1-1-2023

Coastal groundwater-dependent ecosystems are falling through policy gaps

Madeleine Dyring

Melissa M. Rohde

Ray Froend
Edith Cowan University

Harald Hofmann

10.1111/gwat.13352
Dyring, M., Rohde, M. M., Froend, R., & Hofmann, H. (2023). Coastal groundwater-dependent ecosystems are falling through policy gaps. *Groundwater, 62*(2), 184-194. https://doi.org/10.1111/gwat.13352

Groundwater

Issue Paper/

Coastal Groundwater–Dependent Ecosystems are Falling Through Policy Gaps

by Madeleine Dyring[1,2,3], Melissa M. Rohde[4,5,6], Ray Froend[7], and Harald Hofmann[1]

Abstract

Coastal groundwater-dependent ecosystems (GDEs), such as wetlands, estuaries and nearshore marine habitats, are biodiversity hotspots that provide valuable ecosystem services to society. However, coastal groundwater and associated ecosystems are under threat from groundwater exploitation and depletion, as well as climate change impacts from sea-level rise and extreme flood and drought events. Despite many well-intentioned policies focused on sustainable groundwater use and species protection, coastal GDEs are falling through gaps generated by siloed policies and as a result, are declining in extent and ecological function. This study summarized then examined policies related to the management of coastal groundwater and connected ecosystems in two key case study areas: Queensland (Australia) and California (USA). Despite both areas being regarded as having progressive groundwater policy, our analysis revealed three universal policy gaps, including (1) a lack of recognition of the underlying groundwater system, (2) fragmented policies and complex governance structures that limit coordination, and (3) inadequate guidance for coastal GDE management. Overall, our analysis revealed that coastal GDE conservation relied heavily on inclusion within protected areas or was motivated by species recovery, meaning supporting groundwater systems remained underprotected and outside the remit of conservation efforts. To close these gaps, we consider the adoption of ecosystem-based management principles to foster integrated governance between disparate agencies and consider management tools that bridge traditional conservation realms. Our findings advocate for comprehensive policy frameworks that holistically address the complexities of coastal GDEs across the land-sea continuum to foster their long-term sustainability and conservation.

Introduction

Groundwater-dependent ecosystems (GDEs), such as wetlands, rivers, and estuaries, are found within coastal habitats around the world. GDEs consist of species and habitats that require access to groundwater to meet their water needs on a permanent or intermittent basis (Richardson et al. 2011), and they are widely recognized for the valuable ecosystem services they provide such as climate regulation, bioremediation, and water purification (Griebler and Avramov 2015; Howard et al. 2023). Coastal GDEs include an array of habitats,

[1]School of the Environment, The University of Queensland, Brisbane, Queensland, Australia

[2]Centre for Biodiversity and Conservation Science, The University of Queensland, Brisbane, Queensland, Australia

[3]Corresponding author: School of the Environment, The University of Queensland, Brisbane, QLD, Australia; m.dyring@uq.edu.au

[4]California Water Program, The Nature Conservancy, Sacramento, California, USA

[5]Rohde Environmental Consulting, LLC, Seattle, Washington, USA

[6]SUNY College of Environmental Science and Forestry, Syracuse, New York, USA

[7]Edith Cowan University, School of Science, Joondalup, Western Australia, Australia

The author(s) does not have any conflicts of interest or financial disclosures to report.

Article impact statement: Groundwater-dependent ecosystems fall through gaps created by siloed policies and require integrated management for effective conservation.

Received November 2022, accepted August 2023.

doi: 10.1111/gwat.13352

such as freshwater and brackish wetland systems reliant on seasonal groundwater discharge, or ecosystems within the marine zone that rely on submarine groundwater discharge, such as coral reefs. In coastal environments, groundwater plays a critical, though often overlooked role in regulating a range of biological and chemical processes that contribute to the function of ecological communities and the resilience of coastal landscapes, particularly under climatic drying (Dyring et al. 2022).

Despite their importance, coastal GDEs continue to decline in their extent and function due to numerous threatening processes. Increasingly, coastal settlements are turning to groundwater for freshwater supply, particularly in areas that are increasingly experiencing aridity due to climate change (Ferguson and Gleeson 2012). In addition to groundwater depletion threats, coastal GDEs are susceptible to both oceanic and atmospheric climate change drivers such as increased variability in rainfall and recharge (Jasechko et al. 2014), sea-level rise and saltwater intrusion (Werner et al. 2013), storm and tidal surges, and increasing rates of evapotranspiration (Condon et al. 2020). Despite the development of numerous policies and regulations to manage these threats, the continued decline of coastal GDEs highlights the inadequacy of these policies in effectively addressing the collective challenges they face.

This policy gap analysis aims to identify the deficiencies in existing policies and regulations concerning coastal groundwater and dependent ecosystems in Queensland, Australia and California, USA. The key objectives of the analysis are to identify and describe gaps within the existing policy framework, providing examples of how coastal GDEs are either overlooked or are not sufficiently considered. Overall, this gap analysis aims to advise policymakers and stakeholders on policy shortcomings and offer actionable suggestions for enhancing conservation efforts and the sustainable management of these valuable ecosystems.

Queensland and California are suitable case studies as both areas are experiencing rapid coastal population growth and an increasing reliance on groundwater. Queensland remains the fastest growing state in Australia (ABS 2022) and population pressure continues to strain surface water supplies. Similarly, California is the most populous state in the USA with nearly 40 million people (PPIC 2017). Groundwater supplies up to 85% of total water use in some coastal areas, and this has been projected to rise due to urbanization and agricultural intensification (Wilson et al. 2020). As extreme flood and drought events intensify globally (Rodell and Li 2023; Rohde 2023), climate change related impacts are pertinent to large coastal populations, such as those in Queensland and California. Both have experienced "weather whiplash" oscillating between megadroughts and major flooding (Swain et al. 2018; Rodell and Li 2023), with implications for the conjunctive management of groundwater resources. Coastal groundwater resources in Queensland and California are highly susceptible to climate change impacts, and both states are considered to have progressive policies on GDE management (Rohde et al. 2017), making these states useful and relevant case studies to explore policy gaps.

Unlike inland GDEs, coastal GDEs are also vulnerable to seawater intrusion which further highlights the need to examine the effectiveness of coastal groundwater policy. An Australia-wide assessment of the vulnerability of coastal aquifers to seawater intrusion undertaken in 2012 identified Queensland as the state at the greatest risk of saltwater intrusion (Ivkovic et al. 2012). Similarly in California, recent modeling of sea-level rise scenarios found that 1 m of sea-level rise is expected to expand 50–130 m inland (Befus et al. 2020). Overpumping of aquifers remains a leading driver of seawater intrusion throughout the USA, particularly in California (Jasechko et al. 2020). Without effective policy intervention, seawater intrusion and the salinization of coastal aquifers will have a long-lasting and potentially irreversible impact on freshwater ecosystems reliant on groundwater.

Policy Gaps in Coastal GDE Management

To undertake this gap analysis, an extensive literature review was conducted to gather policies, regulations, and guidelines related to groundwater and GDE management in both case study regions. This subset of policy literature was then examined to evaluate its efficacy in safeguarding coastal GDEs from threatening processes, with a focus on groundwater allocation and threat mitigation strategies, monitoring practices, conservation measures, and enforcement.

We began by collating and analyzing current policy literature on groundwater and GDE management in Queensland (Australia) and California (USA). Table 1 summarizes current policies and legislation related to groundwater management in both case study areas by the level of governance and describes how these policies could be applied to coastal GDE management. Each policy has been allocated a management focus which is reflected in Figure 1.

Queensland, Australia

In Australia, there is no federal policy that dictates the management of Australia's coastal zone. Rather, coastal planning and management remain the responsibility of individual states. Similarly, in terms of groundwater management outside of the Murray-Darling basin, there is limited guidance provided by the federal government on the management of GDEs. The *Water Act 2007* relates to the planning, allocation, and use of water; but is principally focused on the Murray-Darling River and managing stakeholders within different industries and across the various states requiring groundwater.

Under Australia's *Environment Protection and Biodiversity Conservation Act 1994*, GDEs are considered a Matter of National Environmental Significance (MNES) and therefore require assessment via an Environmental Impact Statement (EIS) when a project (e.g., a development proposal) is deemed a controlled activity.

Table 1
Summary of Groundwater and GDE Management Related Policies and Legislation in Queensland, Australia and California, USA

Level	Policy Instrument	Responsibility	Focus in Relation to Groundwater and Dependent Ecosystems	Management Focus	How it Relates to Coastal GDE Management
Australia					
Federal	Environmental Protection and Biodiversity Act 1999	Department of Climate Change, Energy, the Environment and Water	Provides a framework for the protection of Australia's environment, focusing on Matters of National Environmental Significance (MNES). Impacts to water resources (which include ecosystems dependent on groundwater) must be assessed so significant impacts can be mitigated.	Mitigation and enforcement	Mechanism that triggers an environmental impact assessment where impacts to MNES are likely to be significant. This could include GDEs in a coastal zone where impacts could be incurred from, for example, a development.
Federal	Guidelines for Groundwater Quality Protection in Australia 2013	Department of Climate Change, Energy, the Environment and Water	Sets out national water quality management strategy.	Water planning and abstraction	The Guidelines rely on a framework that requires the identification of existing and potential environmental value categories for groundwater. "Environmental value" can apply to groundwater that is important for a healthy ecosystem, such as coastal GDEs. Saltwater intrusion is acknowledged as an emerging issue in groundwater quality protection.
Federal	Water Act 2007	Department of Climate Change, Energy, the Environment and Water	Enables the Commonwealth in conjunction with Basin States to manage water resources in the national interest. Promotes the use and management of water resources in a way that optimizes economic, social and environmental outcomes.	Water planning and abstraction	Encourages coordination and groundwater allocations between Basin States (Queensland, New South Wales, Victoria and South Australia). Specific to the Murray Darling Basin.
State (QLD)	Environmental Protection Act 1994	Department of Environment and Science	Lists obligations and duties to prevent environmental harm, nuisances, and contamination.	Protected area management	Lists permitted activities in protected areas. Terrestrial and coastal GDEs, such as wetlands and estuaries, can lay within protected areas, for example. However, groundwater recharge zones and groundwatersheds may be located outside of protected areas.
State (QLD)	Water and Wetland Biodiversity Policy 2019	Department of Environment and Science	The purpose of this policy is to achieve the object of the EP Act in relation to waters and wetlands by: • Identifying environmental values for waters and wetlands, • Identifying management goals for waters, • Stating water quality guidelines and water quality objectives to enhance or protect the environmental values, • Providing a framework for making consistent, equitable and informed decisions about waters, and • Monitoring and reporting on the condition of waters.	Species and habitat protection	Aims to identify and list environmental values of water, which can include groundwater for coastal GDEs.

Table 1
Continued

Level	Policy Instrument	Responsibility	Focus in Relation to Groundwater and Dependent Ecosystems	Management Focus	How it Relates to Coastal GDE Management
State (QLD)	Nature Conservation Act 1992	Department of Environment and Science	Provides the legislative basis for the conservation of nature through the dedication, declaration and management of protected areas and the protection of native wildlife and its habitat.	Species and habitat protection	Protected areas which can include coastal GDEs such as wetlands, estuaries and rivers.
State (QLD)	Water Act 2000	Department of Environment and Science	Provides a framework for the sustainable management of Queensland's water resources by establishing a system for the planning, allocation and use of water and riverine protection.	Water planning and abstraction	Outlines a framework for planning, allocation and use of water and riverine protection. Sustainable management is based on the principles of ecologically sustainable development that sustain the health of ecosystems, water quality, water-dependent ecological processes and diversity associated with watercourses, lakes, springs, aquifers and other natural water systems.
State (QLD)	Water Plans (by basin)	Department of Environment and Science	A water plan is a plan that applies to a part of the State and advances the sustainable management of Queensland's water.	Water planning and abstraction	Water plans must state arrangements for providing water for the environment including the measures, strategies or objectives for environmental flows.
State (QLD)	The Coastal Protection and Management Act 1995	Department of Environment and Science	Provides for the protection, conservation, rehabilitation and management of the coastal zone, including its resources and biological diversity and works alongside the *Planning Act 2016* to guide land use planning and development assessment decisions on Queensland's coast.	Coastal development	Aims to conserve sensitive areas within the coastal zone. If identified and recognized, this could include coastal GDEs but coastal GDEs are not always known or declared.
USA					
Federal	National Environmental Policy Act 1970	U.S. Environmental Protection Agency	Establishes the national framework for protecting the environment.	Species and habitat protection	Requires federal agencies to assess the environmental effects of their proposed actions before making approval decisions. Assessment could include impacts to GDEs if they are identified as being potentially impacted by proposed actions.
Federal	Endangered Species Act 1973	U.S. Fish & Wildlife Service	Establishes protections for fish, wildlife, and plants that are listed as threatened or endangered.	Species and habitat protection	Ensures that actions are not likely to jeopardize the continued existence of any listed species or result in the destruction or adverse modification of designated critical habitat of such species. Where coastal GDEs form critical habitat for a listed species, the GDE is protected from adverse activities.
State (CA)	Common Law Public Trust Doctrine	State of California	Protects the public's right to use and benefit from waterways, tidal and submerged lands for commerce, navigation, fisheries, recreation, and to protect scenic and wildlife habitat values.	Waterways	Protects coastal GDEs that are scenic and wildlife habitats, or provides navigation, recreational, commercial, or fisheries activities within coastal waterways for the benefit of the public.

Table 1
Continued

Level	Policy Instrument	Responsibility	Focus in Relation to Groundwater and Dependent Ecosystems	Management Focus	How it Relates to Coastal GDE Management
State (CA)	The California Endangered Species Act 1997	California Department of Fish and Wildlife	Conserves and protects plant and animal species at risk of extinction.	Species and habitat protection	Promotes the conservation of habitat areas for listed threatened species. If a listed threatened species utilizes coastal GDEs, harmful activities are excluded from this area.
State (CA)	Sustainable Groundwater Management Act 2014	California Department of Water Resources	SGMA requires local agencies to form groundwater sustainability agencies (GSAs) for the high and medium priority basins. GSAs develop and implement groundwater sustainability plans (GSPs) to avoid undesirable results and mitigate overdraft within 20 years.	Water planning and abstraction	Sets the statewide framework to protect groundwater resources over the long-term. SGMA requires local agencies to form groundwater sustainability agencies and implement sustainability plans to avoid undesirable results and overdraft within 20 years. Undesirable impacts can include those to coastal GDEs, including drawdown and other changes to the groundwater regime.
State (CA)	California Environmental Quality Act 1970	Governor's Office of Planning and Research	Requires state and local agencies to assess and reduce the environmental impacts of new development projects before their approval. Aims to prevent significant and avoidable environmental damage.	Water quality	Aims to prevent or minimize damage to the environment through the development of project alternatives, mitigation measures, and mitigation monitoring. Act is triggered for coastal GDEs if they are identified as potentially being impacted from a project development.
State (CA)	California Coastal Act 1976	California Coastal Commission	The Act guides how land along the coast of California is developed, or protected from development. The Act aims to maintain "… the biological productivity and the quality of coastal waters, streams, wetlands, estuaries, and lakes appropriate to maintain optimum populations of marine organisms and for the protection of human health shall be maintained and, where feasible, restored through, among other means, minimizing adverse effects to … Depletion of groundwater supplies …"	Coastal development	Prioritizes ecological resources, which includes marine resources such as wetlands, rocky intertidal areas and the open ocean. Under the Act, Marine resources shall be maintained, enhanced and where feasible, restored. The Act also includes special protection for Environmentally Sensitive Habitat areas. Coastal wetlands maintained by fresh groundwater discharge (coastal GDEs), could be included under these provisions.
Local (CA)	Groundwater Sustainability plans	Groundwater Sustainability Agencies	Under the SGMA local Groundwater Sustainability Agencies are required to develop and implement Groundwater Sustainability Plans (GSP). GSPs provide a framework for how groundwater basins will reach long-term sustainability. The Department of Water Resources evaluates GSPs to determine if they comply with the SGMA.	Water planning and abstraction	SGMA includes specific requirements to identify and consider impacts to GDEs in groundwater management. In this context, coastal GDEs may be identified and recognized to be included in a GSP.

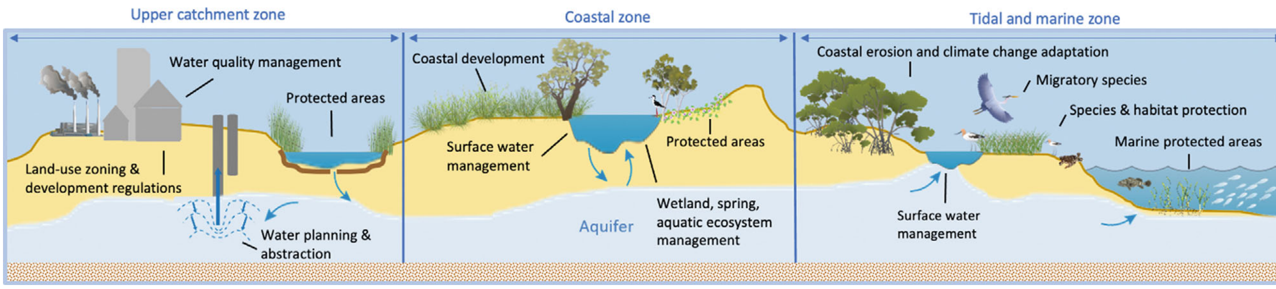

Figure 1. Traditional policy domains in coastal groundwater and ecosystem management. Spatially, policies usually relate to landscape zones (blue text), for example, upper catchments, coastal areas, and tidal and marine zones. Groundwater is managed through siloed policy domains with a specific management focus described in Table 1 (black text). See Table 1 for an overview of organizations and strategies related to groundwater management in Queensland and California.

However, the assessment of potential impacts on GDEs as part of an EIS is triggered by a potential for groundwater drawdown or contamination associated with coal seam gas extraction and coal mining activities (Doody et al. 2019), both of which do not commonly occur on coastal fringes in Australia. Despite GDEs being considered a MNES, the assessment of impacts to coastal GDEs is less likely to be triggered in this policy context, despite ongoing development pressures along Australia's coastlines and the threat to groundwater quality and quantity.

In Queensland, three policy instruments focus on sustainable water planning and use to prevent deterioration in groundwater quality and quantity, with mention of GDEs (Table 1). Where general guidance is provided on protecting GDEs (i.e., Water and Wetland Biodiversity Policy 2019, Table 1), these policies do not provide specific guidance for coastal GDEs. While it is encouraging to see coastal GDEs of the Swan Coastal Plain (Western Australia) included in federal government recommended guidelines (Richardson et al. 2011), they represent a single type of coastal GDE reliant on a shallow perched aquifer, where long-term ecological monitoring data is available. Including a broader range of coastal GDEs examples in policy is crucial for their identification, characterization and effective management and protection. Queensland, and Australia more broadly, could benefit from specific guidelines for managing coastal GDEs in the many forms they come in, considering the unique challenges and vulnerabilities each face.

Water Plans in Queensland, as governed by the *Water Act 2000*, regulate groundwater use; however, their effectiveness in coastal areas is limited by a 10-year implementation period and the absence of mandatory reviews and updates within this timeframe. While consideration is given to maintaining ecological flows for GDEs (McGregor et al. 2018), this timeframe fails to account for the influence of climate change on factors such as recharge, which is crucial for determining future groundwater allocations. While this may not be a pressing concern for large inland aquifers, it poses significant challenges for highly responsive coastal groundwater systems that are sensitive to fluctuations in rainfall and groundwater discharge relative to the threat of saltwater intrusion. Moreover, Water Plans focus on discrete management areas and neglect the consideration of groundwater movement between neighboring basins or from inland watersheds to coastal discharge areas. While Water Plans encourage sustainable use of groundwater through future planning and allocations, without a comprehensive understanding of coastal groundwater dynamics and the absorption of climate change impacts, they are inadequate for coastal GDEs.

In Queensland, coastal habitats and significant species, which can include coastal GDEs and reliant species, are protected under three key legislations (Table 1). These regulations focus on protected areas designated for conservation. Land-based conservation, such as protected areas, overlooks the underlying hydrogeological system supporting coastal GDEs on which significant species and habitats rely. A recent global analysis revealed that 85% of protected areas containing GDEs had underprotected groundwatersheds, with over 50% lying outside protected area boundaries (Huggins et al. 2023), therefore undermining conservation efforts. Documented impacts on GDEs caused by groundwater deterioration outside of a protected area highlight the limitation of relying solely on land-based conservation for GDE conservation. Such approaches leave coastal GDEs vulnerable to groundwater depletion originating outside protected areas.

Gaps generated by protecting land-based assets of GDEs and not the underlying hydrogeological system are apparent in Queensland. For example, while the *Nature Conservation Act 1992* safeguards coastal wetlands and related species from harmful activities, it does not impose restrictions on the installation of private groundwater bores near these habitats. Furthermore, there are no regulations or requirements for monitoring water quality or assessing the potential impacts of groundwater use on adjacent GDEs. As a result, the cumulative impacts of drawdown from multiple private bores and the potential effects on GDEs remain unassessed.

California, USA

Similar to Australia, species protection under the state and federal Environmental Protection Acts are strong drivers of coastal GDE conservation where listed threatened and endangered species are known to use GDEs as habitat (e.g., coastal wetlands; Table 1). However, regulatory agencies tasked with recovering threatened and endangered species (e.g., California Department of Fish and Wildlife, U.S. Fish and Wildlife and Army Corps of Engineers) rarely acknowledge the role of groundwater in supporting species recovery since regulating groundwater (both quality and quantity) is out of their direct purview. This reduces the efficacy of species recovery efforts, as well as introduces a gap where only specific species within the ecosystem dependent on groundwater are protected, leaving the broader ecological and hydrological system underprotected and undermanaged.

The management of coastal GDEs in California is further hindered by fragmented policies that focus on specific aspects such as water quality or sustainable groundwater use. Multiple regulatory bodies, including the California State Water Resources Control Board (SWRCB), the California Coastal Commission, and local Groundwater Sustainability Agencies, oversee different aspects of water management along the coast. However, these entities operate within separate domains, leading to operational management gaps when it comes to the holistic management of coastal groundwater.

For instance, the SWRCB is responsible for regulating water quality, while the California Coastal Commission oversees land and groundwater development in coastal areas. Additionally, Groundwater Sustainability Agencies, established under the *Sustainable Groundwater Management Act 2014* (SGMA), manage groundwater use in designated groundwater basins. Despite SGMA recognizing the interconnection between groundwater and surface water resources and requiring control of groundwater depletion, the legal and management systems for permitting, monitoring and safeguarding surface water and groundwater remain effectively separate (Owen et al. 2019). These examples illustrate how different governance and regulatory entities possess some authority to protect groundwater and dependent ecosystems. However, their actions often operate independently within their respective domains, lacking coordination and synergy. This fragmented approach creates policy gaps and hinders the comprehensive management of coastal GDEs in California.

Coastal GDEs in California also face policy and management gaps when they are reliant on fresh groundwater but located in the marine zone. For example, SGMA mandates that local agencies consider impacts on GDEs, which can be identified through the California Department of Water Resources' GDE database, known as the Natural Communities Commonly Associated with Groundwater dataset (CDWR 2023). However, GDEs present in estuaries and coastal wetlands are excluded from this database because they are considered saltwater-dependent, which disregards the critical role of groundwater discharge for these ecosystems in coastal zones. Local groundwater sustainability agencies have the discretion to include these coastal GDEs in their groundwater sustainability plans, yet many have chosen not to do so. This exclusion largely arises from the perceived regulatory authority of local groundwater sustainability agencies to exclusively manage fresh groundwater. By considering only freshwater ecosystems, agencies overlook important coastal GDEs that would benefit from their ecological groundwater needs being incorporated into sustainable groundwater management plans.

SGMA's shortcomings in addressing coastal GDEs existing across the land-to-sea interface transcend into other hydrogeological aspects and policy realms, such as in the prevention of "undesirable results" arising from deteriorating water quality and streamflow depletion. Both water quality and streamflow fall under the jurisdiction of multiple regulatory authorities, such as the State and Regional Water Resources Control Boards and local groundwater sustainability agencies. This redundant arrangement created by overlapping authorities has resulted in diminished accountability for individual agencies to take necessary actions within their specific regulatory purviews. As a result, there is a need for improved collaboration and alignment between regulatory entities to effectively protect and manage these ecosystems existing across multiple policy realms.

Summary of Policy Gaps

The analysis of policy and legislation relating to coastal groundwater and GDE management has highlighted several significant challenges in Queensland and California. Three key policy gaps have been identified, including: (1) a lack of recognition of the underlying groundwater system, (2) fragmented policies and complex governance structures that limit coordination, and, (3) inadequate guidance for coastal groundwater management. These gaps present obstacles to the effective conservation of coastal groundwater and connected ecosystems. Addressing these challenges is crucial not only for the sustainable management of coastal groundwater in the populous States of Queensland and California but also for informing GDE conservation efforts and policy development worldwide.

Opportunities and Challenges Moving Forward

The Role of Ecosystem-Based Management Principles

The goal of ecosystem-based management (EBM) is to maintain ecosystem productivity and function through scientific understanding and adaptive management that promotes ecosystem resilience (Ansems et al. 2014). EBM principles have successfully been included in various complex socio-ecological systems, including fisheries and forestry, for the past two decades (Woods 2022). The adaptive management approach of EBM allows for the consideration of multiple social and ecological goals (Arkema et al. 2006), which is particularly valuable in the case of consumptive resources like groundwater. Moreover, EBM accounts for the uncertainties inherent in dynamic socio-ecological systems, such as fluctuations in groundwater volume and demand, both for consumptive purposes and ecosystem needs (Rinaudo et al. 2020). By considering the interplay between groundwater, social and ecological systems, EBM has the potential to guide

Table 2
Summary of Identified Policy Gaps With Examples, Recommendations and EBM Principles.

Policy Gap	Description	Example	Recommendations	EBM Principle
Gap 1	Lack of recognition of the underlying groundwater system.	Insufficient consideration of groundwater's ecohydrological support role in coastal habitats and species habitat protection.	• Develop policies that explicitly acknowledge and incorporate the critical role of groundwater in supporting coastal ecosystems. • Establish integrated management approaches that bridge terrestrial and marine realms.	Holistic and integrated approaches that recognize the interdependence of coastal and terrestrial ecosystems and groundwater and surface waters.
Gap 2	Fragmented policies and complex governance structures and limited cross-boundary coordination.	Overlapping authorities and fragmented governance hinder effective management and protection. Policies and legislation primarily focused on specific threats or isolated parts of the landscape.	• Foster coordination and collaboration among regulatory entities at different levels of governance. • Establish mechanisms for cross-boundary coordination and information sharing. • Incorporate transboundary considerations in policies and management approaches, recognizing the interconnected nature of coastal groundwater systems.	Foster participatory governance and stakeholder engagement to facilitate collaborative decision-making processes.
Gap 3	Inadequate guidance for coastal groundwater management.	Limited guidance on managing coastal aquifers susceptible to climate change, particularly changes in recharge and sea-level rise.	• Develop specific guidelines for managing coastal groundwater resources for the environment, considering the unique challenges and vulnerabilities GDEs face. • Incorporate climate change adaptation strategies into coastal groundwater allocation and management policies.	Apply adaptive management approaches that account for the dynamic nature of coastal ecosystems in the face of climate change and consider how current climates will affect future groundwater stores.

policy development which bridges existing gaps and direct management strategies that promote the long-term resilience and function of GDEs.

To bridge the first identified policy gap, EBM could be used to direct the development of policy that explicitly acknowledges and describes the role of groundwater in supporting coastal ecosystems (Table 2). Both Queensland and California lack an overarching policy document that describes the ecological role of groundwater in supporting critical biological and chemical processes within and across coastal watersheds. Within this policy, key biophysical linkages could be used as a basis to build a framework that bridges terrestrial and marine policy domains. The integration of reserve planning and connectivity into groundwater policy is likely to lead to better outcomes for GDEs (Boulton 2020). In Queensland, for example, Water Plans could be amended to include water requirements for ecosystems adjacent to respective management areas. This can be achieved by revising plans to ensure that ecological water requirements for downstream or surrounding coastal GDEs are acknowledged and accounted for in the neighboring plans. In California, the acknowledgement of groundwater as an important aspect of threatened species recovery efforts, particularly under climate change, could encourage greater protections for groundwater. Broadly, there is a push for adaptive water governance to include water rights specifically for GDEs (Nelson 2022). These rights would be quantifiable, and transferable, and would be held and enforced by public or private entities (Nelson 2022). Moreover, grant funding programs that encourage better coordination between management authorities and foster holistic planning can also be used to provide an incentive.

To bridge the second policy gap (Table 2), a review of current governance structures and responsibilities could be undertaken to identify opportunities for enhanced coordination and collaboration among regulatory entities at different governance levels. Fostering participatory governance through stakeholder and agency engagement will lead to collaborative decision-making processes across coastal landscapes, providing better conservation outcomes for coastal GDEs. Enhancing coordination between management agencies working in the coastal realm presents an opportunity to improve the management of coastal GDEs within the existing policy framework. For instance, in California, SGMA does not pre-empt pre-existing laws such as the state and federal Endangered Species Acts yet requires groundwater sustainability agencies to coordinate with county, state and federal agencies to ensure groundwater management does not adversely impact species. Thus, SGMA provides a legal framework to enhance the protection of coastal GDEs, but realizing this opportunity is dependent upon state enforcement and directives, a groundwater sustainability agency's initiative, or funding incentives.

Finally, a lack of guidance specifically for managing coastal groundwater for GDEs, particularly under climate change scenarios, was apparent in both case study areas (Gap 3, Table 2). The challenges of groundwater management for ecosystem function are discussed extensively within the existing literature. Saito et al. (2021) pointed out that traditional solutions, such as sustainable yield, ignore complex spatiotemporal dynamics in groundwater systems. The authors prescribe minimum provisions for planning, managing and monitoring groundwater for ecosystems, and these could be adapted to form key research questions that decipher the specific needs of coastal GDEs using regional case studies. For example, in terms of saltwater intrusion, research questions could be posed to understand saltwater intrusion processes and vulnerabilities, and how monitoring practices could be adapted to effectively mitigate saltwater intrusion in the context of sea-level rise, extreme weather events, and changing precipitation patterns.

The use of case studies has been instrumental in addressing the specific challenges of managing groundwater and GDEs in the context of climate change. New South Wales's (NSW, Australia) Water Strategy was developed using regional case studies which provided details on key challenges within selected basins, allowing for an in-depth understanding of groundwater movement, use and ecological value as well as climate change related risks specific to those regions (DPIE 2021). The Strategy prioritizes landscape scale action, setting out a framework to integrate key management programs and government agencies. For example, in coastal catchments, the Strategy aims to foster collaboration between groundwater management and habitat protection through existing Coastal Zone Management Plans and the Marine Estate Management Strategy. The Water Strategy could serve as a model for a comprehensive policy document guiding coastal groundwater and GDE management in both Australia and the USA. By incorporating key case studies and establishing a framework for collaboration among agencies and existing management initiatives across terrestrial and marine zones, it provides a solid template for an overarching policy document that could be adopted by individual states.

Challenges in the Coastal Realm

Like many natural systems, the management of GDEs is complex. Even a conceptual understanding of GDE function must include hydrogeological, biological and ecological elements and each of these elements operates on independent spatial and temporal scales (Keeley et al. 2022). Barreteau et al. (2016) put it well when they described groundwater as "an interaction space of several interdependent dynamics" (p. 49). Translating complex ecosystem dynamics into management measures that effectively capture and protect ecosystem function under changing climatic conditions is an inherently difficult task (Elshall et al. 2020). This is made more complex in coastal environments which are geomorphically dynamic, have a long history of human exploitation and include both terrestrial, marine and sub-surface policy domains.

There are specific challenges to the use of EBM principles in groundwater management. EBM actions are routinely criticized for being too broad for effective implementation (Arkema et al. 2006). Leslie and McLeod (2007) cited a lack of a common vision and inadequate governance frameworks that do not allow the implementation of EBM as major impediments to its effective use in marine policy design. Considering the complex and layered management of groundwater in Australia and the USA, inadequate governance frameworks could also prove to be an issue for EBM of GDEs. Recently, groundwater experts across Australia listed determining groundwater requirements for the environment as a significant challenge in GDE management (Cook et al. 2022), despite published methodologies (Eamus et al. 2006), suggesting funding and research constraints as limiting factors. Another major challenge to the use of EBM in the GDE space is that groundwater is largely unregulated across the globe and establishing ecosystem requirements within existing sustainable groundwater management laws can be limited (Rohde et al. 2017). In reality, the scientific community must embed EBM concepts in GDE research to operational goals in groundwater management (Olsson et al. 2008). So, while EBM is regarded as an ideal option for the management of complex socio-ecological systems like GDEs, implementation mechanisms require further attention before we can transition to this management model.

Conclusion

Coastal GDEs are highly complex systems that require intentional policy design. This policy gap analysis reveals that known threats to coastal groundwater-dependent ecosystems (GDEs), such as climate change, groundwater extraction and pollution, are actively managed, but in very separate realms – both in terms of governance structures and landscape setting. The integration of policies across landscapes to include multiple ecosystems and domains (i.e., biosphere, atmosphere and hydrosphere, and terrestrial and marine zones) will require a coordinated planning approach. Policymakers, researchers and practitioners will need to consider management beyond traditional conservation realms to effectively conserve coastal ecosystems and the groundwater systems they rely on.

Integrating policies across coastal watersheds and adopting EBM principles can conserve ecohydrological processes and enhance resilience in coastal GDEs. While sustainable groundwater use is often the driver of GDE management, the adoption of EBM principles is another mechanism for providing effective outcomes for the ecological communities that coastal groundwater supports. While our findings highlight policy gaps that hinder the conservation of coastal GDEs in Australia and the USA, these gaps are likely relevant to other coastal areas worldwide. Addressing policy gaps in the management of coastal GDEs is a crucial step toward achieving more sustainable solutions for both groundwater and dependent ecosystems.

Acknowledgment

Open access publishing facilitated by The University of Queensland, as part of the Wiley - The University of Queensland agreement via the Council of Australian University Librarians.

References

Australian Bureau of Statistics (ABS). 2022. Regional populations. https://www.abs.gov.au/statistics/people/population/regional-population/latest-release

Ansems, N., E. Khaka, and K. Villholth. 2014. *Ecosystem-Based Adaptation in Groundwater Management*. United Nations International Groundwater Resources Assessment Centre. https://www.un-igrac.org/resource/ecosystem-based-adaptation-groundwater-management-0

Arkema, K.K., S.C. Abramson, and B.M. Dewsbury. 2006. Marine ecosystem-based management: From characterization to implementation. *Frontiers in Ecology and the Environment* 4, no. 10: 525–532. https://doi.org/10.1890/1540-9295(2006)4[525:Memfct]2.0.Co;2

Barreteau, O., Y. Caballero, S. Hamilton, A. Jakeman, and J.-D. Rinaudo. 2016. Disentangling the complexity of groundwater dependent social-ecological systems. In *Integrated Groundwater Management: Concepts, Approaches and Challenges*, ed. A.J. Jakeman, O. Barreteau, R.J. Hunt, J.-D. Rinaudo, and A. Ross, 49–74. Cham: Springer International Publishing.

Befus, K., P.L. Barnard, D.J. Hoover, J. Finzi Hart, and C.I. Voss. 2020. Increasing threat of coastal groundwater hazards from sea-level rise in California. *Nature Climate Change* 10: 946–952.

Boulton, A.J. 2020. Editorial: Conservation of groundwaters and their dependent ecosystems: Integrating molecular taxonomy, systematic reserve planning and cultural values. *Aquatic Conservation: Marine and Freshwater Ecosystems* 30, no. 1: 1–7. https://doi.org/10.1002/aqc.3268

California Department of Water Resources (CDWR). 2023. Natural communities commonly associated with groundwater dataset. https://gis.water.ca.gov/app/NCDatasetViewer/

Condon, L.E., A.L. Atchley, and R.M. Maxwell. 2020. Evapotranspiration depletes groundwater under warming over the contiguous United States. *Nature Communications* 11, no. 1: 1–8.

Cook, P.G., M. Shanafield, M.S. Andersen, S. Bourke, I. Cartwright, J. Cleverly, M. Currell, T.M. Doody, H. Hofmann, R. Hugmann, D.J. Irvine, A. Jakeman, J. McKay, R. Nelson, and A.D. Werner. 2022. Sustainable management of groundwater extraction: An Australian perspective on current challenges. *Journal of Hydrology Regional Studies* 44: 101262. https://doi.org/10.1016/j.ejrh.2022.101262

Department of Planning, Industry and Environment (DPIE). 2021. *New South Wales Water Strategy*. NSW Government. https://water.dpie.nsw.gov.au/plans-and-programs/nsw-water-strategy

Doody, T., P. Hancock, and J. Pritchard. 2019. Information Guidelines explanatory note: Assessing groundwater-dependent ecosystems. Report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment and Energy, Commonwealth of Australia. https://www.iesc.gov.au/information-guidelines-explanatory-note-assessing-groundwater-dependent-ecosystems.pdf

Dyring, M., H. Hofmann, D. Stanton, P. Moss, and R. Froend. 2022. Ecohydrology of coastal aquifers in humid environments and implications of a drying climate. *Ecohydrology* 16: 2491. https://doi.org/10.1002/eco.2491

Eamus, D., R. Froend, R. Loomes, G.C. Hose, and M. Brad. 2006. A functional methodology for determining the groundwater regime needed to maintain the health of groundwater-dependent vegetation. *Australian Journal of Botany* 54: 97–114.

Elshall, A.S., A.D. Arik, A.I. El-Kadi, S. Pierce, M. Ye, K.M. Burnett, C.A. Wada, L.L. Bremer, and G. Chun. 2020. Groundwater sustainability: A review of the interactions between science and policy. *Environmental Research Letters* 15, no. 9: 093004.

Ferguson, G., and T. Gleeson. 2012. Vulnerability of coastal aquifers to groundwater use and climate change. *Nature Climate Change* 2, no. 5: 342–345. https://doi.org/10.1038/nclimate1413

Griebler, C., and M. Avramov. 2015. Groundwater ecosystem services: A review. *Freshwater Science* 34, no. 1: 355–367. https://doi.org/10.1086/679903

Howard, J.K., K. Dooley, K.A. Brauman, K.R. Klausmeyer, and M.M. Rohde. 2023. Ecosystem services produced by groundwater dependent ecosystems: A framework and case study in California. *Frontiers in Water* 5: 1115416.

Huggins, X., T. Gleeson, D. Serrano, S. Zipper, F. Jehn, M.M. Rohde, R. Abell, K. Vigerstol, and A. Hartmann. 2023. Overlooked risks and opportunities in groundwatersheds of the world's protected areas. *Nature Sustainability* 1-10: 855–864.

Ivkovic, K., S. Marshall, L. Morgan, A. Werner, H. Carey, S. Cook, B. Sundaram, R. Norman, L. Wallace, and L. Caruana. 2012. *National-scale vulnerability assessment of seawater intrusion: summary report*. *Waterlines Report Series No. 85*. National Water Commission. Australian Government. https://www.ga.gov.au/about/projects/water/a-national-scale-vulnerability-assessment-of-seawater-intrusion

Jasechko, S., D. Perrone, H. Seybold, F. Fan, and J.W. Kirchner. 2020. Groundwater level observations in 250,000 coastal US wells reveal scope of potential seawater intrusion. *Nature Communications* 11, no. 1: 3229.

Jasechko, S., S.J. Birks, T. Gleeson, Y. Wada, P.J. Fawcett, Z.D. Sharp, J.J. McDonnell, and J.M. Welker. 2014. The pronounced seasonality of global groundwater recharge. *Water Resources Research* 50, no. 11: 8845–8867. https://doi.org/10.1002/2014wr015809

Keeley, A.T., A.K. Fremier, P.A. Goertler, P.R. Huber, A.M. Sturrock, S.M. Bashevkin, B.A. Barbaree, J.L. Grenier, T.E. Dilts, and M. Gogol-Prokurat. 2022. Governing ecological connectivity in cross-scale dependent systems. *Bioscience* 72, no. 4: 372–386.

Leslie, H.M., and K.L. McLeod. 2007. Confronting the challenges of implementing marine ecosystem-based management. *Frontiers in Ecology and the Environment* 5, no. 10: 540–548. https://doi.org/10.1890/060093

McGregor, G.B., J.C. Marshall, J.S. Lobegeiger, D. Holloway, N. Menke, and J. Coysh. 2018. A risk-based ecohydrological approach to assessing environmental flow regimes. *Environmental Management* 61, no. 3: 358–374. https://doi.org/10.1007/s00267-017-0850-3

Nelson, R. 2022. Water rights for groundwater environments as an enabling condition for adaptive water governance. *Ecology and Society* 27, no. 2.

Olsson, P., C. Folke, and T.P. Hughes. 2008. Navigating the transition to ecosystem-based management of the Great Barrier Reef, Australia. *Proceedings of the National Academy of Sciences United States of America* 105, no. 28: 9489–9494. https://doi.org/10.1073/pnas.0706905105

Owen, D., A. Cantor, N.G. Nylen, T. Harter, and M. Kiparsky. 2019. California groundwater management, science-policy interfaces, and the legacies of artificial legal distinctions. *Environmental Research Letters* 14, no. 4: 045016.

PPIC. 2017. Groundwater in California. Public Policy Institute of California. https://www.ppic.org/publication/groundwater-in-california/

Richardson, S., E. Irvine, R. Froend, P. Boon, S. Barber, and B. Bonneville. 2011. *Australian Groundwater-Dependent Ecosystems Toolbox Part 1: Assessment Framework*. Canberra: The National Water Commission.

Rinaudo, J.-D., C. Holley, S. Barnett, and M. Montginoul. 2020. *Sustainable Groundwater Management: A Comparative Analysis of French and Australian Policies and Implications to Other Countries*, Vol. 24. Switzerland: Springer.

Rodell, M., and B. Li. 2023. Changing intensity of hydroclimatic extreme events revealed by GRACE and GRACE-FO. *Nature Water* 1-8: 241–248.

Rohde, M.M. 2023. Floods and droughts are intensifying globally. *Nature Water* 1-2: 226–227.

Rohde, M.M., R. Froend, and J. Howard. 2017. A global synthesis of managing groundwater dependent ecosystems under sustainable groundwater policy. *Groundwater* 55, no. 3: 293–301. https://doi.org/10.1111/gwat.12511

Saito, L., B. Christian, J. Diffley, H. Richter, M.M. Rohde, and S.A. Morrison. 2021. Managing groundwater to ensure ecosystem function. *Groundwater* 59, no. 3: 322–333.

Swain, D.L., B. Langenbrunner, J.D. Neelin, and A. Hall. 2018. Increasing precipitation volatility in twenty-first-century California. *Nature Climate Change* 8, no. 5: 427–433.

Werner, A.D., M. Bakker, V.E.A. Post, A. Vandenbohede, C. Lu, B. Ataie-Ashtiani, C.T. Simmons, and D.A. Barry. 2013. Seawater intrusion processes, investigation and management: Recent advances and future challenges. *Advances in Water Resources* 51, no. 3: 26. https://doi.org/10.1016/j.advwatres.2012.03.004

Wilson, T.S., N.D. van Schmidt, and R. Langridge. 2020. Land-use change and future water demand in California's central coast. *Land* 9, no. 9: 322.

Woods, P.J. 2022. Aligning integrated ecosystem assessment with adaptation planning in support of ecosystem-based management. *International Council for the Exploration of the Sea Journal of Marine Science* 79, no. 2: 480–494.