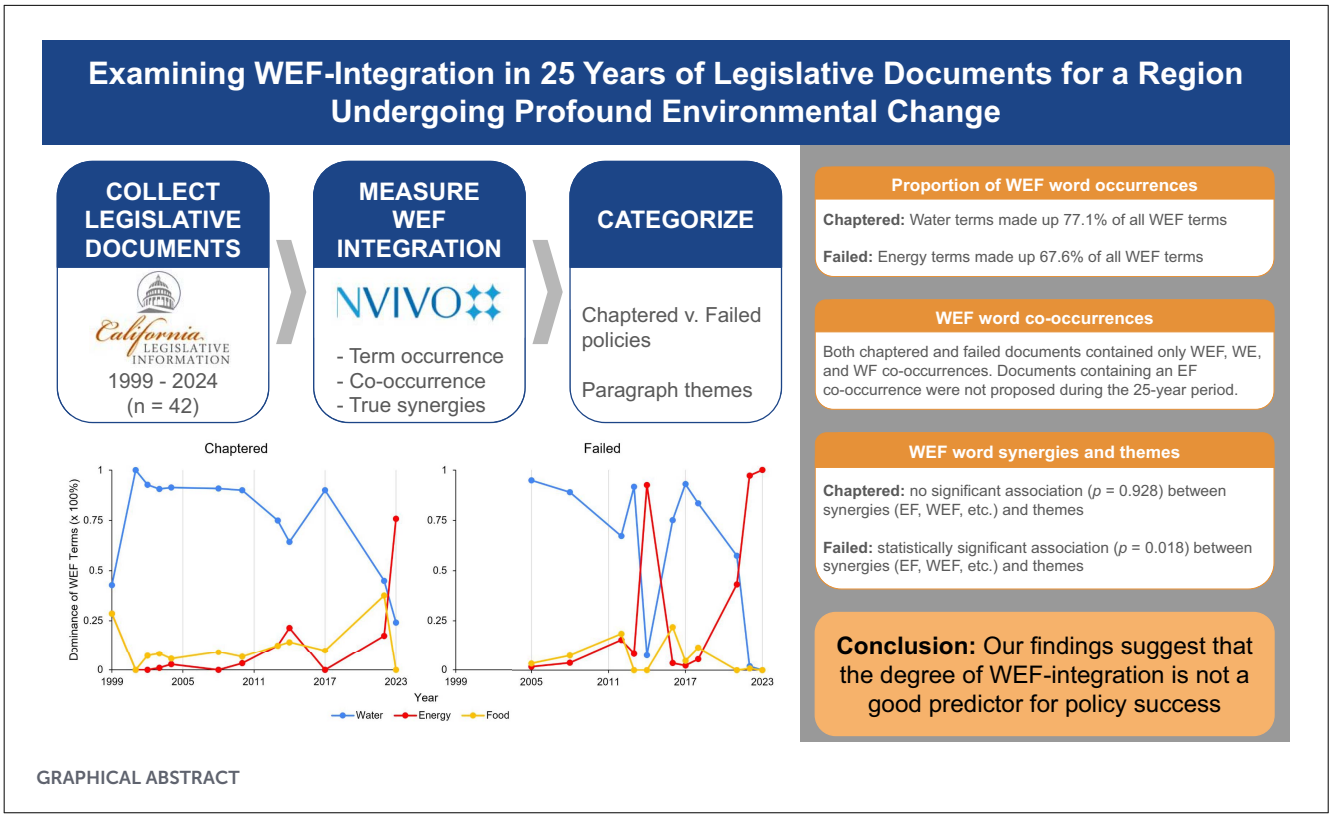
Examining WEF nexus-integration in 25 years of legislative documents for the Salton Sea region undergoing profound environmental change

Dillon Pao [1], Bethany O'Shea [1]*, Amy Quandt [2] and Olusola O. Ololade [3]

[1]Department of Environmental and Ocean Sciences, University of San Diego, San Diego, CA, United States, [2]Department of Geography, San Diego State University, San Diego, CA, United States, [3]Centre for Environmental Management, University of the Free State, Bloemfontein, South Africa

The water–energy–food (WEF) nexus provides a framework for understanding how actions in one sector can influence outcomes in the others, often in complex and unintended ways. Traditional sector-specific policies frequently overlook the trade-offs and synergies between water, energy, and food systems. This study builds on previous policy analyses by examining the evolution of WEF nexus-integration in legislative documents submitted to the California State Legislature over a 25-year period for the Salton Sea region—an area where WEF sectors drive the local economy but face competing interests and significant environmental change. Salton Sea-Focused documents were analyzed using qualitative content analysis in *NVivo*, followed by inferential statistical techniques implemented in SPSS. Findings reveal that a high degree of WEF integration is not necessarily predictive of policy adoption. Some proposals demonstrated "gold-tier" integration, encompassing actionable and meaningful measures across all three sectors, yet failed to become law. Instead, the most successful policies were reactive, addressing environmental threats to food production and prioritizing water–food (WF) synergies. Over time, shifts from WF to water–energy (WE) synergies reflected the non-linear nature of reactive policy-making, even though not all of them were enacted into law (chaptered). We propose that future successful policy-making in the region will likely be grounded in community-led priorities, particularly public health concerns informed by scientific evidence. This approach furthers the historical pattern where science had identified ecological damage, which then shaped conservation-finance legislation aligned with the dominant sectoral synergy of the time—historically, WF, while also accounting for the complex role of energy within the nexus to support enduring, sustainable development. Other locations facing profound environmental change may look to the evolution of policy in this region for lessons on trade-offs between WEF sectoral synergies and reactive, non-linear policy-making.

KEYWORDS
agriculture, lithium, policy, Salton Sea, water-energy-food (WEF/FEW) nexus, WEF-integration



GRAPHICAL ABSTRACT

1 Introduction

Water, energy, and food are globally demanded and interconnected resources essential for life (Liang et al., 2020). The consideration of these three resources as being interdependent and interconnected is what is known as the water-energy-food (WEF) nexus. The WEF nexus is often used to understand how actions in one sector can impact outcomes in the others, often in complex and sometimes unintended ways. For example, water is often needed to produce energy and grow food; energy is required to pump and transport water and to produce food; and food production contributes to runoff carrying fertilizers and requires energy for mechanization (Eriksson et al., 2025). The WEF nexus is a holistic, systemic, and integrated environmental governance approach that considers all three sectors together (water, energy, and food) rather than each as a singular resource. This can be advantageous for sustainable development and use of critical resources, as seen in South Africa, where large amounts of water are needed to produce energy from coal, and this water use competes with agricultural production (Ololade, 2018). In this case, a single-resource approach to governance ignores the interconnectedness of the ecological systems that support water, energy, and food. Further, the WEF nexus approach can also ensure equal access to water, energy, and food resources in areas that have historically experienced significant disparities in access to these resources (Ololade et al., 2017).

Traditional, sectoral policies often ignore the trade-offs and synergies between water, energy, and food, which could result in inadequate solutions (Venghaus and Hake, 2018). Thus, by utilizing the integrated WEF nexus in policy-making, we often aim to create sustainable and fair allocations of resources that consider all three sectors as an interconnected system (Venghaus and Hake, 2018). This approach has been deemed necessary in achieving most of the goals and targets included in the 2030 Agenda for Sustainable Development, particularly in water-scarce regions where the security of one or all the WEF resources could be jeopardized by natural hazards or political challenges (Ololade, 2018; Hejnowicz et al., 2022; Senzanje et al., 2022). WEF policies may also aim to enhance resource efficiency, reduce waste, and anticipate unintended consequences of resource use.

Interest in the WEF nexus has grown in recent years (Rhouma et al., 2024), partially due to the escalating impacts of climate change and extreme events on WEF resources (Pardoe et al., 2018). In a survey carried out by Eriksson et al. (2025), findings indicate that the "WEF nexus approach seems to have moved away from being strictly about resources or sectoral securities, and toward governance and policy, especially in relation to ecosystems and ecosystem services," suggesting that an integrated consideration of WEF sectors and ecological support is required in policy efforts. A lack of integration of WEF sectors in legislative documents can lead to overlapping and unnecessary costs being incurred during the course of managing water, energy, and food resources (Ololade et al., 2017; Pardoe et al., 2018; Norouzi and Kalantari, 2020). A semi-quantitative analysis of nexus thinking in European Union (EU) policy documents revealed the relatively minor roles the WEF nexus played within the EU when compared to other sub-nexuses (Venghaus and Hake, 2018). The study found that past policy design throughout the EU has mostly addressed WEF sectors individually rather than holistically.

Eriksson et al. (2025) continues, "the gap is that it [WEF nexus] is not reflected in methodology or where to focus future research efforts." Additionally, limitations exist between intent and action; an accounting of WEF mentions in policies highlighted intent statements rather than actionable statements (Venghaus and Hake, 2018). WEF nexus integration has also been documented to focus on some sectors and themes, while ignoring others, including public health and agriculture (Rhouma et al., 2024). A gap between science and WEF-influenced policy also exists (Rhouma et al., 2024). Al-Zubari Alrwis (2020) detail a policy brief for the Middle East and North Africa (MENA) region, highlighting the need to establish a research network to bridge the science-policy interface gap. Such a network would help increase the implementation of the WEF nexus as an appropriate solution for sustainable resource management in the MENA region. Further, Bizikova (2019) states that for the effective integration of the WEF nexus into policies and decision-making, there is a need to manage relational equity through institutional partnerships in addition to collaborations between researchers and institutions undertaking WEF assessments, and key policy and decision-making agencies. The challenge that remains is how sectoral policies can be better integrated for sustainable development. Hence, the extent of incorporating the WEF nexus in policies and institutional frameworks may determine its successful implementation at different tiers and levels of resource management in the three sectors.

Our study aims to build upon these previous policy analysis efforts, exploring WEF-integration over time in both chaptered and failed legislative documents submitted to a State Legislature over a 25-year period in the Salton Sea region. In this region, WEF sectors dominate the local economy, yet are challenged by competing interests and profound environmental change. We chose the Salton Sea region because of the importance and integration of its water, energy, and food resources throughout the Western United States and beyond. We chose state legislative documents as our analysis tool because the region has many decision-makers at different scales, including two counties, state and federal interests, tribal sovereignty, and special districts like the Imperial Irrigation District. Thus, a birds-eye view at the State level was selected as a first step toward understanding policy development through a WEF lens at the Salton Sea. The following questions frame this work: (1) To what extent are WEF-incorporated legislative documents more likely to become chaptered compared to those with limited or no WEF-integration? (2) Is the degree of WEF-integration and synergy in a legislative document related to its likelihood of becoming chaptered? (3) What themes differentiate successful versus unsuccessful WEF-related legislative documents? (4) How has the presence and integration of WEF-nexus themes in legislation changed over a 25-year period in this region? Ultimately, an understanding of WEF integration in policy-making supports the design of more effective laws that highlight the interconnected realities of water, energy, and food systems. Such integrative thinking informs future legislative processes that are adaptive, cross-sectoral, and responsive to community needs. Through a case study approach, our results and lessons learned can help other regions facing complex environmental and policy challenges understand their own trade-offs between WEF sectoral synergies and reactive, non-linear policy-making for improved policy-making in the future. The paper begins with an overview of the Water–Energy–Food (WEF) nexus and its policy and sustainability implications. It then outlines the study area and methodological framework of our qualitative content analysis. Results and discussion identify the sectors that are emphasized or de-emphasized in proposed legislation, along with an analysis of trends in WEF-integration over time. The study closes with considerations for other regions globally and provides future research directions.

2 Study area

The Salton Sea region is a complex ecological system with interrelated and often competing demands between water, energy, and food sectors. Located in Southern California just north of the U.S.-Mexico border (Figure 1), the modern Salton Sea formed more than 100 years ago when human-engineered water diversions from the nearby Colorado River mistakenly changed course, filling the desert basin with fresh water. Extreme rates of evaporation cause the Sea to grow increasingly saline, with summer temperatures routinely exceeding 100 °F and annual rainfall averaging just 3 inches (Hopkins et al., 2018).

The food and water sectors dominate in what is often called "America's winter salad bowl" as the region produces two-thirds of the vegetables eaten during the winter in the U.S. (Imperial County Agricultural Commission, 2020). The agricultural sector produces over 100 different commodities, with the top products being leaf lettuce, broccoli, head lettuce, hay, forages, and livestock [USDA (United States Department of Agriculture)., 2017]. This production is made possible by the reliable, affordable, and abundant water supply provided through engineered surface water deliveries via the All-American Canal from the Colorado River (Butler, 2015). The modern Salton Sea has been sustained by agricultural runoff from Imperial Valley irrigation, which contributes fertilizer, pesticides, and salt to the Sea, essentially making it an agricultural drainage dump. Fish and bird population decline both occurred in the 1990s (Salton Sea Authority, 2017), and toxins from the agricultural drainage are now being exposed as the Sea shrinks and reveals its legacy sediments (Jaeger et al., 2024), illustrating the complexity of the ecological system and its connection with water and agriculture.

Energy is harnessed in the southern region of the Sea, where the geological setting enables shallow magma and accompanying hot fluids to produce geothermal energy (Brothers et al., 2009). Geothermal plants are well established in this region. Additionally, the Salton Sea Geothermal Field contains what is estimated to be the highest lithium concentration in the world, with the lithium brine offering the potential to meet more than one-third of global lithium demand and support the development of a domestic lithium supply chain, generating billions in economic opportunity for the region (California Energy Commission, 2022).

Thus, the Salton Sea region converges the water, energy, and food (WEF) sectors through: (1) the area's high agricultural productivity supported by Colorado River water imports (Imperial County Agricultural Commission, 2020); (2) agricultural runoff serving as the primary water source for the Salton Sea (Aguilera, 2019); (3) ongoing geothermal energy production (Goodman

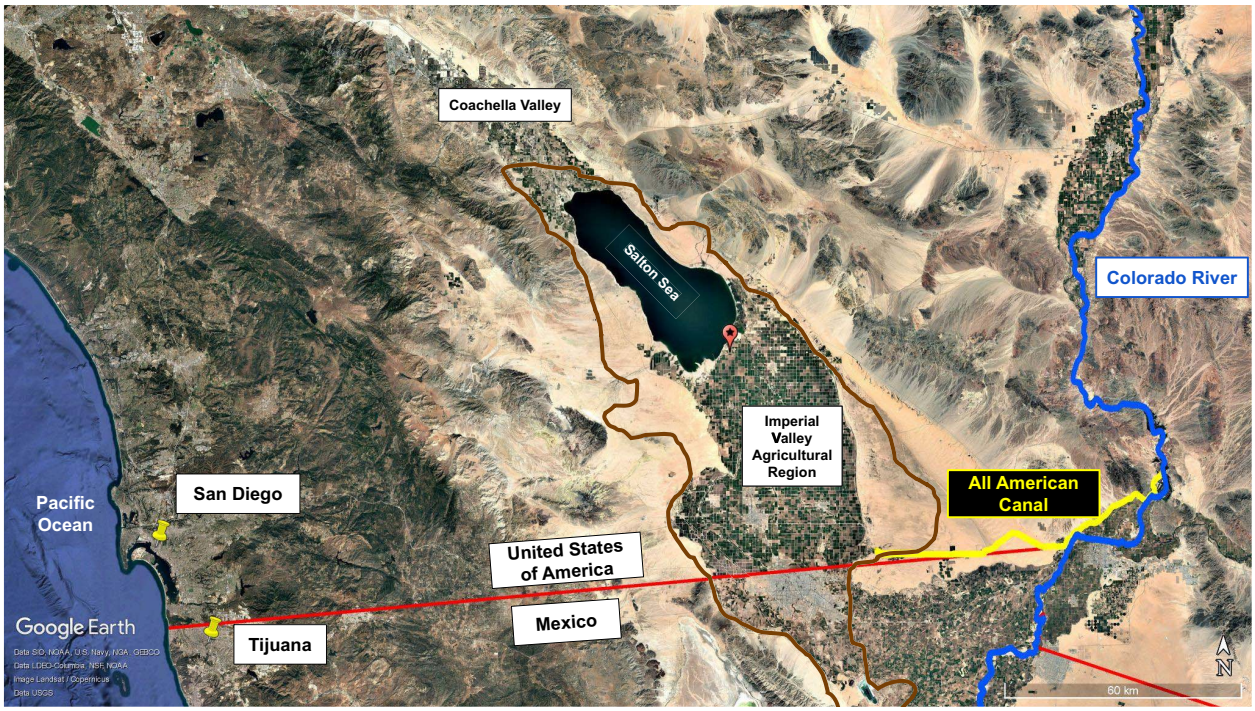


FIGURE 1
Location of the modern-day Salton Sea in Southern California illustrates proximity to the Colorado River and the All-American Canal, which subsequently extends through the farming region of the Imperial Valley in a series of irrigation canals (not shown). The star shows the location of geothermal (and lithium) resources, and the solid brown line approximates the extent of former shorelines when the trough flooded naturally in ancient times.

et al., 2022); and (4) the recent discovery of a major lithium resource with significant economic potential (Office of Energy Efficiency Renewable Energy, 2023). However, water is finite, food is dependent upon that water, and the co-location of energy opportunities presents competing demands in an ecologically stressed and socio-economically challenged environment.

3 Methods

In this study, we use the term "legislation" to refer to chaptered and failed bills, as well as the documents from which we sourced our data. We use "policy" when referring to broader governance, intent, and frameworks, but it can also refer to the outcomes of legislative documents. Legislation is an established procedure, standard, or system of rules that members of a society must follow, whereas a policy is a decision or set of decisions meant to address a long-term purpose or problem (Teitelbaum et al., 2021).

Utilizing *NVivo 14* software, we took an innovative approach to conduct a document analysis incorporating content and thematic analysis to categorize information in 25 years of Salton Sea-focused (SSF) legislative documents (Dalglish et al., 2020). The software did not conduct any automated function besides running a manually vetted search query (Hall and Steiner, 2020). While qualitative content analysis is not a new approach to textual analysis, there are few, if any, studies that have used this approach on environmental law and policy texts (Hall and Steiner, 2020). Statistical analysis was conducted in *R* statistical software (version 4.4.3; R Core Team, 2025). Figure 2 presents an overview of the full methodology to determine the integration of the WEF nexus within the examined documents.

3.1 Legislative document collection

Legislative documents spanning 1999–2024 were extracted from the California Legislative Information database (https://leginfo.legislature.ca.gov/) using the keyword search "Salton Sea," which returned all legislative documents in which the Salton Sea was mentioned during that period (Hall and Steiner, 2020). Each retrieved document was then reviewed manually to determine whether the Salton Sea was the primary focus, subject, or intended beneficiary of the legislation (Dalglish et al., 2020). Documents meeting this criterion were classified as Salton Sea–Focused (SSF) and retained for analysis, while documents that merely mentioned the Salton Sea without making it a central focus were excluded. All SSF documents—comprising Senate and Assembly bills at various stages of the legislative process, including introduced, amended, enrolled, and chaptered bills—were downloaded and uploaded into NVivo for content analysis (Supplementary Figure 1; Supplementary Table 1). This approach enabled a systematic comparison of chaptered (successful) and failed legislative documents to assess patterns of WEF nexus integration. In this study, successful legislation is defined as bills that were chaptered (enacted into law), whereas bills that were introduced (proposed) but not enacted are considered failed legislative efforts.

FIGURE 2
Overview of the methodological approach to document analysis and analysis of WEF co-occurrences and synergistic themes to determine WEF integration in legislative documents.

Although unsuccessful, these failed bills provide valuable insight into legislative intent and the dynamics of WEF integration even in the absence of formal adoption. The study period was constrained by database availability, with 1999 representing the earliest year accessible; although legislative documents from 2024 were reviewed, no Salton Sea–Focused (SSF) documents were identified, making 2023 the most recent year included in the analysis.

3.2 Development of a WEF dictionary and application

Ten SSF legislative documents, evenly distributed across the 1999–2023 study period, were randomly selected and manually reviewed by the first author to identify terms synonymous with or relevant to water, energy, and food. This process was independently verified by the corresponding author to ensure consistency and validity, resulting in the development of a WEF term dictionary (Table 1), consistent with established qualitative content analysis methods (Salehijam, 2018; Dalglish et al., 2020). Sector-specific terms were then imported into *NVivo* to conduct search queries and systematically code term occurrences (see Section 3.4). *NVivo's* stemming function was enabled, allowing related word forms (e.g., "irrigate" and "irrigation") to be captured automatically.

3.3 Proportion of WEF terms appearing in documents

Within each document, the percentage of WEF term counts was calculated. For example, in document AB_18_CH, there were 82 total WEF terms with 71 (86.6%) attributed to water, 0 (0%) to energy, and 11(13.4%) to food. To understand if chaptered or failed bills differ in the proportion of WEF terms, we conducted a Chi-squared test of proportions. To analyze the occurrence of WEF terms over time, counts were also calculated for WEF occurrences in all bills proposed for an individual year, and linear regression examined those trends to gain insight into WEF-term shifts over the 25-year period for both chaptered and failed documents.

TABLE 1 WEF dictionary of all synonymous terms of water, energy, and food in alphabetical order that were used in the study.

Sector	Synonymous Term		
Water	Alamo river	Flood control	Stormwater channel
	Aquatic	Irrigation	Tributaries
	Canal	New river	Water agencies
	Colorado river	Reservoir	Water district
	Desalination	Safe drinking water	Watersheds
	Ditch	Seawater	Whitewater river
	Drains	Shoreline elevation	
Energy	Brine	Geothermal	Mineral extraction
	Electrical	Lithium	Renewable
Food	Agriculture	Farms	
	Crops	Fishery	

3.4 Co-occurrences of WEF terms in a document

To determine if WEF terms were used in isolation to individual sectors (e.g., water terms only) or were multi-sectoral and hence more integrative (e.g., water *and* food), a WEF co-occurrence was designated if that bill contained any WEF-dictionary word from at least two different sectors. If terms from only two sectors appeared, the document was classified as having a Water-Energy (WE), Water-Food (WF), or Energy-Food (EF) co-occurrence, depending on the sectors represented. If terms from all three sectors appeared, the document was designated as having a WEF co-occurrence. For example, SB_223_CH had terms from all three sectors, so it was designated as a document with a WEF co-occurrence, while SB_277_CH only had water and food terms, making it a document with a WF co-occurrence. Because counts of co-occurrences are small, a Fisher's Exact test was used to compare the frequency of co-occurrence types. Co-occurrences indicate if integration of multiple sectors is occurring in the legislative documents, but do not indicate if those occurrences are truly synergistic. For example, energy and food might be discussed in a legislative document, allowing it an EF categorization, but whether those two sectors are discussed separately or in connection with one another is not obvious from the co-occurrence designation alone. The intent of the co-occurrence designation is to determine how often legislation is being proposed that considers more than just one of the WEF sectors, thus providing a first step toward understanding the degree of WEF-representation in SSF policies. But to truly examine if the

WEF sectors are being considered integratively with one another, we analyzed their connections or "synergies" through the process outlined next.

3.5 True WEF synergies within paragraphs in a document

To determine if co-occurrences of WEF-dictionary words were truly integrative, legislative documents were further analyzed. True synergies were identified when terms from different sectors—WEF, WE, WF, or EF appeared in the same paragraph and had an actionable relationship, meaning they were integrated or dependent on each other. This contrasts with co-occurrences, where terms merely appear together without clear interaction. For instance, a paragraph within a legislative document focused on geothermal and lithium resources, encouraging the efficient use of water supplies, would be classified as a WE synergy and not merely a WE co-occurrence.

3.6 Themes applied to WEF synergistic paragraphs within a document

Synergistic paragraphs served as the unit of analysis and were examined for topical themes using both predefined keywords and inductively identified concepts (Salehijam, 2018; Hall and Steiner, 2020). To establish and validate the coding procedure, all authors first jointly reviewed six synergistic paragraphs to identify recurring themes and refine thematic definitions (Table 2). Following this calibration step, the first author coded all remaining synergistic paragraphs, with coding decisions reviewed by the corresponding author for consistency. Paragraphs could only have one synergy designation (WEF, WE, WF, or EF), but could be associated with multiple themes (conservation, public health, finance, or resource use). For example, a WE-synergy paragraph proposing that two counties and two water districts establish a joint "infrastructure financing district" to fund energy use and environmental restoration would be categorized under three themes: finance, due to the creation of a funding mechanism; resource use, because the funds support energy-related activities; and conservation, as the proposal includes environmental restoration. Some keywords and concepts naturally spanned multiple themes; for instance, dust suppression was categorized under both conservation and public health. To assess whether the distribution of WEF synergies across themes differed between chaptered and failed documents, we applied Fisher's Exact Test due to small sample sizes.

In summary, the methodology begins with a broad examination of WEF sectoral inclusion in legislative documents before narrowing to better understand the degree of *WEF integration* within those policies. First, proportions are derived from counting the total number of WEF-dictionary words within documents. Next, co-occurrences are designated to a document if a WEF-dictionary word from more than one WEF sector appears within that document. Then, true synergies count the number of paragraphs within a document where a WEF-dictionary word from one sector appears *in the context of* a dictionary word from another WEF sector. Finally, those paragraphs with true synergies are categorized into a theme. This approach allows both a sweeping overview of WEF sector inclusion in policies as well as a more nuanced understanding of the degree of integration between sectors, examined for both chaptered and failed documents, and for trends over time (Hall and Steiner, 2020). Our approach is innovative in that it is rare to apply this methodology to this type of legislative document. This approach may be utilized in other regions to better understand WEF sector integration and trends.

4 Results

Over the 25-year period, at least one SSF legislative document was proposed in all but seven of those years; however, only 18 of 42 (42.9%) SSF documents were chaptered and became law (Figure 3). Twenty-four (57.1%) SSF documents failed to make it through the legislative process, with 19 (79%) of these failing during the amendment stage. The number of proposed documents per year ranged from 0 to 6, with most years averaging 2–3. The majority of failed SSF documents have occurred since 2012.

4.1 Proportion of WEF word occurrences in legislative documents

Of the chaptered documents, water terms dominate, making up 77.1% of all WEF terms, while energy and food terms each account for around 11% (Figure 4). This pattern differs from what is proposed during policy-making versus what fails. Failed documents have a high proportion of energy terms (67.6%) to water (28.6%) and food (3.8%). There is a statistically significant difference in the distribution of WEF terms across chaptered and failed documents (X-squared = 589.74, $df = 2$, p-value < 0.0001). Chaptered bills contain far more water-related terms, and failed bills emphasize energy terms.

Water-related terms were dominant in chaptered and failed bills over the 25-year period, except for a spike in energy terms in 2014 when water was featured far less (Figure 5). Chaptered bills contained a high proportion of water-related terms in the early part of the twenty-first century and showed only a marginal, non-significant decline over time ($\beta = -0.016$, $p = 0.069$). Both chaptered and failed bills indicate increasing proportions of energy-related terms. However, failed bills show substantially steeper trends ($\beta = 0.044$, $p = 0.052$) than chaptered bills ($\beta = 0.014$, $p = 0.082$), influenced by obvious spikes in word occurrences in 2014 and 2022. This suggests energy-focused language has become more common in unsuccessful legislative efforts in the Salton Sea region. No trend was observed for food terms in chaptered bills ($\beta = 0.0024$, $p = 0.575$), though food was mentioned only 135 times over the 25-year period in both chaptered and failed documents, which is low compared to 909 mentions of water and 699 mentions of energy.

TABLE 2 Theme definitions for synergistic paragraphs within legislative documents.

Theme	Description
Conservation	The preservation or restoration of an ecosystem or mitigation activity that may improve or prevent impairment to that system. Examples include wetland restoration and dust suppression.
Public health	Any topic that may influence the health of humans, such as changes to air or water quality.
Finance	The allotment or procurement of funds or grants, or other economic opportunities. Examples include the establishment of committees to oversee the allotment of funds or to conduct research into new opportunities of financial importance that may improve the local economy.
Resource use	Any human use of a natural resource, typically for economic gain rather than conservation improvement. Examples include the development of biofuels, lithium extraction, and water diversions.

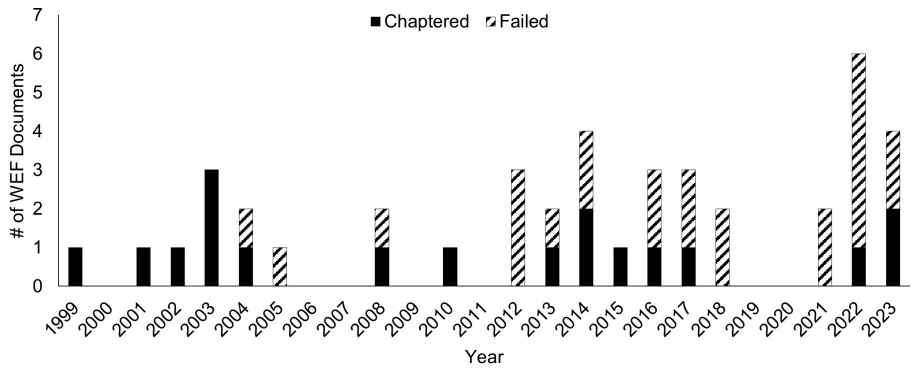


FIGURE 3
Shows the outcome (chaptered or failed) trend of all 42 SSF legislative documents from 1999 to 2023.

4.2 WEF word co-occurrences in legislative documents

About one-third of all proposed SSF documents contained co-occurring terms from two or all three WEF sectors, regardless of whether the bill became law (Figure 6), and these co-occurrences appeared consistently in documents through the 25-year period, indicating a low-moderate consideration of inter-sectoral integration. While there were seven years where no SSF documents were proposed in the legislature, there were two additional years where legislation was proposed, but a WEF co-occurrence was not identified in documents (2001, 2015), increasing the chance of non-integrated WEF sectoral policies becoming law. However, there is no statistical difference between the co-occurrences and whether the document passed into law or failed ($p = 0.185$). Both chaptered and failed documents contained only WEF, WE, and WF co-occurrences. Documents containing an EF co-occurrence were not proposed during the 25-year period. Energy only co-occurred when water or water and food sectors were present, but never independently with food.

4.3 WEF word synergies and themes in legislative documents

Though documents may show co-occurrences between WEF terms, WEF integration is better demonstrated by analyzing the context in which these terms co-occurred. Figure 7 shows the true synergistic integration of WEF sectors by presenting the number of paragraphs within documents where WEF terms were discussed in relation to one another. WF synergies are most common and were often chaptered in the early 2000s, whereas WE synergies failed most. As with EF co-occurrences, even when these sectors were presented in documents in a synergistic and multi-sectoral way, they failed to become law.

Of the synergistic WEF paragraphs, four themes emerged (Figure 8; Table 2). For chaptered documents, there is no statistically significant association between a particular synergy (EF, WEF, etc.) and any of the themes ($p = 0.928$). The themes and synergies in chaptered bills are thus distributed fairly evenly. This is not the case for failed bills, which have a statistically significant association between the type of WEF synergy and theme ($p = 0.018$), meaning some synergies are more likely to appear under specific themes in failed bills. WE synergies often appear under the themes of finance and resource use in failed bills. WF synergies are most frequently chaptered across any theme. Public health is the theme that is considered least. EF synergies are rare and always fail. A detailed record of how themes were applied to individual paragraphs can be found in Supplementary Table 2.

Over time, when bills were proposed with true synergies (hence good WEF-integration), chaptered bills were dominant in the early 2000s and failed bills clustered later ($p = 0.004$; Figure 9), indicating that WEF-integration was not a foolproof mechanism for successful policy-making. Most of the chaptered bills with synergistic WEF-integration occurred by 2004, and after a gap in

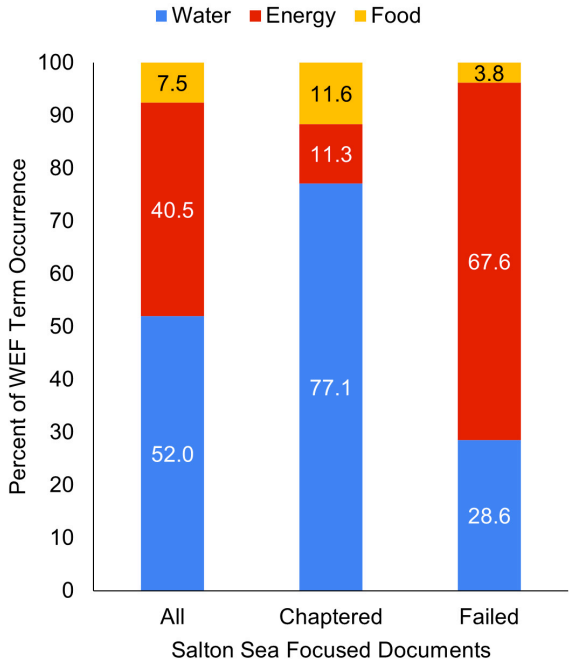


FIGURE 4
This figure shows the percentage of WEF-sector terms in all, chaptered, and failed Salton Sea-focused legislative documents presented to the California State Legislature during 1999–2023.

synergistic proposals, bills were frequently proposed, but failed, after 2012. No bill with a WEF synergy has passed in more than a decade, yet seven WEF-integrated documents have been proposed.

5 Discussion

This study aimed to better understand whether incorporating the WEF nexus in legislative documents may determine successful implementation. We found that the three sectors were not equally considered in the proposed legislation, and even when they were, it didn't guarantee passage into law.

5.1 Water emphasis, energy deficit, food indifference

Our methodology examined the increasing degree of WEF-integration, firstly through the presence of WEF terms, then the co-occurrence of those terms within documents, and finally, whether those co-occurrences were synergistic. Each level of analysis showed the general pattern: water emphasis, energy deficit, food indifference. Chaptered bills emphasize water and de-emphasize energy. Failed bills display the opposite pattern—they emphasize energy and de-emphasize water. The effect is smaller for food terms, which are slightly more common in chaptered bills than statistically expected. When energy and food are considered together in the absence of water, bills never pass.

This water emphasis is not surprising given that water from the Colorado River is the lifeblood of the agricultural sector, and important for energy production (Goodman et al., 2022; Quandt, 2023). The desert region is water-scarce, with temperatures projected to rise by 8–14 °F by 2100 (Hopkins et al., 2018). Trade-offs between water-dependent activities are frequently at the heart of WEF-nexus challenges (De Vos et al., 2021; Opoku et al., 2022) and are seen through policy development in this region over the past two decades. In 2003, the Quantification Settlement Agreement (QSA) was reached, and Imperial Irrigation District agreed to sell water to the San Diego County Water Authority, while implementing water conservation and fallowing programs on farms in the region to make up these water savings (Cohen and Hyun, 2006; Butler, 2015). Importantly, these on-farm and system-wide conservation efforts have led to less agricultural runoff reaching the Salton Sea, exposing the lakebed and leading to wind erosion and air quality issues in the region (Aguilera, 2019). Hence, public health is more frequently included as a theme in recently proposed documents, after the implementation of the water-focused QSA and its subsequent effect on lake desiccation.

Water trade-offs are especially pronounced in the food sector. A recent study by Quandt (2023), which interviewed farmers in the region, revealed that agricultural policies are often perceived as overly burdensome—though at times essential. Historically, legislation related to food and agriculture has been developed at the state or federal level, with little consideration for the specific needs of the Salton Sea region. Current water policies, such as the QSA, have been crucial for farmers. As one farmer noted, "our water rights are our strongest asset" (Quandt, 2023). These findings suggest that water availability posed significant challenges to food production in the earlier years of the study period, underscoring the need for integrated policies that address the interconnections between water and food systems. The results—showing a significant difference in the distribution of WEF terms between chaptered and failed legislative documents—further highlight the central role of water in this nexus.

The water-centric role of the nexus of the sectors in the study area continues over time, with only a slight decrease in water-related terms in chaptered bills, particularly in recent years, which is noteworthy for monitoring (de-emphasizing water in a region that is predicted to become drier over time is not a recommended policy approach). In contrast, energy terms were infrequent in proportion in chaptered bills until the recent success of Senate Bill 797, which established a citizen committee overseeing the allocation of a lithium extraction tax in the community and thus was predominantly energy-focused and responsible for the 2023 increase in energy terms. The dual focus on geothermal and lithium extraction is central to the region's energy policies but receives less success in the legislative process. California Assembly Bill 1657 commissioned a report in 2020 that aimed to explore lithium extraction potential at the Salton Sea. Sourcing lithium domestically is critical to providing a domestic supply chain of lithium, which may contribute to U.S. national security; thus, policymakers may be attempting a shift from water to energy. Such a shift has been attempted through proposals of bills with energy priorities that were unfortunately not enacted into law (chaptered). This may

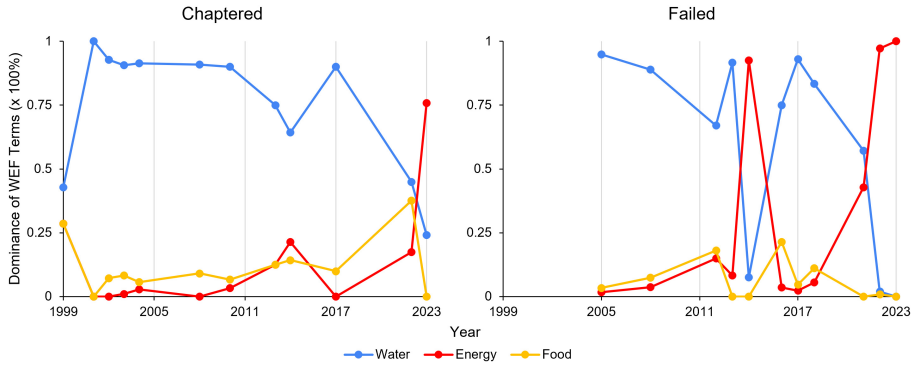


FIGURE 5
Dominance of WEF-sector terms in chaptered **(left)** and failed **(right)** bills, 1999–2023.

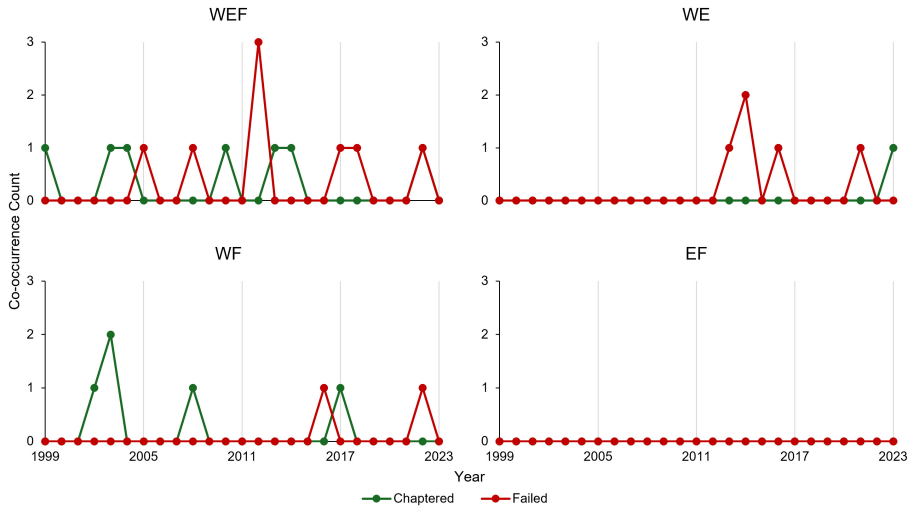


FIGURE 6
WEF co-occurrence types over time by bill status (1999–2023). Years without SSF documents are 2000, 2006–07, 2009, 2011, 2019–20. In 2001 and 2015, SSF documents were presented, but contained no WEF co-occurrences.

be due to political controversies over energy development and policy, as well as local concerns related to environmental justice. Failure to develop comprehensive, successful policies on energy is unfortunately not unique to our study area. As documented by Grossman (2013), these failures have occurred for the past 40 years across the USA. This study examined legislative documents through 2024, a point that coincided with a transition in the U.S. federal administration. Changes in national policy priorities may influence how water, energy, and food issues are addressed in future legislation, presenting an opportunity for comparative analysis of WEF-policy trends across different administrative periods.

Thus far, the observed trends to promote more energy sector interests are not statistically significant, with little to no recognition of the energy sector in SSF legislation. This is a general trend evident in California policies, where, though water and energy are evidently intertwined, there is little to no integration in terms of management of both sectors so as to create climate-resilient infrastructure and policies (Huber-Lee et al., 2020). The water-centric focus of the SSF legislation may be due to the study area being prone to drought and its agricultural intensification, as agriculture consumes a significant amount of water. However, with the advent of lithium extraction combined with the existing geothermal extraction, which involves the use of both water and energy, and a potential competition for water and energy in the agriculture sector, synergistic WEF nexus-focused policies will be well-positioned to bring about sustainable development, as opined by The Pacific Institute (2021).

5.2 WEF integration and success in policy outcome: here and elsewhere

Weitz et al. (2017) argue that while WEF nexus literature often explains why policies remain fragmented, it tends to overlook what true policy coherence involves and how it might be achieved. In the Salton Sea region, water-related issues are prioritized, which reduces the influence of cross-sector WEF integration on policy success. Even when policies attempt to incorporate WEF synergies,

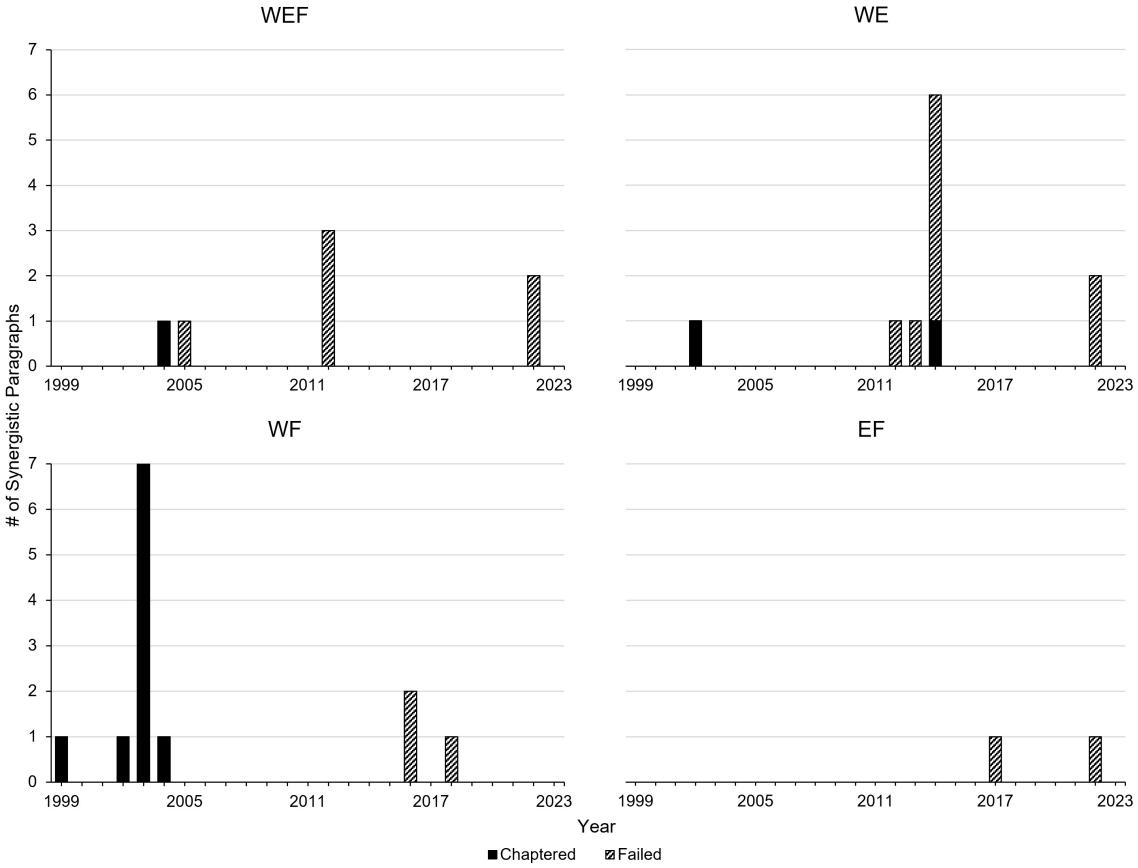


FIGURE 7
The number of true synergistic paragraphs between different WEF sectors over time in SSF legislative documents, differentiated by chaptered and failed status. A single document can have more than one reference paragraph, but a single reference paragraph can only have one synergistic categorization.

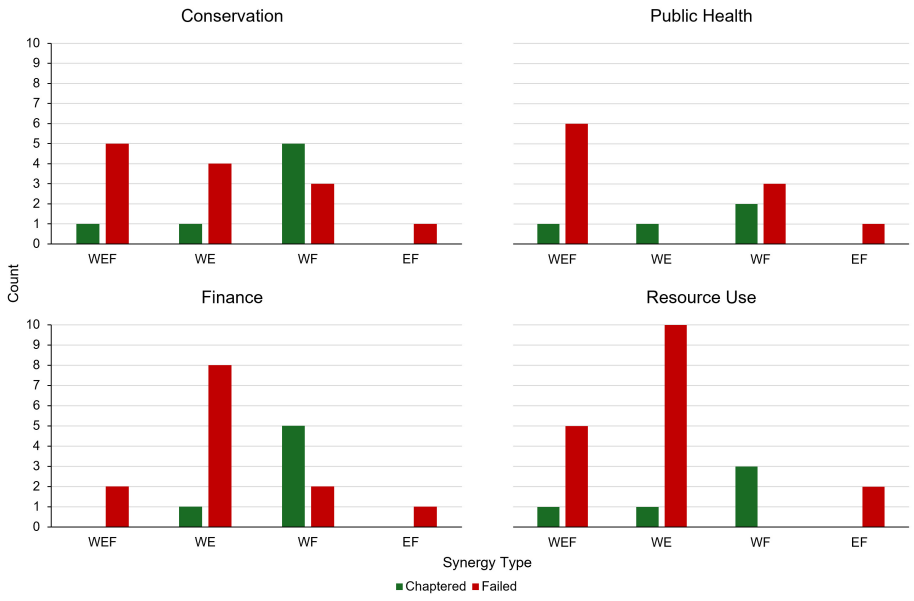


FIGURE 8
WEF synergy by theme and bill outcome. Counts refer to the number of synergistic paragraphs within any legislative document designated as having true WEF synergies, hence a measure of WEF integration in proposed legislative documents.

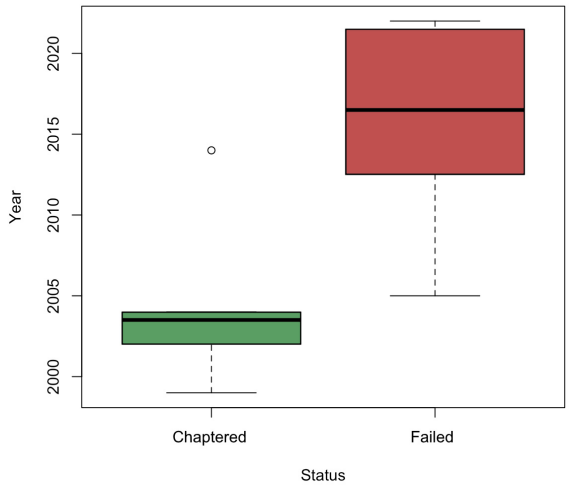


FIGURE 9
WEF-integrated bills proposed over the study period. Chaptered bills cluster earlier while failed bills cluster later ($p = 0.004$).

certain themes—such as conservation and finance—are more commonly chaptered than others. For instance, since 2014, 15 bills incorporating synergies between at least two WEF sectors have been proposed, yet all failed. This suggests that simply embedding WEF integration in a bill is not sufficient to be successful. Likewise, full integration across all three WEF sectors does not guarantee success, as such comprehensive bills are frequently proposed but seldom enacted. The literature identifies several barriers to chaptering such policies, including differing institutional structures across sectors, conflicting goals, poor communication, and unclear distribution of rights and responsibilities (Pittock et al., 2013). Another major barrier to the successful enactment of WEF policies is that research on WEF systems has been dominated by the natural and physical sciences, while receiving relatively little critical engagement from the social and political sciences (Hejnowicz et al., 2022).

An analysis of specific themes in SSF documents, as illustrated in Figure 8, indicates that policies emphasizing financing or conserving water–food (WF) synergies are more likely to be chaptered, suggesting greater success with these particular synergies. The prominence of the conservation theme aligns with a surge of scientific activity in the 1990s and 2000s focused on restoring key ecological functions at the Salton Sea (Case et al., 2013). This emphasis on conservation and finance may also reflect the biophysical orientation of nexus thinking, where conservation addresses environmental concerns and finance is seen as a critical enabler for both current and future nexus implementation efforts (Hejnowicz et al., 2022).

In contrast, among the 15 recent bills that failed, more than half (n=8) involved water–energy (WE) synergies combined with resource-related themes. Although many of these proposals also included finance elements, their mixed outcomes suggest that the success of finance as a thematic focus depends on the specific sectoral combinations it supports. Resource use appeared as a recurring theme across nearly all proposed bills, reflecting increased interest in lithium extraction in conjunction with existing geothermal energy infrastructure. However, the limited success of these initiatives highlights the continued marginalization of the energy sector in policy outcomes.

The initial momentum behind the WEF nexus was largely driven by growing concerns over water scarcity and food insecurity—pressures amplified by population growth and climate change (Nelson and Ghosh, 2024). This led to early research and policy efforts focusing predominantly on the water and food sectors. In contrast, the energy sector remains less integrated, in part due to its complexity: energy systems encompass diverse technologies, infrastructure networks, and regulatory frameworks, making them more difficult to align within a cohesive nexus approach compared to the relatively direct linkages between water and agriculture (Saundry, 2019).

Finance emerged as the second most prominent theme in proposed SSF legislation, with occasional policy successes indicating its strategic role in addressing interdependencies within the WEF nexus. A case in point is AB_148_CH, which advocates for economic development through initiatives such as renewable energy, biofuels, mineral extraction, and algae production—measures designed to generate revenue for Salton Sea restoration efforts. This bill exemplifies how financing the energy sector, when coupled with conservation priorities, can align with historically successful policy pathways (Hejnowicz et al., 2022).

Public health appears to be an emerging theme within the WEF policy landscape; however, no WEF-focused policies that explicitly integrate public health considerations have been passed into law since 2014. This indicates that when SSF legislations are enacted, they rarely reflect meaningful synergies between public health and any of the WEF sectors. For example, in 2023, bill AB_827_IN was introduced with a focus on pulmonary health in the region. However, it did not draw connections between water, energy, or food and public health, and failed to advance beyond the introductory stage. This illustrated a persistent disconnect between scientific evidence and WEF-integrated policymaking. Literature has consistently linked elevated asthma rates in the region to the desiccation of the Salton Sea—a direct consequence of shifting agricultural water use, reflecting a clear water–food (WF) synergy with significant public health implications (Johnston et al., 2019; Biddle et al., 2022). Despite strong scientific evidence, such synergies have yet to influence policy outcomes. While policy implementation may be delayed due to recent attention (health issues emphasized within the last 5 years), the failure to pass relevant legislation underscores the need for a stronger convergence between human development and natural resource management. As Hejnowicz et al. (2022) argue, these issues must be addressed through integrated approaches that consider health, wellbeing, equity, and justice.

5.3 Temporal and future trends in WEF policy

Minor temporal trends can be observed in SSF legislation in our study. The 2003 Quantification Settlement Agreement (QSA) positioned water as the dominant focus throughout much of the study period. A slight decline in water emphasis began to emerge around 2023, accompanied by a modest increase in

attention to energy—likely reflecting growing interest in lithium extraction opportunities at the Salton Sea. However, these shifts were subtle and should be interpreted with caution. While it is possible to statistically model the occurrence of WEF-related terms or integration in future legislative documents, the inherently non-linear nature of legislative processes limits predictive accuracy. Policy trajectories are often shaped by short-term dynamics such as environmental shocks (e.g., drought), shifting public priorities, changes in political leadership across government levels, and broader economic conditions like recessions. As such, forecasting future trends in WEF policy remains inherently uncertain. Although understanding of WEF nexus dynamics continues to evolve, effectively translating this knowledge into coherent and actionable policy remains a significant challenge. Moving forward, future trends are likely to require greater emphasis on the political dimensions of WEF trade-offs, recognizing the essential role of political processes in addressing and navigating these complex, interdependent issues (Srigiri and Dombrowsky, 2022).

The results from our study support this view as the policies are enacted based on reactions to problems emanating from the study area, like the urgent need for regional water (e.g., water diversions to San Diego), prompting the QSA in the early 2000s. With global attention now on renewable energies, a preventive approach, especially in consideration of public health, offers an opportunity to use science to guide policy. Science suggests that the receding Salton Sea presents public health challenges (Miao, 2023; Jaeger et al., 2024) as well as ecological damage (Hung et al., 2024) for which conservation funding has been legislated in the past. Though public health issues are still emerging, the ecological damage of WF integration was known during the early 2000s when successful WF policies were being legislated, highlighting trade-offs between science and policy regarding the effective management of agricultural wastewater (Glenn et al., 1999). Now, management may be implicated in emerging health outcomes 20 years later. Specifically, nutrient and pesticide runoff in agricultural waters have been entering the Sea for decades, feeding algal blooms and reducing water quality (Voyles, 2021). Recently, scientists have posited that the actual sea "spray" might be implicated in pulmonary responses, though data are only available for mouse exposures thus far (Biddle et al., 2021). Nevertheless, this scenario shows the reactive "catch-up" nature of science after policy-making has occurred.

As the region opens up for lithium growth opportunities in the energy sector, policies emphasizing public health or new themes such as community integration may guide future success, and can be enriched with scientific studies integrated within policy-making. For example, how will future desiccation impact the health of the lithium workforce? What is the environmental impact of any lithium extraction technologies?

5.4 Limitations in this approach

Our study examined legislation proposed at the state level, which can miss WEF-sectoral integration occurring at other levels, like locally or federally. A parallel example is the Aral Sea, which is often documented as a high-profile example of human water use outstripping environmental water supplies; the result is a desiccating saline lake, ecological damage, human health threats, and dust storms (Guillaume et al., 2015; Doede and DeGuzman, 2020)—similar to current issues experienced at the Salton Sea. The two sites are politically managed at different levels, the Aral Sea is closely connected with five countries competing for self-sufficiency after the fall of the Soviet Union (Saidmamatov et al., 2020), while the Salton Sea occurs within one state in one country (California, USA) bisected into demographically different counties with locally elected representatives, influencing their respective capacities to advance policies through state legislature. On a positive note, legislation examined for the Salton Sea showed integration between these regulatory divisions. For example, at the local level, AB_177_AA notes a Memorandum of Understanding between the County and Irrigation District to better manage WE synergies. At the federal level, the 2022 Inflation Reduction Act allotted funding for the state to accelerate management plans for the Salton Sea, which typically leads to state-level legislative proposals created to carry out federal-level directives. Thus, while examining state-level legislative proposals that focus on state directives, good working relationships at all levels ensure this methodology captures most WEF-nexus decision-making in this particular region. Though a formalized "Salton Sea Region" defined by ecological boundaries, rather than political, might prove more successful than the current county division of resources in reaching enhanced WEF integration. In some ways, the former Soviet Union management of the Aral Sea provided an integrated WEF approach whereby strong upstream-downstream water coordination and shared energy benefited the system (Saidmamatov et al., 2020). Nevertheless, both sites highlight the problematic dichotomy of placing human boundaries over interconnected ecological systems.

6 Conclusion

This study pioneered an iterative document analysis approach to determine the degree of WEF-integration in Salton Sea-Focused (SSF) legislation in California. Our findings suggest that the degree of WEF-integration is not a good predictor for policy success; some proposed legislation contained the "gold tier" of WEF-integration by including all three sectors in actionable and meaningful ways, but they weren't always successfully enacted into law (chaptered). Rather, policies were reactive to environmental needs that threatened food production, making WF synergies the most successful form of policy-making for this region over the 25-year period. A shift to include the energy sector reflects the lithium extraction opportunities recently discovered in the region. Though policy-making is not moving quickly to pass legislation reflecting this shift, many WE and EF policies are failing to become law. At the Salton Sea, synergistic WEF-integration may not be the most important aspect for policy success, reflecting the rapidly changing environmental conditions occurring alongside nationally important sectoral priorities; first food, now energy, both driven by water. Transitions between dominant synergies, WF to WE, reflect the non-linear nature of reactive policy-making.

We propose that community-led issues like public health—often informed by science—form the thematic basis of future

successful policy-making. This furthers the historical approach where science explained ecological damage that conservation-finance-themed legislation aimed to address for the synergy of the time; WF. Ultimately, understanding the complexity of ecological systems, how they interact with WEF sectors, and the barriers imposed by human boundaries should be considered along with local input to produce successful policies in profoundly stressed regions undergoing environmental change. We encourage further studies like this one, which analyze the content of policies relevant to environmentally stressed regions where the political climate faces competing interests, to examine how the WEF-nexus is integrated. Perhaps the best approach is a political, ecological, and community-informed WEF-integrated nexus; a PEC-WEF. Such an approach would allow science to explain impacts to the complex ecological system burdened by improper WEF management, so that politicians can then lobby effectively for change, while amplifying the voices of the community, who ultimately drive the WEF sectors where they live.

6.1 Future directions

While this study demonstrates that WEF integration alone does not predict policy success, future work should examine whether nexus-informed policies lead to improved environmental, economic, and public health outcomes once implemented. Moving beyond legislative intent to evaluate policy implementation and outcomes would provide a clearer understanding of how integrated governance performs in practice. Additionally, comparative studies with other environmentally stressed regions could determine whether the reactive, sector-dominant policy patterns observed here are unique to the Salton Sea or indicative of broader governance challenges.

As lithium extraction and geothermal development emerge as central energy priorities in our study area, future research should evaluate how these transitions can be aligned with water conservation, agricultural sustainability, and public health protection. Understanding how energy-focused policies would interact with the water and food sectors will be critical to avoiding unintended consequences and ensuring long-term regional resilience. Together, these directions highlight the need for adaptive, outcome-oriented policy research that reflects the rapidly changing environmental and economic conditions facing the Salton Sea. To advance more actionable policy outcomes, the following recommendations are made:

- Expand evidence-based research to provide policy-relevant context for legislative discussions on the WEF nexus.
- Engage key stakeholders to translate complex nexus relationships into practical and actionable policy interventions.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary material.

Author contributions

DP: Writing – original draft, Formal analysis, Visualization, Methodology, Writing – review & editing, Investigation, Data curation, Software. BO'S: Validation, Writing – review & editing, Methodology, Formal analysis, Resources, Writing – original draft, Conceptualization, Visualization. AQ: Methodology, Writing – original draft, Writing – review & editing. OO: Methodology, Writing – original draft, Writing – review & editing, Visualization, Conceptualization.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author OO declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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