Earth-Science Reviews 221 (2021) 103742

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

The social implications of Submarine Groundwater Discharge from an Ecosystem Services perspective: A systematic review

Aaron Alorda-Kleinglass [a,*], Isabel Ruiz-Mallén [b,*], Marc Diego-Feliu [a], Valentí Rodellas [a], Joan Manuel Bruach-Menchén [c], Jordi Garcia-Orellana [a,c]

[a] Institut de Ciència i Tecnologia Ambientals (ICTA), Universitat Autònoma de Barcelona, E-08193 Bellaterra, Catalonia, Spain
[b] Internet Interdisciplinary Institute (IN3), Universitat Oberta de Catalunya, E-08860 Castelldefels, Catalonia, Spain
[c] Departament de Física, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Catalonia, Spain

ARTICLE INFO

Keywords:
Submarine groundwater discharge
Coastal Ocean
Ecosystem Services
Social implications, SGD-ES

ABSTRACT

Submarine Groundwater Discharge (SGD) is recognized as a fundamental hydrological process that supports many coastal biogeochemical cycles and social-ecological systems. However, very little has been investigated about how SGD affects society and, specifically, human well-being. This study systematically examines the published scientific literature on the social implications of SGD by using an Ecosystem Service (ES) perspective. Coastal services provided by ecosystems dependent on SGD are analyzed and clustered in the four main categories of Ecosystem Services (i.e., Provisioning, Supporting, Regulating and Cultural), which are in turn divided into subcategories defined as outcomes. This allows identifying and discussing both benefits and threats to coastal societies resulting from SGD outcomes. From the 1532 articles initially reviewed, the most frequently mentioned category was the supporting services (835) due to the mainstream trend in scientific literature to focus on the role of SGD as a process influencing coastal biogeochemical cycles. Conversely, cultural ES were mentioned in only 49 cases, which should not necessarily be interpreted as a lack of research or interest in this topic, but that this type of references are often not found in the scientific literature but in the grey literature. A detailed publication review was additionally conducted, identifying 114 case-studies from 96 different locations worldwide that reported cases in which SGD had social implications on the well-being. Our review also shows how the different types of Ecosystem Services can have multiple synergies and trade-offs between them, resulting in unequal impacts among stakeholder groups. Overall, this study identifies research gaps related to Ecosystem Services provided by SGD as well as opportunities for further studies, while developing an analytical framework that relies on the Ecosystem Services approach to guide future research on the social implications of SGD.

1. Introduction

Humans have historically used and managed coastal ecosystems and their resources as services towards their own benefit. Currently, coastal environments support a wide range of economic sectors (e.g., tourism, fisheries, and mining) and provide important socio-environmental benefits (e.g., temperature regulation, shoreline protection against storms and floods, and water quality maintenance) (Alder et al., 2006). The ecological richness of a coastal habitat, as well as its complexity, is in part dependent upon land-ocean interactions. The supply of freshwater and solutes from terrestrial sources, such as rivers, streams, glaciers, and groundwater, support coastal ecosystems (Alder et al., 2006). Among these sources, Submarine Groundwater Discharge (SGD) has received increasing attention since the 1980s (Bokuniewicz, 1980; Johannes, 1980; Kohout et al., 1979), when it was recognized to play a relevant role in coastal hydrological and biogeochemical cycles (Knee and Paytan, 2011; Luijendijk et al., 2020; Ma and Zhang, 2020; Santos et al., 2021; Slomp and Van Cappellen, 2004). SGD is composed of groundwater with different compositions (e.g., fresh, brackish or saline groundwater), origins (e.g., terrestrial, marine) and driven by a wide range of physical processes (e.g., terrestrial hydraulic gradient, waves, tides, etc.) (Garcia-Orellana et al., 2021; Moore, 2010; Santos et al., 2012; Taniguchi et al., 2019). SGD is characterized by its often diffusive inflows along large areas and below the water surface, resulting in an "invisible" process in comparison to surficial and point-sourced riverine discharge. SGD is also characterized by a unique biogeochemical signature (i.e., characteristic physiochemical parameters and solute concentrations) compared to other sources, owing to the

---

* Corresponding authors.
E-mail addresses: aaron.alorda@uab.cat (A. Alorda-Kleinglass), iruiz_mallen@uoc.edu (I. Ruiz-Mallén).

https://doi.org/10.1016/j.earscirev.2021.103742
Received 11 January 2021; Received in revised form 11 July 2021; Accepted 14 July 2021

biogeochemical transformations occurring in the coastal aquifer, which are often mediated by bacteria (Ruiz-González et al., 2021; Santos et al., 2021).

SGD is an important source of fresh groundwater representing between 0.6% and 1% of the total global freshwater inputs into the oceans (Luijendijk et al., 2020; Zhou et al., 2019). Although it represents a small fraction of freshwater discharge into the ocean on a global scale, the high spatial variability of SGD fluxes results on locally important fluxes in specific areas (Luijendijk et al., 2020). Fresh SGD might thus ensure water resources for people's livelihoods, particularly in arid or semi-arid coastal regions were freshwater resources are limited (Erostate et al., 2020; Moosdorf and Oehler, 2017). In addition, SGD supplies solutes to the coastal ocean (e.g., Cho et al., 2018; Johannes, 1980; Moore, 2008; Rodellas et al., 2015), which directly impact the productivity of coastal ecosystems (e.g., Erostate et al., 2020; Johannes, 1980; Johannes and Hearn, 1985; Lecher and Mackey, 2018; Taniguchi et al., 2019; Valiela et al., 1990). SGD can also supply dissolved contaminants to the coastal ocean derived from anthropogenic sources (e.g., agriculture, industrial, mining activities, domestic wastewaters) (e.g., Alorda-Kleinglass et al., 2019; Pavlidou et al., 2014; Rodellas et al., 2014; Sternal et al., 2017; Szymczycha et al., 2020; Trezzi et al., 2016), which can endanger the coastal ecosystems and the well-being of local population living around them. In this regard, societies living around SGD-influenced zones may benefit or be harmed by the services and goods provided by the ecosystems influenced by SGD.

The benefits that are obtained from ecosystems that support, directly or indirectly, the survival and quality of life can be defined as Ecosystem Services (ES) (Costanza et al., 2017, 1997; Harrington et al., 2010). ES in coastal areas have been the foundations for many coastal civilizations (Costanza et al., 1997). For instance, coastal environments have provided water and food for human consumption for millennia and maintained coral reefs or mangroves, which have buffered wave storms and protected the coastline erosion (Hassan et al., 2005). Those ES have also inspired myths, tales or even gods, and provided habitats for the fisheries that coastal societies rely on (Alder et al., 2006). Conversely, the effects of global change (e.g., increase of demographic pressure, climate change, groundwater squeeze, increased industrial pollution) are threatening coastal environments (Islam and Tanaka, 2004; Michael et al., 2017; Paoli et al., 2017; Williams, 1996). ES provided by rivers or streams (Yeakley et al., 2016), lakes (Schallenberg et al., 2013), estuaries (Barbier et al., 2011) or mangroves (Queiroz et al., 2017) are well studied, but there is a lack of studies examining SGD from an ES perspective or evaluating the synergies and trade-offs derived from SGD-related ES. Only two studies have preliminary explored this topic; Erostate et al. (2020), who discussed the policies and management of ES linked to groundwater-dependent coastal ecosystems in Mediterranean regions; and Moosdorf and Oehler (2017), who reviewed social uses of SGD-derived freshwater (e.g., drinking, hygiene, agriculture, fishing, tourism or culture).

In this study, we conduct a systematic review of the scientific literature to gather the available and existing knowledge on the social implications of SGD worldwide. Specifically, we review the peer-reviewed scientific academic literature published in English to analyze coastal ES derived from SGD, understood as both positive and negative effects on human well-being and quality of life, and classify the information obtained using the Millennium Ecosystem Assessment (MEA, 2005) as a conceptual framework baseline. Furthermore, we review the direct social impacts of SGD, in terms of synergies and trade-offs towards well-being, and the research gaps and opportunities for further studies. The new insights derived from this review will allow the development of an ES-based analytical framework that will guide future research on the social implications of SGD. This review also highlights the importance of SGD from a social perspective, closing the gap between physical and social disciplines that have often worked independently.

2. Analytical framework

SGD is defined as "*the flow of water through continental and insular margins from the seabed to the coastal ocean, regardless of fluid composition or driving force*" (Garcia-Orellana et al., 2021; Burnett et al., 2003; Taniguchi et al., 2019). SGD includes thus both fresh groundwater discharge (fresh or terrestrial SGD) and seawater circulating through the coastal aquifer (saline or marine SGD). Fresh and marine SGD can be supplied via 5 different pathways: 1) Terrestrial groundwater discharge (usually fresh groundwater); 2) Density-driven seawater circulation; 3) Seasonal exchange of seawater; 4) Shoreface seawater circulation; and 5) cm-scale porewater exchange (PEX) (Garcia-Orellana et al., 2021). Whilst pathways 1 and 2 may represent a net input of freshwater to the coastal ocean, pathways 3, 4, and 5 only involve the recirculation of seawater through permeable sediments. In this study, we will only refer to the fresh or saline fraction of SGD, regardless of the pathway driving the discharge of groundwater (Fig. 1). Previous research has highlighted

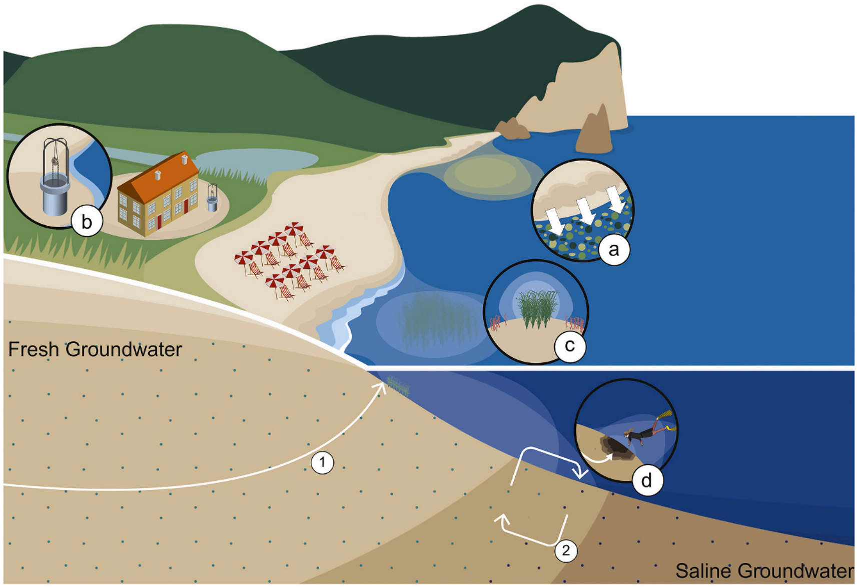

Fig. 1. Conceptual diagram of a coastal society influenced by Submarine Groundwater Discharge and its four categories of Ecosystem Services: a) Supporting; b) Provisioning; c) Regulating; d) Cultural. The different components of SGD are also shown: 1) Fresh component of SGD; 2) Saline component of SGD. Figure based on Garcia-Orellana et al. (2021).

that coastal ecosystems provide diverse and valuable goods and services as a result of fresh SGD (Erostate et al., 2020; Moosdorf and Oehler, 2017). However, coastal ecosystems can also be supported by saline SGD, which constitutes a relevant source of dissolved solutes to the coastal ocean (Cho et al., 2018; Moore et al., 2008; Rodellas et al., 2015). Following Erostate et al. (2020) and Richardson et al. (2011), we define coastal groundwater dependent ecosystem (coastal GDE) as the marine coastal ecosystems that require permanent or intermittent access to groundwater (including fresh and saline SGD) for maintaining their biological communities, their ecological processes, and the associated ecosystem services. Furthermore, we define the ecosystem services inherent to coastal GDE, that are directly provided by submarine groundwater discharge as SGD-ES.

To develop a common and interdisciplinary framework to assess the social implications of SGD, we used the ES approach based on the Millennium Ecosystem Assessment (MEA, 2005). The MEA (2005) was used as baseline due to its sound relevance as the first robust framework to classify and quantify the social benefits and losses that humans obtain from the functioning of ecosystems. An academic debate exists about what to call "negative" effects provided by ecosystems. Some authors define harmful effects as Ecosystem Dis-services, being "the ecological processes that affect human well-being in negative ways, causing harm or costs" (Barnaud et al., 2018; Zhang et al., 2007). On the other hand, other researchers argue that such dichotomy is a matter of perception as some people can be damaged while others can benefit from them, highlighting that such an approach does not reflect reality (Saunders and Luck, 2016). Following this second line of thinking, in this study we consider both positive and negative coastal processes impact on human well-being as ES. This facilitates detecting and discussing potential trade-offs and synergies between organisms, ecosystems and human activities that cannot be related to a single ES (Norberg, 1999; Saunders and Luck, 2016).

We divided our conceptual framework into the four broad ES categories identified in the MEA (Fig. 2): (i) Supporting; (ii) Provisioning; (iii) Regulating; and (iv) Cultural, which are in turn subdivided in Outcomes, reflecting the different services of each category. A wide range of outcomes derived from each ecosystem service category were already established by MEA (2005) framework, but only those relevant for SGD-influenced ecosystems have been selected in the framework.

(i) *Supporting ES* are defined as services provided by SGD that sustain the existence of other ecosystem services. These services are indirect since they do not directly affect human well-being but are fundamental to the existence of the other categories identified in the MEA (2005). In this sense, we consider any SGD-driven input of water and solutes, including chemical dissolved compound (e.g., nutrients, bacteria, trace metals, oxygen, or rare-earth elements) or water that modifies the physicochemical characteristics (e.g., salinity, temperature or pH) of the coastal environment, and the biogeochemical implications of these inputs. For example, coastal human societies do not use nutrients as they are delivered to the environment, but they are essential to support the photic zone, where primary production will be produced, and therefore will be able to support the production of food (e.g., algae or fish) for human and animal consumption, or to maintain the habitat. As Outcomes derived from this category, we consider: Water Cycle, Nutrient Cycling, Primary Production, and Habitat.

   a. *Water Cycle* as the role of SGD within the hydrological cycle.
   b. *Nutrient cycling* as the transfer of nutrients delivered by SGD from the coastal aquifer into the coastal GDE, from the inorganic compounds to the assimilation of super depredators at the top of the chain.
   c. *Primary Production* as the transformation of energy and inorganic compounds delivered by SGD into organic compounds by those organisms living in the coastal GDE.
   d. *Habitat* as the coastal GDE that promotes life due to the physicochemical and biological conditions which are sustained by SGD.

(ii) *Provisioning ES* are defined as products that SGD provides to society. As Outcomes we consider Freshwater and Food.

   a. *Freshwater* as the fresh component of SGD that is directly used as a water resource for human consumption, agriculture or other industrial purposes.
   b. *Food* as organisms that have their habitat in coastal GDE or that their survival depends on SGD and are consumed by society.

(iii) *Regulating ES* are defined as services that control crucial processes for habitats and coastal ecosystems influenced by SGD. As Outcomes we consider Biological Control and Human Disease (as Disease Regulation in the MEA (2005)).

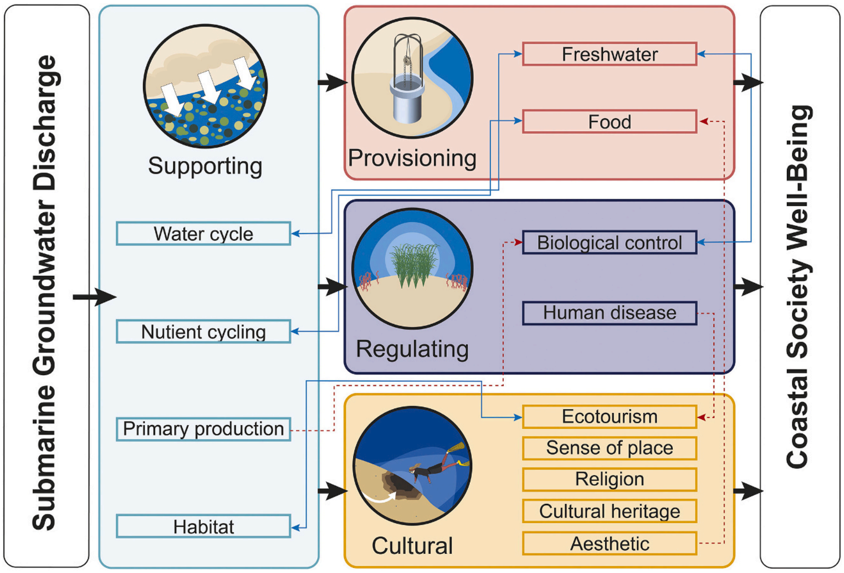

Fig. 2. SGD-ES conceptual framework. SGD derives into the four ES categories and their outcomes (represented by squared boxes). Those outcomes depend on each other by creating synergies or trade-offs shown with blue and red arrows, respectively, as an example. Finally, those interactions influence the coastal society well-being, based on the MEA (2005). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

a. *Biological control* as those changes or conditions induced by SGD that affect the prevalence of certain species, ecosystems, or limit the entrance of other species into coastal GDE.
b. *Human Disease* refers to the transport or restriction of pathogens or pollutant compounds delivered by SGD that can compromise human health.

(iv) *Cultural ES* are defined as the non-material benefits provided by SGD that contribute to human values and influence behavior. The perception of those ES can vary across stakeholders or communities, due to the subjectivity of the observer. As Outcomes we consider Recreational Activities or Ecotourism, Sense of Place, Religion, Cultural Heritage and Aesthetic or Inspirational values.

a. *Recreational Activities or Ecotourism* as any leisure activity (economically exploited or not) developed on an environment influenced by SGD.
b. *Sense of place* as the feeling of belonging to a certain site or toponyms that have been given to certain places after the occurrence of SGD, as well as buildings' names.
c. *Religion* as those stories, tales, myths, or religious ceremonies that are based on SGD.
d. *Cultural heritage* as those ways of doing, traditions, knowledge, objects, or values related to SGD that the present society continues from older generations.
e. *Aesthetic or Inspirational values* as the subjective sensory-emotional values provided by SGD, such as inspiration, intrigue to explore nature, or beauty.

Each of those Outcomes can be related with each other by means of synergies or can be prioritized by coastal societies by trade-offs in order to achieve their well-being. Following the MEA (2005) we define:

- *Well-being* as “the capacity of an ES to provide the conditions for physical, social, psychological, and spiritual fulfillment”.
- *Synergies* as the relation between two or more outcomes that benefit mutually due to their existence.
- *Trade-off* as the choice taken by society that involves prioritizing one outcome in exchange of another one or more.

Table 1
Data selection criteria.

Stage	Criteria	Screened studies	Selected studies
Preliminary	*Key words* “Submarine Groundwater Discharge” “Soci*”	30	2
First	*Key words* “Submarine Groundwater Discharge” “Submarine Spring”	1532	503
Second	*Title analyses* SGD impacts	503	92
Third	*Abstract analysis* Social implications	92	32
Fourth	*Detailed review* Social implications	32	32 (114 cases)

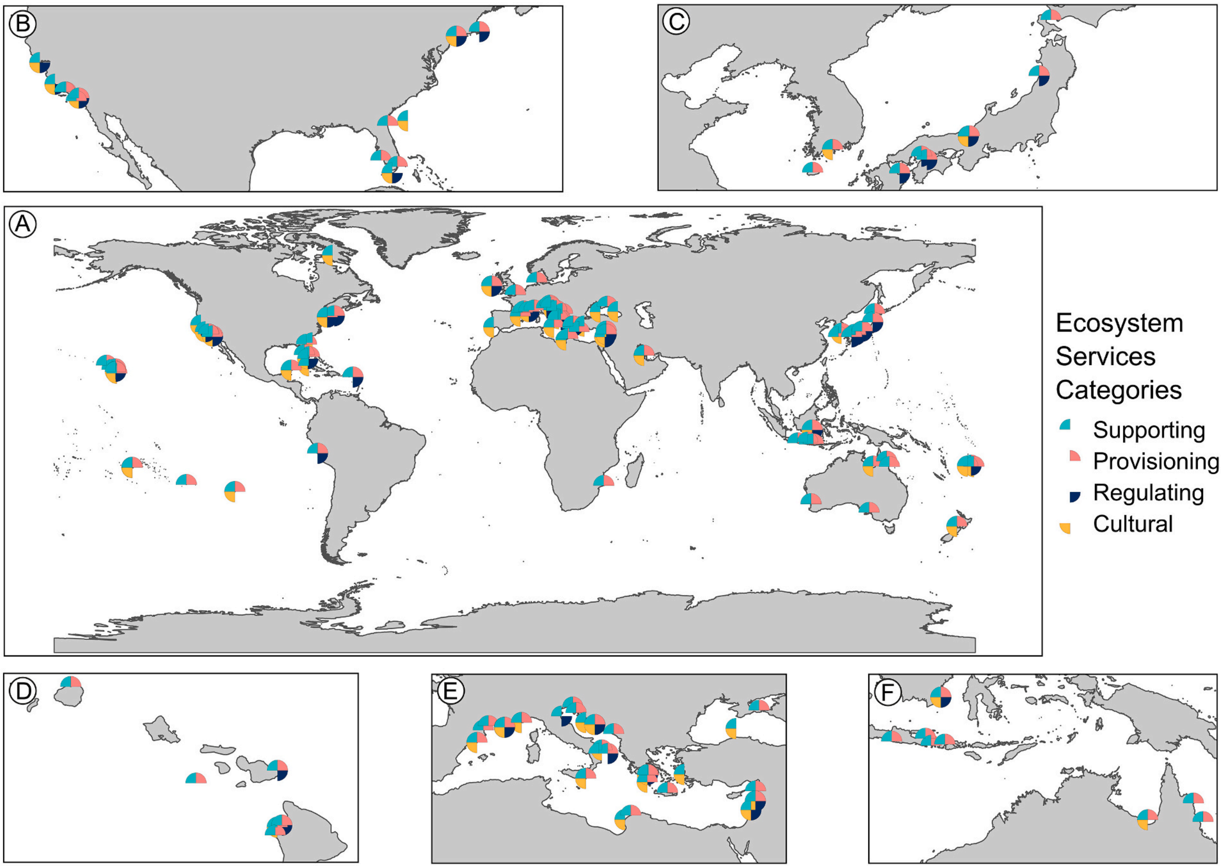

Fig. 3. Worldwide distribution of locations where Ecosystem Services provided by SGD were identified and reported in scientific literature (A). Pink, turquoise, dark blue and yellow quadrant of the circle corresponds to sites where Provisioning, Supporting, Regulating and Cultural Ecosystem Services were identified, respectively. Zooms into the areas where most of the studies are located are also provided: B) North America; C) Japan and the Korean peninsula; D) Hawaiian archipelago; E) Mediterranean Sea; F) Indonesia and North Australia. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Data collection and analysis

The scientific literature review process has been carried out in five stages (Table 1). In order to provide an overview on the state of the art of the SGD-ES, according to well-established guidelines for systematic reviews by Petticrew and Roberts (2006), a systematic literature review was conducted by using the search engine Web of Science (hereinafter, WoS). As a preliminary review, we used "submarine groundwater discharge" and "soci*" as keywords in WoS. Results from this preliminary review search provided 30 studies of which only two (i.e., Duarte et al., 2010; Moosdorf and Oehler, 2017) explicitly reported direct social implications.

Considering the limited number of studies obtained from the preliminary review, a broader search using the terms "Submarine Groundwater Discharge", or "Submarine Springs" was conducted as first stage of the systematic review. A total of 1532 studies were registered with these search terms from 1900 to April 2020. Considering the MEA (2005) as a baseline, a re-search within this sample of articles was done by establishing a set of keywords for each ES category and outcome derived from SGD-ES (see Supplementary material).

The content of the articles (reported in Supplementary material) indicated that most studies could be categorized as supporting ES, suggesting that these articles did not explicitly examine the social implications of SGD. To readdress the review and focus on the social implications of SGD, the title of all the publications identified at the first stage ($n = 1532$) was reviewed to only include those studies which focused on SGD impacts as the second stage of the systematic review. With the remaining ($n = 503$), a detailed publication review was made to double check for suitable publications that established direct relations between SGD processes, ES, and social implications. As third stage the abstracts of the manuscripts were screened to select only publications that referred to social implications of SGD. The fourth and final stage consisted on the full text analysis of the selected manuscripts ($n = 92$), which was carefully reviewed to identify the social implications of SGD. As a result, 32 publications were finally included in the analysis of social implications, in which a total of 114 cases from different locations worldwide were identified and analyzed by using the MEA-based framework described in Section 2 as a baseline (Fig. 3).

4. Results and discussion

In the following sections we describe how SGD is directly related to those ES and how those interact with each other, what dependences they have and what consequences affect the coastal societies. As it will be explained, supporting, provisioning, regulating and cultural ES can have multiple synergies between them (see Section 4.1). In any case, those ES do not interact spontaneously but the different stakeholders from any coastal society interact with the SGD process. Either to take advantage or remove the threat to guarantee their well-being, there are trade-offs between ES that will take place in each society (see Section 4.2). Therefore, those situations will make difficult to achieve a win-win scenario, which can result into social conflicts.

4.1. Submarine groundwater dependent ecosystem services

Most of the SGD studies are focused on understanding the role of SGD in the water cycle and its biogeochemical impacts on coastal and marine ecosystems. Indeed, the results derived from the first stage of the systematical review reinforce this fact; 55% of the literature has been focused on evaluating supporting ES of SGD. This evidences that direct ES such as providing, regulating, and cultural, which only comprise 7%, 8%, and 3%, respectively, of the examined literature, have been significatively overlooked in research pertaining to SGD (Fig. 4). Notice that according to the MEA (2005), supporting ES are services that create synergies between categories, or their effects are so long term that they cannot be perceived by the coastal societies (Fig. 2). Therefore, according to this definition, any provisioning, regulating or cultural ES are related to the Supporting category and there is an overlap of some SGD-ES. In this direction, the same study can be accounted for the supporting category and any other. For instance, Duarte et al. (2010) showed that an aquiculture macroalgae farm that is provided by the nutrients of SGD is directly related to the provision of food by the algae farm (provisioning ES) and, indirectly, but not less important, the support of habitat for those organisms (supporting ES). In this direction, any other example described in the following sections is always related to supporting ES.

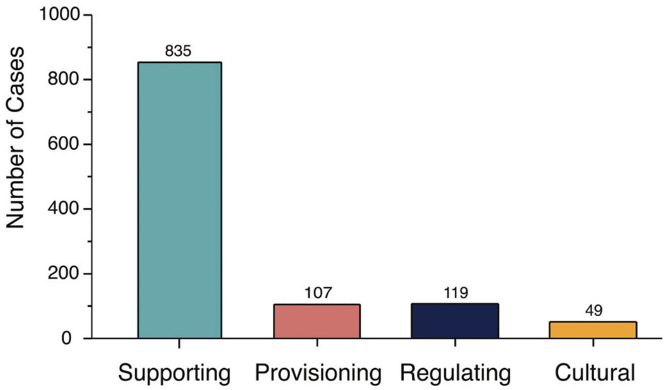

Fig. 4. Number of reported cases in the first stage for each SGD-ES for the systematical search key words using WoS.

Focusing on the studies explicitly referring to SGD social implications (fourth stage), the identified 114 cases from the 32 publications in the systematic review showed the following results in terms of the reported ES: 100% Supporting, 80% Provisioning, 25% Regulating, and 41% Cultural ES (Fig. 5). The higher incidence of Provisioning services seems to be the result of the major scientific effort done over the last 40 years to link SGD as a fresh water resource (Moore, 2010; Taniguchi et al., 2019). Accordingly with results obtained in the first stage, the smaller relevance of Regulating and Cultural ES suggests that these topics have only recently received scientific attention.

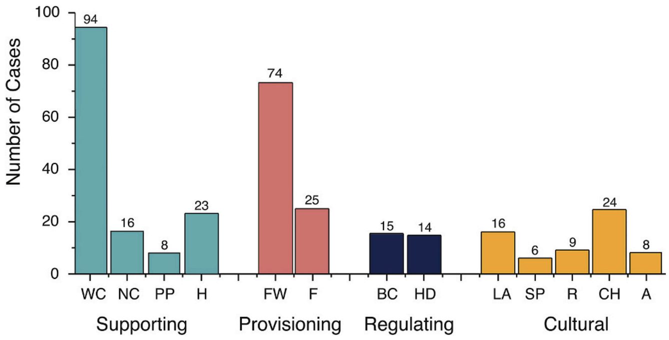

Fig. 5. Number of reported cases for each SGD-ES categories and derived outcomes from the fourth stage. WC: water cycle; NC: nutrient cycling; PP: primary production; H: habitat; FW: freshwater; F: food; BC: biological control; HD: human disease; LA: leisure activities or ecotourism; SP: sense of place; R: religion or myth; CH: cultural heritage; A: aesthetical values.

The analyzed 114 cases where at least one SGD-ES can be identified with a direct social implication correspond to 96 different locations worldwide (Fig. 3). Nevertheless, there were vast areas of the planet where few SGD studies were performed and little scientific information is available on ES provided by SGD. These areas include the coast of Africa, South America, the Arabian Peninsula, Antarctica or the Indian subcontinent, which altogether represent less than 10% of the cases found in the review (Fig. 3). This distribution of case studies is mainly explained by the inherent bias in this search because most of the research conducting SGD studies is concentrated in specific areas (e.g., USA, Australia, Europe) and the selection of scientific publications written only in English.

4.1.1. *Supporting ecosystem services*

As one process involving the transference of water across the land-ocean interface, SGD has a role on the global *Water Cycle* (Church, 1996; Zhou et al., 2019), which is understood as a SGD-ES. During the 1960s, several studies were conducted to evaluate the fresh groundwater driven by SGD as part of the local water budget (Burdon and Papakis, 1961; Isbister, 1966; Muir, 1968; Newport and Haddor, 1963) and as part of the global budget that was estimated to represent 5% of surface runoff (Nace, 1967). Since then, other attempts were performed to estimate the fresh SGD contribution to the water cycle (Church, 1996; Taniguchi, 2002; Zektser and Loaiciga, 1993), including the recent investigations that have estimated that the fresh component of SGD represents ~1.3% of river discharge (Zhou et al., 2019) or ~0.6% of the total freshwater into the global ocean (Luijendijk et al., 2020). However, when the saline or brackish component of SGD is integrated, SGD has a broader influence into the world oceans representing between 80% and 160% of the amount of freshwater entering the Atlantic Ocean from rivers (Moore et al., 2008), or up to 4 times taking also into account the Indo-Pacific Oceans (Kwon et al., 2014).

In addition to its relevance for the hydrological cycle, SGD also supplies nutrients from natural or anthropogenic sources into the coastal ocean (Basterretxea et al., 2010; Johannes, 1980; Johannes and Hearn, 1985; Lecher and Mackey, 2018; McClelland et al., 1997; Santos et al., 2021; Slomp and Van Cappellen, 2004; Valiela et al., 1990). Nutrients supplied to the coastal sea by SGD, which form part of the *nutrient cycling*, continue their cycle interacting with the biota. Indeed, microbiota (bacterioplankton or phytoplankton) are the first organisms to transform those nutrients and make them available for other secondary producers (Lecher and Mackey, 2018). One of the most important processes in this nutrient cycling is to support the *primary production.* Many publications have related the role of SGD-driven nutrients to support higher productivity of phytoplankton blooms in coastal areas (Garcés et al., 2011; Machado and Imberger, 2014; Troccoli-Ghinaglia et al., 2010), cyanobacteria blooms (Blanco et al., 2011, 2008; Umezawa et al., 2002), macroalgae blooms (Amato et al., 2016; Derse et al., 2007; Ouisse et al., 2011; Yoshioka et al., 2016) or enhance macrophytes spatial coverage, leaf growth and meadow productivity (Carruthers et al., 2005; Dadhich et al., 2017; Darnell and Dunton, 2017; Kamermans et al., 2002; Peterson et al., 2012). Primary producers, from both the benthos and the water column, are able to incorporate inorganic nutrients into the trophic chain upholding nutrient cycling and food for more complex organisms (Lecher and Mackey, 2018). Isotopic analysis of ∂^{15}N and ∂^{13}C and N:P ratio have allowed identifying the direct uptake of inorganic nutrients by phytoplankton (e.g., diatoms and dinoflagellates) and macrophytes (Amato et al., 2016; Andrisoa et al., 2019b; Hata et al., 2016; Lecher and Mackey, 2018; McClelland et al., 1997). The utilized nutrients can then be transferred to zooplankton and to higher trophic levels in the food web (Lecher and Mackey, 2018).

The discharge of groundwater to the coastal sea can also modify or stabilize temperature, pH, salinity or water transparency conditions of the receiving water bodies, which might be essential to maintain or support many coastal *habitats* and ecosystems (e.g., coral reefs or seagrass meadows). However, the effects of SGD also may harm those habitats. For instance, SGD from karst springs may reduce the net calcification capacity of corals, and therefore the extension of habitat that they can provide to other species by provisioning high amounts of CO_2 stabilizing low pH (Álvarez-Góngora and Herrera-Silveira, 2006; Crook et al., 2012; Troccoli-Ghinaglia et al., 2010). Also the low salinities provided by fresh SGD were reported to reduce the diversity and richness in coral reefs (Lirman et al., 2003) and meiofaunal communities (Kotwicki et al., 2014; Migné et al., 2011). Contrarily, diatoms (Welti et al., 2015), cyanobacteria from benthic communities (Lee and Kim, 2007) and juvenile snails (*Lobatus gigas*) showed to find stable habitats due to freshwater conditions supported by SGD (Stieglitz and Dujon, 2017). Moreover, SGD inputs from karstic springs showed to represent the principal source of freshwater to some coastal lagoons, contributing to maintain them under non-hypersaline conditions for most of the year and thus playing a relevant role for coastal lagoon ecosystem functioning (Rodellas et al., 2018; Stieglitz et al., 2013).

SGD can also contribute to stabilize temperatures of coastal ecosystems, which might have a key role on the maintenance or weakening of coastal habitats. On the one hand, SGD-driven inputs of nutrients accompanied with stable temperatures promote primary production and support more complex organisms across the trophic chain and richer habitats. Such effects are known to create biological hotspots, where biomass, richness, diversity, net community production and ecosystem complexity are enhanced (Encarnação et al., 2015; Foley, 2018; Garcés et al., 2011; Utsunomiya et al., 2017). For example, in Salses - Leucate coastal lagoon (France) the higher temperature and nutrients availability related to SGD were correlated to the higher growth of Mediterranean mussels (*M. galloprovincialis*) (Andrisoa et al., 2019a). On the other hand, the same constant supply of nutrients and stable temperature can enhance the dominance of opportunistic species, which can displace others or affect them by cascading effect (Lecher and Mackey, 2018). The dominance of opportunistic species inevitably reduces richness and diversity in some coastal ecosystem. These consequences were studied in coral reefs of Japan (Blanco et al., 2008) and benthic communities in Delaware (USA) (Miller and Ullman, 2004), where zones directly influenced by SGD had communities with less ecological richness than others which were not influenced.

In addition, such processes can support Harmful Algal Blooms (HAB's) such as red tides, brown tides, cyanobacteria blooms or macroalgal green tides (e.g., Gobler and Sañudo-Wilhelmy, 2001; Hu et al., 2006; Hwang et al., 2005; Kwon et al., 2017; Lapointe, 1997; Lapointe et al., 2005; Laroche et al., 1997; Lee et al., 2009; Su et al., 2012) enhancing primary production but at the same time destroying the habitat of other species and ecosystems. The presence of HAB's supported by SGD-driven anthropogenic nutrients may have cascading effects to entire ecosystems, as the massive kills observed in the USA (Hu et al., 2006) and South Korea (Lee et al., 2010). The presence of dense phytoplankton blooms was reported to reduce light availability for benthic communities, in seagrass meadows (Short and Burdick, 1996) and coral reefs (Laroche et al., 1997; Richardson et al., 2017). Similar effects were produced by macroalgal blooms in coral reefs and turf algae in Hawaii, where the massive presence of those organisms covering the benthos has prompted the habitat to change (Amato et al., 2016).

4.1.2. *Provisioning ecosystem services*

Freshwater resources in coastal areas, particularly in arid or semi-arid zones, are of vital importance to any type of human settlement. Several studies documented the use of the freshwater component of SGD since the Phoenician times along the Mediterranean coasts (Kohout, 1966) and the ancient Rapa Nui civilization in Easter Island (Brosnan et al., 2018). In this regard, SGD has been intensively studied in several countries (e.g., southern coasts of France, Lebanon, Libya and Greece) to be exploited as a freshwater resource (Bakalowicz, 2018; Fleury et al., 2007; Mijatović, 2006; UNESCO, 2004). Fresh SGD is also used for other purposes, such as agriculture or livestock (Moosdorf and Oehler, 2017; Pereira et al., 1996). Still today, the fresh SGD is used for drinking, laundering or hygiene in several islands of Indonesia (e.g., Java, Lombok, Bali) (Moosdorf and Oehler, 2017) or built-in tap water facilities in the Mediterranean (e.g., Trieste bay, Italy; Port-Miou, France; Chekka, Lebanon; or Benghazi, Libya) (Mijatović, 2006). This SGD-ES can be crucial in semi-arid regions, which are strongly dependent on groundwater resources, especially under climate change forecasts that consider these regions as hot spots due to their sensitivity to climatic disturbances (IPCC, 2014). Forecasting models predict changes in rainfall seasonality patterns, an increase of evapotranspiration and a declining of groundwater reserves (IPCC, 2007). Aside from its importance as a direct good, fresh SGD has numerous synergies with supporting, regulating and cultural ES provided by SGD that are explored in the following sections (see 4.1.1, 4.1.3 and 4.1.4).

The provisioning of *food* through fishing or aquaculture activities is another ES provided by SGD (UNEP-MAP, 2015). SGD can play a key role on the support of productivity and functioning of coastal ecosystems (see 4.1.1), resulting in favorable habitat conditions to provision food to human societies. This creates a synergy between the supporting ES and this provisioning ES. Due to the enhancement on high productivity derived from the SGD-driven nutrients, secondary producers can grow, habitats and ecosystems can develop, and ultimately, human consumed species are present in those areas. Sites where SGD contributes to provisioning of food include algae aquaculture in Hawaii (Duarte et al., 2010; Pongkijvorasin et al., 2010), crustacea in Portugal (Silva et al., 2012), fish in Japan (Burnett et al., 2018, 2015; Fujita et al., 2019; Utsunomiya et al., 2017), mussels in south France (Andrisoa et al., 2019a), or oysters in China and USA (Chen et al., 2018; Spalt et al., 2020). SGD can also endanger the provision of food through the supply of pollutants by deteriorating the ecosystems that support aquaculture and fisheries and endangering local communities' health (Erostate et al., 2020). SGD can also introduce large amounts of metals from mining activities (Alorda-Kleinglass et al., 2019; Trezzi et al., 2016), which can act as pollutants instead of micronutrients, affecting primary producers and subsequently higher trophic levels used for human consumption. In addition, SGD-driven HAB's may not directly affect humans but their toxins can be accumulated in food that then will be consumed by humans (Lee et al., 2010).

4.1.3. *Regulating ecosystem services*

Biological control has been observed where fresh SGD influences the salinity levels of coastal areas. This process regulates the presence of species depending on their tolerance to low salinities as in Okinawa (Japan) (Blanco et al., 2008), Florida (USA) (Lirman et al., 2003) and Roscoff Aber Bay (France) (Migné et al., 2011). This process, often referred to as zonation (Kohout and Kolipinski, 1967), can also be produced by the reduction of the pH due to the influence of SGD and, therefore, the difficulties of some organisms with external carbonate or silicate structures to live (e.g., coral reefs or foraminifera) (Crook et al., 2013, 2012; Martinez et al., 2018; Prouty et al., 2017). For example, it was recognized that juvenile teleost fish had higher growth rates in coastal GDE (Lilkendey et al., 2019) or that the higher temperatures in winter supported by SGD provided shelter for other species (Miller and Ullman, 2004). SGD may thus concurrently provide habitat (supporting ES) and biological control (regulating ES). Excessive nutrient or contaminants loadings supplied by SGD can enable the presence of those species that are adapted to these live conditions (e.g., *Ulva spp.*) (Hwang et al., 2005; Kwon et al., 2017; Yoshioka et al., 2016) or opportunistic species of diatoms, dinoflagellates or cyanobacteria (Blanco et al., 2011). SGD investigations showed that eelgrass living in coastal GDE can have fewer herbivory organisms (Peterson et al., 2012). Turtle grass (*Thalassia testudinum*) can change their biological strategy, under high nutrient levels, by not growing flowers and developing bigger leaves (Darnell and Dunton, 2017), while the Australian dhufish (*Glaucosoma hebraicum)* can use low salinities to remove parasites (Pironet and Jones, 2000). Humans take direct advantage of such sites, where the abundance of certain species are a source of food to catch fish in Australia (Stieglitz, 2005), or create aquaculture in Japan (Hosono et al., 2012; Utsunomiya et al., 2017).

Human diseases can also be introduced into the coastal waters by bacteria or viruses supplied by SGD. Polluting microorganisms can be driven by groundwater (Abaya et al., 2018; De Sieyes et al., 2016; Paytan et al., 2004; Yau et al., 2014), delivering bacterial foreign communities (Knee et al., 2008) or viruses (Futch et al., 2010) into the coastal environments. Either from leaks or spills from septic tanks or injection wells from water treatment plants, sewage can infiltrate in coastal aquifers polluting groundwater with high concentrations of fecal bacteria and viruses, which can be transported by SGD to the coastal seawater. In different study sites in California (De Sieyes et al., 2016; Paytan et al., 2004; Yau et al., 2014), Florida (Futch et al., 2010) and Hawaii (Knee et al., 2008) it was demonstrated that zones influenced by SGD from coastal aquifers contaminated with wastewater, had elevated levels of Fecal Indicator Bacteria (FIB). According to Yau et al. (2014), the discharge of fecal bacteria into Avalon beach (California, USA) could be directly related to certain diseases among swimmers who entered in contact with the SGD influenced zones.

The provisioning of freshwater is also used to reduce human diseases and improve hygiene. Moosdorf and Oehler (2017) reported the use of groundwater to make laundry, bathing or to heal wounds in Indonesia, Fiji and Mozambique. The use of SGD in these societies contributes to the citizens health via two ways: directly, by using SGD for hygiene purposes, and indirectly, by allowing saving their cleaner freshwater resources only for drinking purposes. SGD can also represent a pathway delivering pollutants into the coastal ocean from anthropogenic activities and settlements (e.g., cities, harbors or mines), which could represent a great threat towards people's health that have not yet been evaluated. These pollutants supplied by SGD include nutrients, which can trigger HABs that may liberate toxins and can pollute commercial species of shellfish (Anderson et al., 2000; Laroche et al., 1997), and finally endanger the health of the consumers; metals, which can accumulate on commercial mussel species (e.g., *M. edulis* grown in SGD-influenced sites had twice the concertation of Hg on soft tissue compared to non-SGD influenced mussels (Laurier et al., 2007); as well as other contaminants such as radionuclides from nuclear power plant accidents (Fukushima, Japan) (Sanial et al., 2017) or from high naturally occurring radioactive areas, which can bioaccumulate in biota (Garcia-Orellana et al., 2013; 2016). Other studies have reported that SGD can also supply pharmaceutical and caffeine residues (CEC's) (Knee et al., 2010; Szymczycha et al., 2020), pesticides and persistent organic pollutants (POP's) (Dzierzbicka-Głowacka et al., 2019; Pavlidou et al., 2014) to the coastal ocean.

4.1.4. *Cultural ecosystem services*

Recreational activities or Ecotourism resulting from the existence of SGD are mainly linked to the presence of submarine springs (Burnett et al., 2015; Lougheed, 2006; Moosdorf and Oehler, 2017). Sites-influenced by submarine springs receive the attention of divers and swimmers due to the existence of a biodiversity hotspot supported and regulated by SGD. A clear example of the cultural relevance that these springs have is the case of La Source ("The Spring", in French) in Tahiti, where leisure companies have established guided routes to visit SGD-influenced sites as a result of their enhanced biodiversity (Moosdorf and Oehler, 2017). Other recreational activities linked to the occurrence of SGD can also be found through grey literature sources. On the coasts of the Balearic Islands (western Mediterranean Sea), several caves in karstified limestone massifs influenced by SGD are visited by divers, swimmers, and recreational underwater fisherman due to the specific low light biodiversity that lives in them (Rützler, 1996). During the cold winters of Canada, it was also reported that a polynya was maintained due to the discharge of groundwater with higher temperatures, allowing Arctic shipping (Sadler and Serson, 1980). SGD can also affect recreational activities, particularly when SGD-driven HAB's are occurring or when swimming beaches are closed for sanitary reasons due to the presence of FIB derived from SGD inputs (Yau et al., 2014). Although less frequent, it was observed that navigation of recreational small boats was compromised along Croatian shorelines as result of point-sourced large-flow groundwater discharge (Alfirevic, 1966; Keller, 1963).

Several toponyms along world shorelines were named after the occurrence of SGD, especially in areas where groundwater inputs represented a freshwater resource or lead to biological hotspots, giving people a *sense of place*. Examples of such particularity are: “Olhos de Água” in Portugal (“eyes of water” in Portuguese) (Carvalho et al., 2013; Encarnação et al., 2015; Foley, 2018), “Punalu'u” in Hawaii (USA) (“diving spring” in Hawaiian language) (Moosdorf and Oehler, 2017), “Es Dolç” or “Sa Font de Sa Cala” in the Balearic Islands (“the freshwater” and “the spring of the cove” in Catalan) (Tovar-Sánchez et al., 2014). Symbolic constructions and places were also built in areas linked to SGD. Some human settlements located in coastal areas with a semi-arid climate were built near SGD springs because they depended on the freshwater resource provided by SGD. These sources of freshwater were often protected or venerated through the construction of defense, strategic or mystical buildings. Examples of such are the Cala Figuera in Maó (Menorca, Balearic Islands, western Mediterranean), where the Romans already exploited a spring with the construction of a nymphaeum and ships stopped to load freshwater (Murray-Mas, 2006). In Rapa Nui (Easter Island), it is believed that the original civilization that built the famous face statues (moai) around the island were able to survive thanks to the construction of wells and “punas” (dams) taking advantage of the fresh SGD, which created a sense of belonging to the place (Brosnan et al., 2018). The Yokokujo Castle of Hiji, Ohita Prefecture (Japan), was built at the shores of the beach to allow the catchment of the Marbled flounder (*Pseudopreulonectes yokohamae*), a highly-prized fish species that thrives in a SGD-dependent ecosystem (Shoji and Tominaga, 2018).

SGD is also related to *religion or myths*, both through iconic buildings and legends. A clear example is the Hindu temple Tanah Lot, Bali (Indonesia), which was built to protect a spring that was magically moved from inland to the sea (Lubis and Bakti, 2013; Moosdorf and Oehler, 2017). The ancient Greek civilization also created different myths and legends related to the occurrence of SGD. According to the ancient Greek geographer Pausanias (2.5.3), an old legendary tale explained how the Turkish River Meander went under the Aegean seabed to the surface 390 km away, in the northeast Peloponnese (Clendenon, 2009). This same legend, according to Strabo (6.2.271) was originated by the Greek lyric poet Ibycus around the 6th century B.C. (Clendenon, 2009). Pausanias (8:VII) also described how the inhabitants of Argos made sacrifices to Poseidon in the location of a SGD spring, currently named Kiveri spring (Leake, 1830; Moosdorf and Oehler, 2017). One of the best-known and oldest myths related to SGD is the story of the spring nymph Arethusa and the river god Alpheus, originated in the 8th century BCE (Bilić, 2009; Clendenon, 2009). In this Greek myth, Arethusa transformed into water and traveled underground through the Ionian Sea to escape from Alpheus's amorous advances. Arethusa resurfaced as freshwater spring in Syracuse (Sicily, Italy) together with Alpheus that had followed her and traveled the same submarine journey, remaining always fresh by never mixing with the sea (Clendenon, 2009).

These SGD-linked myths, stories, buildings and villages have become part of the current *Cultural Heritage*. Different cultures around the globe place high value to keep alive the old uses that SGD had for their ancestors. In Australia, the Aboriginal community of Kaurna finds an important part of their identity to the story of the ancient creator Tjilbruke, who wept for his nephew, and from his tears freshwater springs were created on the beach (Amery, 2016; Moosdorf and Oehler, 2017). In the Island of Kona, Hawaii (USA), many of the algae (e.g., limu manauea (*Gracilaria coronopifolia*)), which are harvested in sites influenced by SGD, are valued by the indigenous cultures for centuries (Duarte et al., 2010; Pongkijvorasin et al., 2010). Fishing spots related to SGD has been part of communities' traditional knowledge, which has passed across fishers' generations. Examples of SGD-linked fishing hotspots that can be considered cultural heritage include the “wonky holes” of the Great Coral Reef in Australia (Stieglitz, 2005), the “Mud Hole” in Florida (USA) (Kohout et al., 1979) and in the Yucatan Peninsula (Mexico) (Stieglitz and Dujon, 2017).

Additionally, Zektser et al. (1973) mention submarine springs as “the most spectacular manifestation of groundwater discharge to the seas”, indicating the *aesthetic value* of SGD. Submarine springs or SGD continue to inspire and motivate new generations of authors and researchers. The inspiration has gone from one of the first documents that explained SGD, where Aristotle on his treatise “Meteorology” (ca. 350 BCE), explains how karstic streams sink underground and travel short distances to discharge into sea (Clendenon, 2009), to today's latest publications on SGD. This aesthetical value of SGD has reached ancient poets as Lucretius or geographers as Pausanias and Strabo, to inspire songs in the Hawaiian folklore (Pukui, 1949). Nowadays, people continue to find the aesthetic value to SGD by visiting submarine springs on a scuba diving experiences or by discovering new features in new SGD investigations.

4.2. SGD trade-offs

The ES provided by SGD and the synergies between them cannot be fully understood without a detailed consideration of the interactions of the different stakeholders from any coastal society with SGD-influenced ES. Therefore, trade-offs (i.e., the prioritization of one service in exchange of another one) play a key role in understanding the social implications of SGD. For example, if a community perceives SGD as a freshwater resource and decides to collect and use this water for their own consumption, this action could reduce the flux of water and solutes to the coastal ecosystem. In that case, the community will trade-off the provision of freshwater resource in exchange to reduce the regulating and supporting ES of SGD derived from the supply of water and nutrients to the ecosystem. This action might be in detriment of nearby coastal communities that could see their provision of food reduced (Duarte et al., 2010; Pongkijvorasin et al., 2010), or also see affected their cultural heritage if those consumed SGD dependent species formed part of their culture (McDermid et al., 2019). This example is summarized in Fig. 6, highlighting the synergies between the four categories of ES (blue double arrows) and the effects of a human decision that choses to trade-off most of the outcomes by just the provision of the freshwater (red arrows). Further trade-offs related with SGD-ES can become especially complex when economic, cultural or political interests are at stake. Thus, in order to achieve or maintain the well-being of a coastal community, policies and management strategies need to be developed considering the synergies and trade-offs between the different SGD-ES.

One of the main targets of the coastal policies and management strategies dealing with coastal ecosystem services is to guarantee the supply and shortage of materials or goods necessary for good life and economic sustainability (Costanza et al., 2017). In this regard, SGD has been used and managed for centuries as a freshwater resource. Nowadays, climate change-induced drought and high anthropogenic pressure (e.g., groundwater withdrawal, irrigation) makes management of fresh SGD more necessary (Stigter et al., 2014; UNEP/MAP, 2012). This is critical for those societies that have scarce supplies of freshwater (e.g., North African and Middle East coasts). However, management strategies rarely take trade-offs into account. Research findings have assessed, conceptually and economically, the impacts of management interventions aimed to exploit such resources in these regions. For example, Ayoub et al. (2002) developed a cost-benefit survey in order to identify the viability of exploiting offshore SGD through a pumping freshwater project in Cheka Bay (Lebanon). They found that the exploitation of fresh SGD would drastically reduce the marine zonation around the submarine springs, and consequently the availability of commercial fish species, affecting the well-being of fishermen communities. In contrast, local citizens and industries would gain an additional volume of freshwater and therefore security for their future good living.

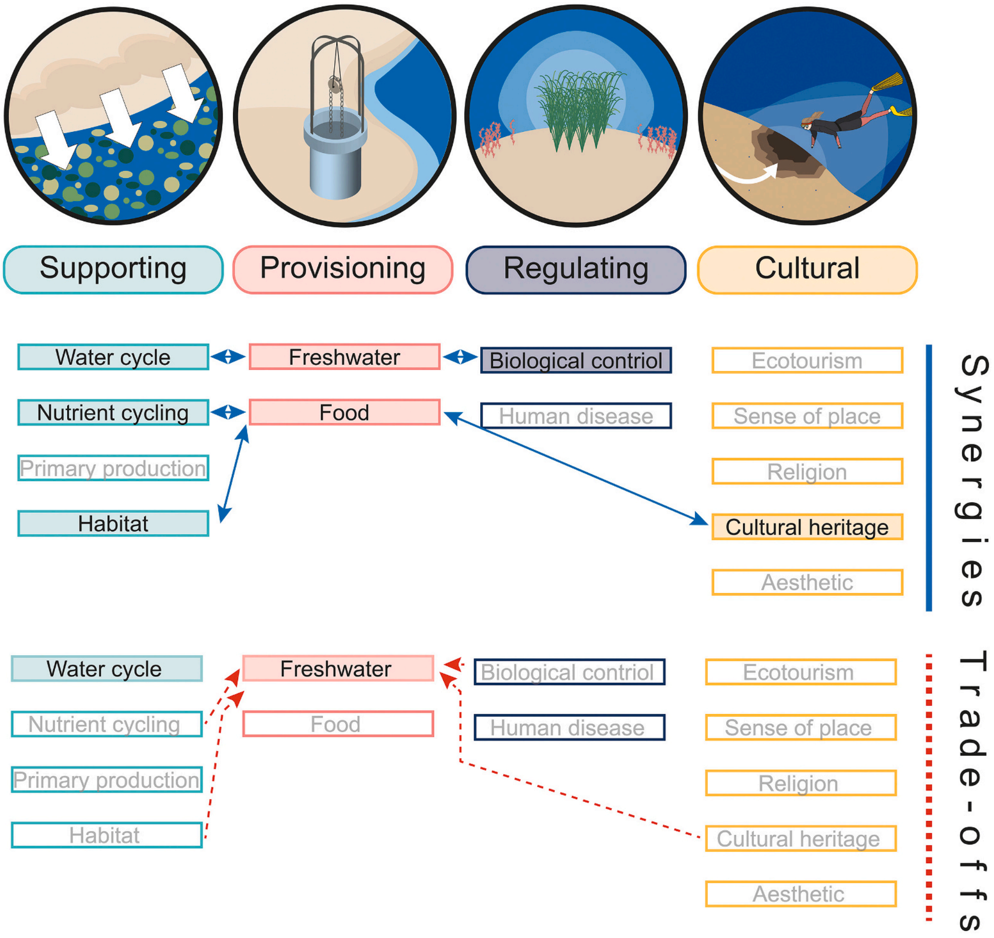

Fig. 6. Diagram exemplifying how the SGD-ES framework is applied to a hypothetical case described in the text. Filled boxes correspond to outcomes identified and empty boxes to outcomes that have been removed or do not exist. Blue double arrows correspond to synergies between outcomes and red arrows correspond to trade-offs between outcomes that were preferred (filled box) in exchange of those renounced (empty box). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Other concerning trade-offs that exist between freshwater and SGD-dependent commercial species have been described for algae in Hawaii (USA) (Duarte et al., 2010; Pongkijvorasin et al., 2010) and fish in Obama Bay (Japan) (Burnett et al., 2018, 2015). In these cases, there were direct linkages between the use of groundwater as a freshwater resource and the exploitation of nearshore biomass productivity fueled by SGD, where a gain of one goes in detriment of the other. Guaranteeing a minimum provision of food stock might require significantly decreasing groundwater extraction (Duarte et al., 2010; Pongkijvorasin et al., 2010). On the contrary, according to another investigation in Japan (Burnett et al., 2018), the economic benefits that provisioning of groundwater might provide, in terms of freshwater stock, could be greater than the losses to the nearshore fisheries. The management strategy implemented should thus deal with the dichotomy between the benefits of provisioning freshwater and the benefits of provisioning food stock.

Anthropogenic actions devoted to improve the management of hydrological or biological coastal resources can also indirectly affect other ES (e.g., the construction of subterranean dams, grout curtains, conducts or pipes, and tapping water plants) (Mijatović, 2006; Tamborski et al., 2020; Tardieu and Poité, 2015). Similarly, in the exploitation of brackish submarine springs as a freshwater resource, desalinization of mined groundwater is required and the brine produced can have hazardous consequences for the social-ecological system when it is discharged into the sea (e.g., destruction of the surrounding habitats and potential commercial species, Bakken et al., 2012).

Coastal management strategies shaping the SGD-ES can lead to confrontation between the different stakeholders involved. When one individual or group perceives that their gains on the SGD-ES are threatened by another individual or group that is also exploiting the same resource, confrontation can converge into a social conflict. Access to freshwater is the ES provided by SGD that is more likely to lead to conflicts, due to its importance for human survival. Due to the political need and willingness to explore SGD as an option to face freshwater shortages, fresh groundwater is widely studied around the Mediterranean (Ayoub et al., 2002; Bakalowicz, 2018; Bakken et al., 2012; Fleury et al., 2007; Ghannam et al., 1998; Mijatović, 2006; Tardieu and Poité, 2015). In Hawaii (USA), serious political battles are already raging with respect to terrestrial anthropogenic impacts on nearshore environments related to the supply of terrestrial anthropogenic pollutants through SGD (Duarte et al., 2010; Pongkijvorasin et al., 2010). These impacts can in turn effect the algae aquaculture, feeding social conflicts because the cultural ES of the algae aquaculture are deeply rooted into the Hawaiian community (McDermid et al., 2019). On the one side, most political parties understand that groundwater extraction reduce SGD and can impact coastal marine ecosystems. On the opposite side, landowners and developers insist that the effects of reducing SGD in exchange of the freshwater supply are irrelevant. Such discrepancy between both sides is what leads to a conflict towards the future management of this coastal society (Duarte et al., 2010). Recently, for the first time, the US Supreme Court has ruled in favor to protect the connection between the coastal aquifer and the coastal ocean (SGD) (Cornwall, 2020). The case was based on the demonstration that the injection of wastewater effluents into the coastal aquifer directly affected the coastal ecosystem (Glenn et al., 2013) and should be protected according to the Clean Water Act. That sets a new base on the social conflicts induced by SGD (Santos et al., 2021).

5. Future perspectives

This review has also identified that studies on direct ES (provisioning, regulating or cultural ES) are vastly outnumbered by publications related to supporting ES. This is a consequence of the large effort made during the last 40 years on the SGD research field to demonstrate the importance of this process on the hydrological and biogeochemical cycles. The consulted scientific literature has also evidenced lack of attention towards potential impacts and benefits that supporting ES have on coastal societies or other provisioning, regulating or cultural ES. In this regard, future studies on ES provided by SGD should consider expanding their research to address how their findings could have potential social implications or be related to any of the other SGD-ES categories and outcomes. There is thus a need on the SGD research field to develop more interdisciplinary studies involving social scientists, hydrologists and oceanographers to work together.

5.1. Exploration of grey literature

This review reveals that the published scientific literature on Submarine Groundwater Discharge has neglected its social dimension, particularly regarding those cultural Ecosystem Services provided by SGD. Rather than being reported in conventional scientific research, many of the cultural ES related to SGD have only been published through grey literature publications. This grey literature can be defined as "all documents except journal articles that appear in widely known, easily accessible electronic databases will be considered grey literature" (Rothstein and Hopewell, 2009). These publications are generally written in local languages, and thus we acknowledge that by only focusing on English written scientific publications, this review has excluded both academic publications in other languages and grey literature. Gathering together all the available information on social implications of SGD is challenging both because local and regional documents are not easily accessible and also because this research requires involving people proficient with those local languages. As an example to highlight this complexity, there are more than 85 languages spoken in the Mediterranean region. Focusing on the 44 submarine springs around the Mediterranean mentioned by Gilli (2020), the systematic review conducted in this study only allowed identifying direct ES (providing, regulating or cultural) in two sites. If literature available online (both scientific and non-scientific) is screened using English, Italian, French, Catalan and Spanish (languages in which the authors are proficient) the number of sites with reported ES increases to 14. For example, in France, the spring of Estramar is related to leisure activities such as fishing and speleology. The springs of Port-Miou (France) are documented as an important freshwater resource for human consumption and also used as a diving spot by different companies. In Italy, the spring of Galeso has become a Tourist attraction to go and see the "citri", terminology used to describe the bubbling pools inside the sea surface that SGD creates under vigorous flow. Widening the search possibilities (e.g., more languages, including paper-based documents) would have surely resulted in a significant increase of the reported ES. A comprehensive understanding of the ES provided by SGD should thus try to incorporate this locally-based knowledge, and this can only be attained by conducting local investigations that focus on social and cultural perceptions and local people's experience and knowledge. Further research should thus attempt to incorporate this grey literature, dealing with the challenge of tackling different languages in which most of the information is provided. In this regard, engaging citizens and communities (citizen science) to inform about these SGD-social links can decisively contribute to produce a comprehensive understanding of social implications of SGD.

5.2. A global change perspective

This study provides, for the first time, an overview and classification of the Ecosystem Services linked to SGD (SGD-ES), as well as the synergies and trade-offs between different SGD-ES. However, the scarcity of literature relating SGD to ES and the fact that the results obtained provide a point-in-time view, means that we only understand a small fraction of the current interactions between coastal dwellers and SGD-ES. Importantly, the links between SGD and ES are of a dynamic nature, implying that their synergies and trade-offs are likely to continuously evolve together with societies and the coastal environment, both at a local, regional and global scale. This is particularly relevant in the actual context of global change. In this regard, the overpopulation of coastal areas is likely to continue increasing, rising the demand of freshwater and therefore the provisioning SGD-ES. In addition, fresh resources would be prejudiced by the likely decrease of mean precipitations, due to climate change, and increase of evapotranspiration in many mid-latitude and subtropical regions (IPCC, 2014). Such change would involve a major reduction on the fresh SGD input into the oceans (Kundzewicz and Döll, 2009; Stigter et al., 2014). Sea level rise is also expected to reach up to ~0.8 m by 2100 (IPCC, 2014), affecting large coastal areas and reducing the hydrologic gradient and consequently the quantity of fresh SGD (Robinson et al., 2018). Moreover, important disruptions are expected on the biogeochemical cycles due to contamination of multiple anthropogenic factors (e.g., the agriculture nutrient pollution of aquifers, mining and industrial wastes, growing cities waste waters) (Lafortezza and Chen, 2016). Such changes on coastal aquifers will directly affect the quality of SGD inflowing into the coastal ocean (e.g., fluxes of nutrients, trace metals, contaminants) and thus the role of SGD on the nutrient cycle, productivity or habitat support. Sea level rise will also likely affect nutrient cycling and productivity in coastal areas, mobilize terrestrial anthropogenic pollutants to the sea and critically impact those habitats with low-salinity conditions that are supported by SGD (Danielopol et al., 2003; Michael et al., 2013; Pope et al., 2011). Global change will thus definitely impact the supporting Ecosystem Services supported by SGD, including water cycle, nutrient cycle, primary production or habitats. Once the supporting ES are affected, all the other dependent ES could be affected by cascading effects. For instance, the reduction of the habitats, due to the lack of freshwater, could make disappear the biological control, reduce the amount of food due to a reduction of productivity or displacement of species. In addition, some of the cultural ES could disappear or be endangered (e.g., leisure activities related to the fresh SGD). Therefore, in order to develop new management programs to preserve SGD-ES for next generations, it is necessary to study the evolution of SGD-ES under the current global change scenario, with special emphasis on new synergies and trade-offs.

5.3. Valuation of submarine groundwater discharge ecosystem services

Ecosystem Services where born under the question of "how much are nature's services worth?" (Westman, 1977). Since then there was a pursue towards valuing those services, until Daily (1997) and Costanza et al. (1997) came up with their respective publications, boosting the research on Ecosystem Services during more than two decades (Costanza et al., 2017). Since then, the economic value of world ecosystem services was initially estimated to represent trillions of USD (10^{12}) (Costanza et al., 1997; Pimm, 1997) and researchers continue to look for new techniques and categorizations to refine these evaluations (Costanza et al., 2017). However, there are ES that can hardly be economically valued, such as the supporting or cultural ES. Therefore, alternative frameworks that can integrate the non-monetary values of the SGD-ES (TEEB, 2012) might be more accurate to study these services and are being applied worldwide.

Ecosystem Services have already been valued in seagrass meadows, salt marshes, mangroves and coastal fisheries (Himes-Cornell et al., 2018; Tuya et al., 2014). In the SGD literature, most studies normally evidenced the importance of SGD indirectly relating it to the fisheries or economical activities that surrounded the discharging areas. However, to our knowledge, SGD has only been valued in two studies, where the authors estimated the economic value of i) fresh SGD for human consumption and SGD-dependent commercial algae species in Hawaii (Duarte et al., 2010; Pongkijvorasin et al., 2010) and ii) fish supported by SGD-driven nutrient inputs in Japan (Burnett et al., 2018, 2015). Although there remains great ambiguity on which is the value of SGD-ES (Burnett et al., 2018, 2015; Duarte et al., 2010; Pongkijvorasin et al., 2010), this study offers an opportunity for natural and social scientists to work together and develop monetary and non-monetary approaches to estimate SGD-ES values which results can support and guide future management and policies for the evaluation and preservation of Ecosystem Services supported by Submarine Groundwater Discharge.

6. Conclusions

This study reviews the existing knowledge on the social implications of Submarine Groundwater Discharge (SGD) from an ecosystem services perspective. It also offers for the first time a conceptual and analytical framework to identify and classify the ecosystem services provided by SGD and their effects on local societies' well-being based on the Millennium Ecosystem Assessment (MEA, 2005). From the use of SGD as a water resource to its cultural influence, this process and its zones of influence (coastal GDE) has proven to be deeply rooted in many coastal societies. Worldwide, most of the described ES in the scientific literature in English are related to the supporting and provisioning categories. However, it has been proven that SGD-ES are fundamental for coastal societies in all four categories (Supporting, Provisioning, Regulating and Cultural), even though regulating and cultural ES have not had much attention until now. Moreover, those identified SGD-ES in the academic literature have also shown to rarely be in a win-win scenario. Contrarily, in most studies there can be identified strong synergies between the different ES categories that normally have to end into a trade-off scenario. These trade-offs can develop into a social confrontation or even conflicts, which require further interventions in terms of policies and management strategies.

In addition, it is important to consider that, at local and regional scales, coastal services linked to SGD have a key role for the survival and maintenance of many coastal societies and their well-being, and even more in the current context of climate change. Therefore, this line of research offers the opportunity to explore the different role of SGD regarding societal well-being to better understand those relations from the lenses of interdisciplinarity. This study contributes thus to bridge the gap between natural and social research on the topic of SGD. Unraveling the ES derived to SGD offers an opportunity for new academic insights as well as novel evidence and knowledge for managers and policymakers for the preservation and management of coastal ecosystems while upholding the well-being of the coastal societies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors acknowledge the financial support of the Spanish Ministry of Science, Innovation and Universities, through the “Maria de Maeztu” programme for Units of Excellence (CEX2019-000940-M), the Generalitat de Catalunya (MERS; 2017 SGR – 1588) and the project OPAL (PID2019-110311RB-C21). We would like to thank all the colleagues from the Grup de Recerca en Radioactivitat Ambiental de Barcelona (Universitat Autònoma de Barcelona). A. Alorda-Kleinglass acknowledges financial support from ICTA “Unit of Excellence” (MinECo, MDM2015-0552-17-1) and PhD fellowship, BES-2017-080740. I. Ruiz-Mallén acknowledges financial support from the Spanish government's Research Agency through a “Ramón y Cajal” research fellowship (RYC-2015-17676). V. Rodellas acknowledges financial support from the Beatriu de Pinós postdoctoral program of the Generalitat de Catalunya autonomous government (2019-BP-00241). M. Diego-Feliu acknowledges the economic support from the FI-2017 fellowships of the Generalitat de Catalunya autonomous government (2017FI_B_00365). The authors would also like to acknowledge the help and financial support provided by the Foundation Iniciatives del Mediterrani. Also, the authors deeply appreciate the comments and revisions done by Dr. J. Tamborski and Professor S. Rossi. Finally, the authors thank the proofreading by Ruby and Tania Easton.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.earscirev.2021.103742.

References

Abaya, L.M., Wiegner, T.N., Beets, J.P., Colbert, S.L., Carlson, M., Kramer, K.L., 2018. Spatial distribution of sewage pollution on a Hawaiian coral reef. Mar. Pollut. Bull. 130, 335–347. https://doi.org/10.1016/j.marpolbul.2018.03.028.

Alder, J., Arthurton, R., Ash, N., 2006. Marine and coastal ecosystems and human well-being. In: United Nations Environmental Programme. Nairobi, Kenya.

Alfirevic, S., 1966. Les Sources Sous-Marines de la baie de Kastela; Morphologie, Structure Hydrologique, Conditions Hydrogeologiques, Relations Geotectoniques.

Alorda-Kleinglass, A., Garcia-Orellana, J., Rodellas, V., Cerdà-Domènech, M., Tovar-Sánchez, A., Diego-Feliu, M., Trezzi, G., Sánchez-Quilez, D., Sanchez-Vidal, A., Canals, M., 2019. Remobilization of dissolved metals from a coastal mine tailing deposit driven by groundwater discharge and porewater exchange. Sci. Total Environ. 688, 1359–1372. https://doi.org/10.1016/j.scitotenv.2019.06.224.

Álvarez-Góngora, C., Herrera-Silveira, J.A., 2006. Variations of phytoplankton community structure related to water quality trends in a tropical karstic coastal zone. Mar. Pollut. Bull. 52, 48–60. https://doi.org/10.1016/j.marpolbul.2005.08.006.

Amato, D.W., Bishop, J.M., Glenn, C.R., Dulai, H., Smith, C.M., 2016. Impact of submarine groundwater discharge on marine water quality and reef biota of Maui. PLoS One 11, 1–28. https://doi.org/10.1371/journal.pone.0165825.

Amery, R., 2016. Warraparna Kaurna!: Reclaiming an Australian Language. University of Adelaide Press.

Anderson, D.M., Hoagland, P., Kaoru, Y., White, A.W., 2000. Estimated Annual Economic Impacts from Harmful Algal Blooms (HABs) in the United States. https://doi.org/10.1575/1912/96.

Andrisoa, A., Lartaud, F., Rodellas, V., Neveu, I., Stieglitz, T.C., 2019a. Enhanced growth rates of the Mediterranean mussel in a coastal lagoon driven by groundwater inflow. Front. Mar. Sci. 6, 1–14. https://doi.org/10.3389/fmars.2019.00753.

Andrisoa, A., Stieglitz, T.C., Rodellas, V., Raimbault, P., 2019b. Primary production in coastal lagoons supported by groundwater discharge and porewater fluxes inferred from nitrogen and carbon isotope signatures. Mar. Chem. 210, 48–60. https://doi.org/10.1016/j.marchem.2019.03.003.

Ayoub, G., Khoury, R., Ghannam, J., Acra, A., Hamdar, B., 2002. Exploitation of submarine springs in Lebanon: assessment of potential. J. Water Supply Res. Technol. - AQUA 51, 47–64. https://doi.org/10.2166/aqua.2002.0005.

Bakalowicz, M., 2018. Coastal Karst groundwater in the mediterranean: a resource to be preferably exploited onshore, not from Karst Submarine springs. Geosciences 8. https://doi.org/10.3390/geosciences8070258.

Bakken, T.H., Ruden, F., Mangset, L.E., 2012. Submarine groundwater: a new concept for the supply of drinking water. Water Resour. Manag. 26, 1015–1026. https://doi.org/10.1007/s11269-011-9806-1.

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. Ecol. Monogr. 81 (2), 169–193.

Barnaud, C., Corbera, E., Muradian, R., Salliou, N., Sirami, C., Vialatte, A., Choisis, J.P., Dendoncker, N., Mathevet, R., Moreau, C., Reyes-García, V., Boada, M., Deconchat, M., Cibien, C., Garnier, S., Maneja, R., Antona, M., 2018. Ecosystem services, social interdependencies, and collective action: a conceptual framework. Ecol. Soc. 23 https://doi.org/10.5751/ES-09848-230115.

Basterretxea, G., Tovar-Sánchez, A., Beck, A.J., Masqué, P., Bokuniewicz, H.J., Coffey, R., Duarte, C.M., Garcia-Orellana, J., Garcia-Solsona, E., Martinez-Ribes, L., Vaquer-Sunyer, R., 2010. Submarine groundwater discharge to the coastal environment of a Mediterranean island (Majorca, Spain): ecosystem and biogeochemical significance. Ecosystems 13, 629–643. https://doi.org/10.1007/s10021-010-9334-5.

Bilić, T., 2009. The myth of alpheus and arethusa and open-sea voyages on the mediterranean—stellar navigation in antiquity. Int. J. Naut. Archaeol. 38, 116–132.

Blanco, A.C., Nadaoka, K., Yamamoto, T., 2008. Planktonic and benthic microalgal community composition as indicators of terrestrial influence on a fringing reef in Ishigaki Island, Southwest Japan. Mar. Environ. Res. 66, 520–535. https://doi.org/10.1016/j.marenvres.2008.08.005.

Blanco, A.C., Watanabe, A., Nadaoka, K., Motooka, S., Herrera, E.C., Yamamoto, T., 2011. Estimation of nearshore groundwater discharge and its potential effects on a fringing coral reef. Mar. Pollut. Bull. 62, 770–785. https://doi.org/10.1016/j.marpolbul.2011.01.005.

Bokuniewicz, H., 1980. Groundwater seepage into Great South Bay, New York. Estuar. Coast. Mar. Sci. 10, 437–444. https://doi.org/10.1016/S0302-3524(80)80122-8.

Brosnan, T., Becker, M.W., Lipo, C.P., 2018. Coastal groundwater discharge and the ancient inhabitants of Rapa Nui (Easter Island), Chile. Hydrogeol. J. 27, 519–534.

Burdon, D.J., Papakis, Ni, 1961. Methods of investigating the groundwater resources of the Parnassos-Ghiona limestones. Int. Assoc. Sci. Hydro 57, 143–159.

Burnett, W.C., Bokuniewicz, H., Huettel, M., Moore, W.S., Taniguchi, M., 2003. Groundwater and pore water inpunts to the coastal zone. Biogeochemistry 66, 3–33. https://doi.org/10.1023/B:BIOG.0000006066.21240.53.

Burnett, K.M., Wada, C., Endo, A., Taniguchi, M., 2015. The economic value of groundwater in Obama. J. Hydrol. Reg. Stud. 11, 44–52. https://doi.org/10.1016/j.ejrh.2015.10.002.

Burnett, K.M., Wada, C.A., Taniguchi, M., Sugimoto, R., Tahara, D., 2018. Evaluating the tradeoffs between groundwater pumping for snow-melting and nearshore fishery productivity in Obama City, Japan. Water 10, 1556. https://doi.org/10.3390/w10111556.

Carruthers, T.J.B., Van Tussenbroek, B.I., Dennison, W.C., 2005. Influence of submarine springs and wastewater on nutrient dynamics of Caribbean seagrass meadows. Estuar. Coast. Shelf Sci. 64, 191–199. https://doi.org/10.1016/j.ecss.2005.01.015.

Carvalho, L.F., Rocha, C., Fleming, A., Veiga-Pires, C., Aníbal, J., 2013. Interception of nutrient rich submarine groundwater discharge seepage on European temperate beaches by the acoel flatworm, Symsagittifera roscoffensis. Mar. Pollut. Bull. 75, 150–156. https://doi.org/10.1016/j.marpolbul.2013.07.045.

Chen, X., Lao, Y., Wang, J., Du, J., Liang, M., Yang, B., 2018. Submarine groundwater-borne nutrients in a tropical bay (Maowei Sea, China) and their impacts on the oyster aquaculture. Geochemistry, Geophys. Geosystems 19, 932–951. https://doi.org/10.1002/2017GC007330.

Cho, H.M., Kim, G., Kwon, E.Y., Moosdorf, N., Garcia-Orellana, J., Santos, I.R., 2018. Radium tracing nutrient inputs through submarine groundwater discharge in the global ocean. Sci. Rep. 8, 4–10. https://doi.org/10.1038/s41598-018-20806-2.

Church, T.M., 1996. An underground route for the water cycle. Nature 380, 579–580.

Clendenon, C., 2009. Ancient Greek hydromyths about the submarine transport of terrestrial fresh water through seabeds offshore of Karstic regions. Acta Carsologica 38, 293–302. https://doi.org/10.3986/ac.v38i2-3.129.

Cornwall, W., 2020. 'Hydrologists should be happy.' Big Supreme Court ruling bolsters groundwater science. Science (80-.). https://doi.org/10.1126/science.abc4292.

Costanza, R., D'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260.

Costanza, R., de Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., Grasso, M., 2017. Twenty years of ecosystem services: how far have we come and how far do we still need to go? Ecosyst. Serv. 28, 1–16. https://doi.org/10.1016/j.ecoser.2017.09.008.

Crook, E.D., Potts, D., Rebolledo-Vieyra, M., Hernandez, L., Paytan, A., 2012. Calcifying coral abundance near low-pH springs: implications for future ocean acidification. Coral Reefs 31, 239–245. https://doi.org/10.1007/s00338-011-0839-y.

Crook, E.D., Cohen, A., Rebolledo-Vieyra, M., Hernandez, L., Paytan, A., 2013. Reduced calcification and lack of acclimatization by coral colonies growing in areas of persistent natural acidification. Proc. Natl. Acad. Sci. U. S. A. 110, 11044–11049. https://doi.org/10.1073/pnas.1301589110.

Dadhich, A.P., Nadaoka, K., Motomura, Y., Watanabe, A., 2017. Potential impacts of land use change dynamics and submarine groundwater discharge on fringing reefs of Kuroshima Island, Japan. J. Coast. Conserv. 21, 245–254. https://doi.org/10.1007/s11852-017-0495-7.

Daily, G.C., 1997. Nature's Services. Island Press, Washington, DC.

Danielopol, D.L., Griebler, C., Gunatilaka, A., Notenboom, J., 2003. Present state and future prospects for groundwater ecosystems. Environ. Conserv. 30, 104–130. https://doi.org/10.1017/S0376892903000109.

Darnell, K.M., Dunton, K.H., 2017. Plasticity in turtle grass (*Thalassia testudinum*) flower production as a response to porewater nitrogen availability. Aquat. Bot. 138, 100–106. https://doi.org/10.1016/j.aquabot.2017.01.007.

De Sieyes, N.R., Russell, T.L., Brown, K.I., Mohanty, S.K., Boehm, A.B., 2016. Transport of enterococci and F+ coliphage through the saturated zone of the beach aquifer. J. Water Health 14, 26–38. https://doi.org/10.2166/wh.2015.290.

Derse, E., Knee, K.L., Wankel, S.D., Kendall, C., Berg, C.J., Paytan, A., 2007. Identifying sources of nitrogen to Hanalei Bay, Kauai, utilizing the nitrogen isotope signature of macroalgae. Environ. Sci. Technol. 41, 5217–5223. https://doi.org/10.1021/es0700449.

Duarte, T.K., Pongkijvorasin, S., Roumasset, J., Amato, D.W., Burnett, K.M., 2010. Optimal management of a Hawaiian coastal aquifer with nearshore marine ecological interactions. Water Resour. Res. 46, 1–12. https://doi.org/10.1029/2010WR009094.

Dzierzbicka-głowacka, L., Janecki, M., Dybowski, D., Szymczycha, B., Obarska-pempkowiak, H., Wojciechowska, E., Zima, P., Pietrzak, S., Pazikowska-sapota, G., Jaworska-szulc, B., Nowicki, A., Kłostowska, Ż., Szymkiewicz, A., Galer-tatarowicz, K., Wichorowski, M., Białoskórski, M., 2019. A new approach for investigating the impact of pesticides and nutrient flux from agricultural holdings and land-use structures on baltic sea coastal waters. Polish Journal of Environmental Studies 28, 2531–2539. https://doi.org/10.15244/pjoes/92524.

Encarnação, J., Leitão, F., Range, P., Piló, D., Chícharo, M.A., Chícharo, L., 2015. Local and temporal variations in near-shore macrobenthic communities associated with submarine groundwater discharges. Mar. Ecol. 36, 926–941. https://doi.org/10.1111/maec.12186.

Erostate, M., Huneau, F., Garel, E., Ghiotti, S., Vystavna, Y., Garrido, M., Pasqualini, V., 2020. Groundwater dependent ecosystems in coastal Mediterranean regions: characterization, challenges and management for their protection. Water Res. 172, 115461. https://doi.org/10.1016/j.watres.2019.115461.

Fleury, P., Bakalowicz, M., de Marsily, G., 2007. Submarine springs and coastal karst aquifers: a review. J. Hydrol. 339, 79–92. https://doi.org/10.1016/j.jhydrol.2007.03.009.

Foley, L.J., 2018. Karst-channelled intertidal submarine groundwater discharge (SGD) conditions the form of the rock pool sessile assemblage. Estuar. Coast. Shelf Sci. 213, 236–244. https://doi.org/10.1016/j.ecss.2018.08.014.

Fujita, K., Shoji, J., Sugimoto, R., Nakajima, T., Honda, H., Takeuchi, M., Tominaga, O., Taniguchi, M., 2019. Increase in fish production through bottom-up trophic linkage in coastal waters induced by nutrients supplied via submarine groundwater. Front. Environ. Sci. 7, 1–10. https://doi.org/10.3389/fenvs.2019.00082.

Futch, J.C., Griffin, D.W., Lipp, E.K., 2010. Human enteric viruses in groundwater indicate offshore transport of human sewage to coral reefs of the Upper Florida Keys. Environ. Microbiol. 12, 964–974. https://doi.org/10.1111/j.1462-2920.2010.02141.x.

Garcés, E., Basterretxea, G., Tovar-Sánchez, A., 2011. Changes in microbial communities in response to submarine groundwater input. Mar. Ecol. Prog. Ser. 438, 47–58. https://doi.org/10.3354/meps09311.

Garcia-Orellana, J., Rodellas, V., Casacuberta, N., Lopez-Castillo, E., Vilarrasa, M., Moreno, V., Garcia-Solsona, E., Masqué, P., 2013. Submarine groundwater discharge: Natural radioactivity accumulation in a wetland ecosystem. Mar. Chem. 156, 61–72. https://doi.org/10.1016/j.marchem.2013.02.004.

Garcia-Orellana, J., López-Castillo, E., Casacuberta, N., Rodellas, V., Masqué, P., Carmona-Catot, G., Vilarrasa, M., García-Berthou, E., 2016. Influence of submarine groundwater discharge on 210Po and 210Pb bioaccumulation in fish tissues. J. Environ. Radioact. 155–156, 46–54. https://doi.org/10.1016/j.jenvrad.2016.02.005.

Garcia-Orellana, J., Rodellas, V., Tamborski, J., Diego-Feliu, M., Van Beek, P., Weinstein, Y., Charette, M.A., Alorda-Kleinglass, A., Michael, H.A., Stieglitz, T.C., Scholten, J.C., 2021. Radium isotopes as submarine groundwater discharge (SGD) tracers: review and recommendations. Earth-Science Rev., 103681 https://doi.org/10.1016/j.earscirev.2021.103681.

Ghannam, J., Ayoub, G.M., Acra, A., 1998. A profile of the submarine springs in lebanon as a potential water resource. Water Int. 23, 278–286. https://doi.org/10.1080/02508069808686783.

Gilli, E., 2020. A Messinian model explains the salt contamination of the Mediterranean Coastal Springs. Environ. Earth Sci. 79, 1–6. https://doi.org/10.1007/s12665-020-08928-1.

Glenn, C., Whittier, R., Dailer, M.L., Dulai, H., El-Kadi, A., Fackrell, J., Kelly, J., Waters, C., Sevadjian, J., 2013. Lahaina groundwater tracer study Lahaina, Maui, Hawai'i. Final Rep. EPA Rep. 502.

Gobler, C.J., Sañudo-Wilhelmy, S.A., 2001. Temporal variability of groundwater seepage and brown tide blooms in a Long Island embayment. Mar. Ecol. Prog. Ser. 217, 299–309. https://doi.org/10.3354/meps217299.

Harrington, R., Anton, C., Dawson, T.P., de Bello, F., Feld, C.K., Haslett, J.R., Kluvánkova-Oravská, T., Kontogianni, A., Lavorel, S., Luck, G.W., Rounsevell, M.D.A., Samways, M.J., Settele, J., Skourtos, M., Spangenberg, J.H., Vandewalle, M., Zobel, M., Harrison, P.A., 2010. Ecosystem services and biodiversity conservation: concepts and a glossary. Biodivers. Conserv. 19, 2773–2790. https://doi.org/10.1007/s10531-010-9834-9.

Hassan, R., Scholes, R., Ash, N., 2005. Ecosystems and Human Well-Being: Current State and Trends.

Hata, M., Sugimoto, R., Hori, M., Tomiyama, T., Shoji, J., 2016. Occurrence, distribution and prey items of juvenile marbled sole *Pseudopleuronectes yokohamae* around a submarine groundwater seepage on a tidal flat in southwestern Japan. J. Sea Res. 111, 47–53. https://doi.org/10.1016/j.seares.2016.01.009.

Himes-Cornell, A., Pendleton, L., Atiyah, P., 2018. Valuing ecosystem services from blue forests: a systematic review of the valuation of salt marshes, sea grass beds and mangrove forests. Ecosyst. Serv. 30, 36–48. https://doi.org/10.1016/j.ecoser.2018.01.006.

Hosono, T., Ono, M., Burnett, W.C., Tokunaga, T., Taniguchi, M., Akimichi, T., 2012. Spatial distribution of submarine groundwater discharge and associated nutrients within a local coastal area. Environ. Sci. Technol. 46, 5319–5326. https://doi.org/10.1021/es2043867.

Hu, C., Muller-Karger, F.E., Swarzenski, P.W., 2006. Hurricanes, submarine groundwater discharge, and Florida's red tides. Geophys. Res. Lett. 33, 1–5. https://doi.org/10.1029/2005GL025449.

Hwang, D.W., Lee, Y.W., Kim, G., 2005. Large submarine groundwater discharge and benthic eutrophication in Bangdu Bay on volcanic Jeju Island, Korea. Limnol. Oceanogr. 50, 1393–1403. https://doi.org/10.4319/lo.2005.50.5.1393.

IPCC, 2007. Climate Change 2007-Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Fourth Assessment Report of the IPCC. Cambridge University Press.

IPCC, 2014. Summary for policymakers, climate change 2014: synthesis report. In: Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. https://doi.org/10.1017/CBO9781107415324.

Isbister, J., 1966. Geology and Hydrology of Northeastern Nassau County, Long Island, New York. US Government Printing Office.

Islam, M.S., Tanaka, M., 2004. Impacts of pollution on coastal and marine ecosystems including coastal and marine fisheries and approach for management: a review and synthesis. Mar. Pollut. Bull. 48, 624–649. https://doi.org/10.1016/j.marpolbul.2003.12.004.

Johannes, R.E., 1980. The ecological significance of the submarine discharge of groundwater. Mar. Ecol. Prog. Ser. 3, 365–373. https://doi.org/10.3354/meps003365.

Johannes, R.E., Hearn, C.J., 1985. The effect of submarine groundwater discharge on nutrient and salinity regimes in a coastal lagoon off Perth, Western Australia. Estuar. Coast. Shelf Sci. 21, 789–800. https://doi.org/10.1016/0272-7714(85)90073-3.

Kamermans, P., Hemminga, M.A., Tack, J.F., Mateo, M.A., Marbà, N., Mtolera, M., Stapel, J., Verheyden, A., Van Daele, T., 2002. Groundwater effects on diversity and abundance of lagoonal seagrasses in Kenya and on Zanzibar Island (East Africa). Mar. Ecol. Prog. Ser. 231, 75–83.

Keller, M., 1963. Die Vruljes an der Adriaküste. Neptun 3, 171.

Knee, K.L., Paytan, A., 2011. Submarine Groundwater Discharge: A Source of Nutrients, Metals, and Pollutants to the Coastal Ocean, Treatise on Estuarine and Coastal Science. Elsevier Inc. https://doi.org/10.1016/B978-0-12-374711-2.00410-1

Knee, K.L., Layton, B.A., Street, J.H., Boehm, A.B., Paytan, A., 2008. Sources of nutrients and fecal indicator bacteria to nearshore waters on the north shore of Kaua’i (Hawai’i, USA). Estuar. Coasts 31, 607–622. https://doi.org/10.1007/s12237-008-9055-6.

Knee, K.L., Gossett, R., Boehm, A.B., Paytan, A., 2010. Caffeine and agricultural pesticide concentrations in surface water and groundwater on the north shore of Kauai (Hawaii, USA). Mar. Pollut. Bull. 60, 1376–1382. https://doi.org/10.1016/j.marpolbul.2010.04.019.

Kohout, F.A., 1966. Submarine springs: a neglected phenomenon of coastal hydrology. Hydrology 26, 391–413.

Kohout, F.A., Kolipinski, M., 1967. Biological zonation related to groundwater discharge along the shore of Biscayne Bay, Miami, Florida. In: Eatuaries Conf. on Estuaries. Am. Assoc. Adv. Sci., pp. 488–499.

Kohout, F.A., Munson, K.M., Turner, R.M., Royal, W.R., 1979. Satellite observations of a geothermal submarine spring off Florida west coast. Satell. Hydrol. 570–578.

Kotwicki, L., Grzelak, K., Czub, M., Dellwig, O., Gentz, T., Szymczycha, B., Böttcher, M. E., 2014. Submarine groundwater discharge to the Baltic coastal zone: impacts on the meiofaunal community. J. Mar. Syst. 129, 118–126. https://doi.org/10.1016/j.jmarsys.2013.06.009.

Kundzewicz, Z.W., Döll, P., 2009. Will groundwater ease freshwater stress under climate change? Hydrol. Sci. J. 54, 665–675. https://doi.org/10.1623/hysj.54.4.665.

Kwon, E.Y., Kim, G., Primeau, F., Moore, W.S., Cho, H.M., DeVries, T., Sarmiento, J.L., Charette, M.A., Cho, Y.-K., 2014. Global estimate ofsubmarine groundwater discharge based on an observationally constrained radium isotope model. Geophys. Res. Lett. 41, 8438–8444. https://doi.org/10.1002/2014GL061574.Received.

Kwon, H.K., Kang, H., Oh, Y.H., Park, S.R., Kim, G., 2017. Green tide development associated with submarine groundwater discharge in a coastal harbor, Jeju, Korea. Sci. Rep. 7, 1–9. https://doi.org/10.1038/s41598-017-06711-0.

Lafortezza, R., Chen, J., 2016. The provision of ecosystem services in response to global change: evidences and applications. Environ. Res. 147, 576–579. https://doi.org/10.1016/j.envres.2016.02.018.

Lapointe, B.E., 1997. Nutrient thresholds for bottom-up control of macroalgal blooms on coral reefs in Jamaica and Southeast Florida. Limnol. Oceanogr. 42, 1119–1131. https://doi.org/10.4319/lo.1997.42.5_part_2.1119.

Lapointe, B.E., Barile, P.J., Littler, M.M., Littler, D.S., 2005. Macroalgal blooms on southeast Florida coral reefs: II. Cross-shelf discrimination of nitrogen sources indicates widespread assimilation of sewage nitrogen. Harmful Algae 4, 1106–1122. https://doi.org/10.1016/j.hal.2005.06.002.

Laroche, J., Nuzzi, R., Waters, R., Wyman, K., Falkowski, P., Wallace, D., 1997. Brown Tide blooms in Long Island’s coastal waters linked to interannual variability in groundwater flow. Glob. Chang. Biol. 3, 397–410. https://doi.org/10.1046/j.1365-2486.1997.00117.x.

Laurier, F.J.G., Cossa, D., Beucher, C., Brévière, E., 2007. The impact of groundwater discharges on mercury partitioning, speciation and bioavailability to mussels in a coastal zone. Mar. Chem. 104, 143–155. https://doi.org/10.1016/j.marchem.2006.10.010.

Leake, W.M., 1830. Travels in the Morea: with a Map and Plans. John Murray.

Lecher, A.L., Mackey, K.R.M., 2018. Synthesizing the effects of submarine groundwater discharge on marine biota. Hydrology 5, 1–21. https://doi.org/10.3390/hydrology5040060.

Lee, Y.W., Kim, G., 2007. Linking groundwater-borne nutrients and dinoflagellate red-tide outbreaks in the southern sea of Korea using a Ra tracer. Estuar. Coast. Shelf Sci. 71, 309–317. https://doi.org/10.1016/j.ecss.2006.08.004.

Lee, Y.W., Hwang, D.W., Kim, G., Lee, W.C., Oh, H.T., 2009. Nutrient inputs from submarine groundwater discharge (SGD) in Masan Bay, an embayment surrounded by heavily industrialized cities, Korea. Sci. Total Environ. 407, 3181–3188. https://doi.org/10.1016/j.scitotenv.2008.04.013.

Lee, Y.W., Kim, G., Lim, W.A., Hwang, D.W., 2010. A relationship between submarine groundwater-borne nutrients traced by Ra isotopes and the intensity of dinoflagellate red-tides occurring in the southern sea of Korea. Limnol. Oceanogr. 55, 1–10. https://doi.org/10.4319/lo.2010.55.1.0001.

Lilkendey, J., Pisternick, T., Neumann, S.I., Dumur Neelayya, D., Bröhl, S., Neehaul, Y., Moosdorf, N., 2019. Fresh submarine groundwater discharge augments growth in a reef fish. Front. Mar. Sci. 6, 1–11. https://doi.org/10.3389/fmars.2019.00613.

Lirman, D., Orlando, B., Maciá, S., Manzello, D., Kaufman, L., Biber, P., Jones, T., 2003. Coral communities of Biscayne Bay, Florida and adjacent offshore areas: diversity, abundance, distribution, and environmental correlates. Aquat. Conserv. Mar. Freshw. Ecosyst. 13, 121–135. https://doi.org/10.1002/aqc.552.

Lougheed, V., 2006. Belize Adventure Guide.

Lubis, R.F., Bakti, H., 2013. Mata Air Tawar Di Tengah Laut. Geomagz 3, 38–42.

Luijendijk, E., Gleeson, T., Moosdorf, N., 2020. Fresh groundwater discharge insignificant for the world's oceans but important for coastal ecosystems. Nat. Commun. 11, 1260. https://doi.org/10.1038/s41467-020-15064-8.

Ma, Q., Zhang, Y., 2020. Global research trends and hotspots on submarine groundwater discharge (SGD): a bibliometric analysis. Int. J. Environ. Res. Public Health 17. https://doi.org/10.3390/ijerph17030830.

Machado, D.A., Imberger, J., 2014. Modeling the impact of natural and anthropogenic nutrient sources on phytoplankton dynamics in a shallow coastal domain, Western Australia. Environ. Fluid Mech. 14, 87–111. https://doi.org/10.1007/s10652-013-9296-1.

Martinez, A., Hernández-Terrones, L., Rebolledo-Vieyra, M., Paytan, A., 2018. Impact of carbonate saturation on large Caribbean benthic foraminifera assemblages. Biogeosciences 15, 6819–6832. https://doi.org/10.5194/bg-15-6819-2018.

McClelland, J.W., Valiela, I., Michener, R.H., 1997. Nitrogen-stable isotope signatures in estuarine food webs: a record of increasing urbanization in coastal watersheds. Limnol. Oceanogr. 42, 930–937. https://doi.org/10.4319/lo.1997.42.5.0930.

McDermid, K.J., Martin, K.J., Haws, M.C., 2019. Seaweed resources of the Hawaiian Islands. Bot. Mar. 62, 443–462. https://doi.org/10.1515/bot-2018-0091.

MEA, 2005. Ecosystems and human well-being: a report on the conceptual framework working group of the Millennium Ecosystem Assessment. Ecosystems. https://doi.org/10.1196/annals.1439.003.

Michael, H.A., Russoniello, C.J., Byron, L.A., 2013. Global assessment of vulnerability to sea-level rise in topography-limited and recharge-limited coastal groundwater systems. Water Resour. Res. 49, 2228–2240. https://doi.org/10.1002/wrcr.20213.

Michael, H.A., Post, V.E.A., Wilson, A.M., Werner, A.D., 2017. Water Resources Research. AGU Publ., pp. 1–8. https://doi.org/10.1002/2017WR020851.Received

Migné, A., Ouisse, V., Hubas, C., Davoult, D., 2011. Freshwater seepages and ephemeral macroalgae proliferation in an intertidal bay: II. Effect on benthic biomass and metabolism. Estuar. Coast. Shelf Sci. 92, 161–168. https://doi.org/10.1016/j.ecss.2010.12.023.

Mijatović, B., 2006. The groundwater discharge in the Mediterranean karst coastal zones and freshwater tapping: set problems and adopted solutions. Case studies. Environ. Geol. 51, 737–742. https://doi.org/10.1007/s00254-006-0390-2.

Miller, D.C., Ullman, W.J., 2004. Ecological consequences of ground water discharge to Delaware Bay, United States. Ground Water 42, 959–970. https://doi.org/10.1111/j.1745-6584.2004.tb02635.x.

Moore, W.S., 2008. Fifteen years experience in measuring 224Ra and 223Ra by delayed-coincidence counting. Mar. Chem. 109, 188–197. https://doi.org/10.1016/j.marchem.2007.06.015.

Moore, W.S., 2010. The effect of submarine groundwater discharge on the ocean. Annu. Rev. Mar. Sci. 2, 59–88. https://doi.org/10.1146/annurev-marine-120308-081019.

Moore, W.S., Sarmiento, J.L., Key, R.M., 2008. Submarine groundwater discharge revealed by 228Ra distribution in the upper Atlantic Ocean. Nat. Geosci. 1, 309–311. https://doi.org/10.1038/ngeo183.

Moosdorf, N., Oehler, T., 2017. Societal use of fresh submarine groundwater discharge: an overlooked water resource. Earth-Sci. Rev. 171, 338–348. https://doi.org/10.1016/j.earscirev.2017.06.006.

Muir, K.S., 1968. Groundwater reconnaissance of the Santa Barbara-Montecito Area, Santa Barbara County, California. USGS Water. Supply Pap. 1859, 28p.

Murray-Mas, I., 2006. Menorca, la isla de dos cabezas. Govern de les Illes Balears: Institut Balear del Turisme (Ed.). In: VIII Coloquio y Jornadas de Campo de Geografía Urbana. Guía de Campo, Palma.

Nace, R.L., 1967. Are we running out of water? US Geological Survey.

Newport, T.G., Haddor, Y., 1963. Ground-Water Exploration in Al Marj Area, Cyrenaica. United Kingdom of Libya, US Government Printing Office.

Norberg, J., 1999. Linking nature’s services to ecosystems: some general ecological concepts. Ecol. Econ. 29, 183–202. https://doi.org/10.1016/S0921-8009(99)00011-7.

Ouisse, V., Riera, P., Migné, A., Leroux, C., Davoult, D., 2011. Freshwater seepages and ephemeral macroalgae proliferation in an intertidal bay: I effect on benthic community structure and food web. Estuar. Coast. Shelf Sci. 91, 272–281. https://doi.org/10.1016/j.ecss.2010.10.034.

Paoli, C., Montefalcone, M., Morri, C., Vassallo, P., Nike-Bianchi, C., 2017. Marine Animal Forests: The Ecology of Benthic Biodiversity Hotspots, Marine Animal Forests: The Ecology of Benthic Biodiversity Hotspots. https://doi.org/10.1007/978-3-319-21012-4.

Pavlidou, A., Papadopoulos, V.P., Hatzianestis, I., Simboura, N., Patiris, D., Tsabaris, C., 2014. Chemical inputs from a karstic submarine groundwater discharge (SGD) into an oligotrophic Mediterranean coastal area. Sci. Total Environ. 488–489, 1–13. https://doi.org/10.1016/j.scitotenv.2014.04.056.

Paytan, A., Boehm, A.B., Shellenbarger, G.G., 2004. Bacterial contamination and submarine groundwater discharge - a possible link. Environ. Chem. 1, 29–30. https://doi.org/10.1071/EN04002.

Pereira, L.S., Gilley, J.R., Jensen, M.E., 1996. Research agenda on sustainability of irrigated agriculture. J. Irrig. Drain. Eng. - ASCE 122, 172–177. https://doi.org/10.1061/(ASCE)0733-9437(1996)122:3(172).

Peterson, B.J., Stubler, A.D., Wall, C.C., Gobler, C.J., 2012. Nitrogen-rich groundwater intrusion affects productivity, but not herbivory, of the tropical seagrass *Thalassia testudinum*. Aquat. Biol. 15, 1–9. https://doi.org/10.3354/ab00413.

Petticrew, M., Roberts, H., 2006. Systematic Reviews in the Social Sciences, Systematic Reviews in the Social Sciences. Blackwell, Cornwall, United Kingdom. https://doi.org/10.1002/9780470754887.

Pimm, S.L., 1997. The value of everything. Nature 387, 231–232.

Pironet, F.N., Jones, J.B., 2000. Treatments for ectoparasites and diseases in captive Western Australian dhufish. Aquac. Int. 8, 349–361. https://doi.org/10.1023/A:1009257011431.

Pongkijvorasin, S., Roumasset, J., Duarte, T.K., Burnett, K.M., 2010. Renewable resource management with stock externalities: coastal aquifers and submarine groundwater discharge. Resour. Energy Econ. 32, 277–291. https://doi.org/10.1016/j.reseneeco.2009.09.001.

Pope, N.D., O'Hara, S.C.M., Imamura, M., Hutchinson, T.H., Langston, W.J., 2011. Influence of a collapsed coastal landfill on metal levels in sediments and biota - a portent for the future? J. Environ. Monit. 13, 1961–1974. https://doi.org/10.1039/c0em00741b.

Prouty, N.G., Cohen, A., Yates, K.K., Storlazzi, C.D., Swarzenski, P.W., White, D., 2017. Vulnerability of coral reefs to bioerosion from land-based sources of pollution. J. Geophys. Res. Ocean. 122, 9319–9331. https://doi.org/10.1002/2017JC013264.

Pukui, M.K., 1949. Songs (Meles) of Old Ka'u, Hawaii. J. Am. Folk. 62, 247–258.

Queiroz, L. de S., Rossi, S., Calvet-Mir, L., Ruiz-Mallén, I., García-Betorz, S., Salvà-Prat, J., Meireles, A.J. de A., 2017. Neglected ecosystem services: highlighting the socio-cultural perception of mangroves in decision-making processes. Ecosyst. Serv. 26, 137–145. https://doi.org/10.1016/j.ecoser.2017.06.013.

Richardson, S., Irvine, E., Froend, R., Boon, P., Barber, S., Bonneville, B., 2011. Australian Groundwater-Dependent Ecosystem Toolbox. Part 1: Assessment Framework. Waterlines report, Natl. Water Comm. Canberra.

Richardson, C.M., Dulai, H., Popp, B.N., Ruttenberg, K., Fackrell, J.K., 2017. Submarine groundwater discharge drives biogeochemistry in two Hawaiian reefs. Limnol. Oceanogr. 62, S348–S363. https://doi.org/10.1002/lno.10654.

Robinson, C.E., Xin, P., Santos, I.R., Charette, M.A., Li, L., Barry, D.A., 2018. Groundwater dynamics in subterranean estuaries of coastal unconfined aquifers: controls on submarine groundwater discharge and chemical inputs to the ocean. Adv. Water Resour. 115, 315–331. https://doi.org/10.1016/j.advwatres.2017.10.041.

Rodellas, V., Garcia-Orellana, J., Tovar-Sánchez, A., Basterretxea, G., López-Garcia, J.M., Sánchez-Quiles, D., Garcia-Solsona, E., Masqué, P., 2014. Submarine groundwater discharge as a source of nutrients and trace metals in a Mediterranean bay (Palma Beach, Balearic Islands). Mar. Chem. 160, 56–66. https://doi.org/10.1016/j.marchem.2014.01.007.

Rodellas, V., Garcia-Orellana, J., Masqué, P., Feldman, M., Weinstein, Y., 2015. Submarine groundwater discharge as a major source of nutrients to the Mediterranean Sea. Proc. Natl. Acad. Sci. U. S. A. 112, 3926–3930. https://doi.org/10.1073/pnas.1419049112.

Rodellas, V., Stieglitz, T.C., Andrisoa, A., Cook, P.G., Raimbault, P., Tamborski, J., van Beek, P., Radakovitch, O., 2018. Groundwater-driven nutrient inputs to coastal lagoons: the relevance of lagoon water recirculation as a conveyor of dissolved nutrients. Sci. Total Environ. 642, 764–780. https://doi.org/10.1016/j.scitotenv.2018.06.095.

Rothstein, H.R., Hopewell, S., 2009. Grey literature. Handb. Res. Synth. Meta-Analysis 2, 103–125.

Ruiz-González, C., Rodellas, V., Garcia-Orellana, J., 2021. The microbial dimension of submarine groundwater discharge: current challenges and future directions. FEMS Microbiol. Rev. 1–25. https://doi.org/10.1093/femsre/fuab010.

Rützler, K., 1996. Sponge diving - professional but not for profit. Methods Tech. Underw. Res. 183–204.

Sadler, H.E., Serson, H.V., 1980. An unusual polynya in an artic fjord. Fjord Oceanogr. 299–300. https://doi.org/10.1007/978-1-4613-3105-6.

Sanial, V., Buesseler, K.O., Charette, M.A., Nagao, S., 2017. Unexpected Source of Fukushima-Derived Radiocesium to the Coastal Ocean of Japan, pp. 1–5. https://doi.org/10.1073/pnas.1708659114.

Santos, I.R., Eyre, B.D., Huettel, M., 2012. The driving forces of porewater and groundwater flow in permeable coastal sediments: a review. Estuar. Coast. Shelf Sci. 98, 1–15. https://doi.org/10.1016/j.ecss.2011.10.024.

Santos, I.R., Chen, X., Lecher, A.L., Sawyer, A.H., Moosdorf, N., Rodellas, V., Tamborski, J., Cho, H.-M., Dimova, N., Sugimoto, R., Bonaglia, S., Li, H., Hajati, M.-C., Li, L., 2021. Submarine groundwater discharge impacts on coastal nutrient biogeochemistry. Nat. Rev. Earth Environ. https://doi.org/10.1038/s43017-021-00152-0, 0123456789.

Saunders, M.E., Luck, G.W., 2016. Limitations of the ecosystem services versus disservices dichotomy. Conserv. Biol. 30, 1363–1365. https://doi.org/10.1111/cobi.12740.

Schallenberg, M., De Winton, M.D., Verburg, P., Kelly, D.J., Hamill, K.D., Hamilton, D.P., 2013. Ecosystem services of lakes. Ecosyst. Serv. New Zeal. - Cond. Trends 203–225.

Shoji, J., Tominaga, O., 2018. Relationships between submarine groundwater discharge and coastal fisheries as a water-food nexus. In: Endo, A., Oh, T. (Eds.), The Water-Energy-Food Nexus, Global Environmental Studies. Springer Nature Singapore Pte Ltd., Singapore, pp. 117–131. https://doi.org/10.1007/978-981-10-7383-0_9.

Short, F.T., Burdick, D.M., 1996. Quantifying eelgrass habitat loss in relation to housing development and nitrogen loading in Waquoit Bay, Massachusetts. Estuaries 19, 730–739. https://doi.org/10.2307/1352532.

Silva, A.C.F., Tavares, P., Shapouri, M., Stigter, T.Y., Monteiro, J.P., Machado, M., Cancela da Fonseca, L., Ribeiro, L., 2012. Estuarine biodiversity as an indicator of groundwater discharge. Estuar. Coast. Shelf Sci. 97, 38–43. https://doi.org/10.1016/j.ecss.2011.11.006.

Slomp, C.P., Van Cappellen, P., 2004. Nutrient inputs to the coastal ocean through submarine groundwater discharge: controls and potential impact. J. Hydrol. 295, 64–86. https://doi.org/10.1016/j.jhydrol.2004.02.018.

Spalt, N., Murgulet, D., Abdulla, H., 2020. Spatial variation and availability of nutrients at an oyster reef in relation to submarine groundwater discharge. Sci. Total Environ. 710, 136283. https://doi.org/10.1016/j.scitotenv.2019.136283.

Sternal, B., Junttila, J., Skirbekk, K., Forwick, M., Carroll, J.L., Pedersen, K.B., 2017. The impact of submarine copper mine tailing disposal from the 1970s on Repparfjorden, northern Norway. Mar. Pollut. Bull. 120, 136–153. https://doi.org/10.1016/j.marpolbul.2017.04.054.

Stieglitz, T.C., 2005. Submarine groundwater discharge into the near-shore zone of the Great Barrier Reef, Australia. Mar. Pollut. Bull. 51, 51–59. https://doi.org/10.1016/j.marpolbul.2004.10.055.

Stieglitz, T.C., Dujon, A.M., 2017. A groundwater-fed coastal inlet as habitat for the Caribbean queen conch Lobatus gigas-an acoustic telemetry and space use analysis. Mar. Ecol. Prog. Ser. 571, 139–152. https://doi.org/10.3354/meps12123.

Stieglitz, T.C., van Beek, P., Souhaut, M., Cook, P.G., 2013. Karstic groundwater discharge and seawater recirculation through sediments in shallow coastal Mediterranean lagoons, determined from water, salt and radon budgets. Mar. Chem. 156, 73–84. https://doi.org/10.1016/j.marchem.2013.05.005.

Stigter, T.Y., Nunes, J.P., Pisani, B., Fakir, Y., Hugman, R., Li, Y., Tomé, S., Ribeiro, L., Samper, J., Oliveira, R., Monteiro, J.P., Silva, A., Tavares, P.C.F., Shapouri, M., Cancela da Fonseca, L., El Himer, H., 2014. Comparative assessment of climate change and its impacts on three coastal aquifers in the Mediterranean. Reg. Environ. Chang. 14, 41–56. https://doi.org/10.1007/s10113-012-0377-3.

Su, N., Burnett, W.C., Eller, K.T., MacIntyre, H.L., Mortazavi, B., Leifer, J., Novoveska, L., 2012. Radon and radium isotopes, groundwater discharge and harmful algal blooms in Little Lagoon, Alabama. In: Interdiscip. Stud. Environ. Chem. Vol 6 Adv. Environ. Stud. by Young Sci., pp. 329–338.

Szymczycha, B., Borecka, M., Białk-Bielińska, A., Siedlewicz, G., Pazdro, K., 2020. Submarine groundwater discharge as a source of pharmaceutical and caffeine residues in coastal ecosystem: Bay of Puck, southern Baltic Sea case study. Sci. Total Environ. 713 https://doi.org/10.1016/j.scitotenv.2020.136522.

Tamborski, J., van Beek, P., Conan, P., Pujo-Pay, M., Odobel, C., Ghiglione, J.F., Seidel, J.L., Arfib, B., Diego-Feliu, M., Garcia-Orellana, J., Szafran, A., Souhaut, M., 2020. Submarine karstic springs as a source of nutrients and bioactive trace metals for the oligotrophic Northwest Mediterranean Sea. Sci. Total Environ. 732, 1–14. https://doi.org/10.1016/j.scitotenv.2020.139106.

Taniguchi, M., 2002. Tidal effects on submarine groundwater discharge into the ocean. Geophys. Res. Lett. 29, 9–11. https://doi.org/10.1029/2002GL014987.

Taniguchi, M., Dulai, H., Burnett, K.M., Santos, I.R., Sugimoto, R., Stieglitz, T.C., Kim, G., Moosdorf, N., Burnett, W.C., 2019. Submarine groundwater discharge: updates on its measurement techniques, geophysical drivers, magnitudes, and effects. Front. Environ. Sci. 7, 1–26. https://doi.org/10.3389/fenvs.2019.00141.

Tardieu, B., Poité, L., 2015. Engineering geology for society and territory – volume 3: River basins, reservoir sedimentation and water resources. In: Freshwater Submarine Springs: Role of a Dam in Submerged Karst—Investigations Measurement and Works in Subterranean Rivers of Cassis—France from 1964 to 2013, pp. 1–657. https://doi.org/10.1007/978-3-319-09054-2.

TEEB, 2012. The Economics of Ecosystems and Biodiversity in Local and Regional Policy and Management. Routledge.

Tovar-Sánchez, A., Basterretxea, G., Rodellas, V., Sánchez-Quiles, D., Garcia-Orellana, J., Masqué, P., Jordi, A., López, J.M., Garcia-Solsona, E., 2014. Contribution of groundwater discharge to the coastal dissolved nutrients and trace metal concentrations in Majorca Island: Karstic vs detrital systems. Environ. Sci. Technol. 48, 11819–11827. https://doi.org/10.1021/es502958t.

Trezzi, G., Garcia-Orellana, J., Santos-Echeandia, J., Rodellas, V., Garcia-Solsona, E., Garcia-Fernandez, G., Masqué, P., 2016. The influence of a metal-enriched mining waste deposit on submarine groundwater discharge to the coastal sea. Mar. Chem. 178, 35–45. https://doi.org/10.1016/j.marchem.2015.12.004.

Troccoli-Ghinaglia, L., Herrera-Silveira, J.A., Comín, F.A., Díaz-Ramos, J.R., 2010. Phytoplankton community variations in tropical coastal area affected where submarine groundwater occurs. Cont. Shelf Res. 30, 2082–2091. https://doi.org/10.1016/j.csr.2010.10.009.

Tuya, F., Haroun, R., Espino, F., 2014. Economic assessment of ecosystem services: monetary value of seagrass meadows for coastal fisheries. Ocean Coast. Manag. 96, 181–187. https://doi.org/10.1016/j.ocecoaman.2014.04.032.

Umezawa, Y., Miyajima, T., Yamamuro, M., Kayanne, H., Koike, I., 2002. Fine-scale mapping of land-derived nitrogen in coral reefs by δ15N in macroalgae. Limnol. Oceanogr. 47, 1405–1416. https://doi.org/10.4319/lo.2002.47.5.1405.

UNEP/MAP, 2012. State of the Mediterranean marine and coastal environment. In: United Nations Environment Programme/Mediterranean Action Plan (UNEP/MAP)—Barcelona Convention: Athens, p. 96.

UNEP-MAP, U.-I., 2015. Final Report on Mediterranean Coastal Aquifers and Groundwater Including the Coastal Aquifer Supplement to the TDA-MED and the Subregional Action Plans. Paris: Strategic Partnership for the Mediterranean Sea Large Marine Ecosystem (MedPartnership). UNESCO.

UNESCO, 2004. Submarine Groundwater Discharge. https://doi.org/10.1007/978-90-481-2639-2_220.

Utsunomiya, T., Hata, M., Sugimoto, R., Honda, H., Kobayashi, S., Miyata, Y., Yamada, M., Tominaga, O., Shoji, J., Taniguchi, M., 2017. Higher species richness and abundance of fish and benthic invertebrates around submarine groundwater discharge in Obama Bay, Japan. J. Hydrol. Reg. Stud. 11, 139–146. https://doi.org/10.1016/j.ejrh.2015.11.012.

Valiela, I., Costa, J., Foreman, K., Teal, J.M., Howes, B., Aubrey, D., 1990. Transport of groundwater-borne nutrients from watershed and their effects on coastal waters. Biogeochemistry 10, 177–197.

Welti, N., Gale, D., Hayes, M., Kumar, A., Gasparon, M., Gibbes, B., Lockington, D., 2015. Intertidal diatom communities reflect patchiness in groundwater discharge. Estuar. Coast. Shelf Sci. 163, 116–124. https://doi.org/10.1016/j.ecss.2015.06.006.

Westman, W.E., 1977. How much are nature's services worth? Science (80-.) 197, 960–964.

Williams, C., 1996. Combatting marine pollution from land-based activities: Australian initiatives. Ocean Coast. Manag. 33, 87–112. https://doi.org/10.1016/S0964-5691(96)00046-4.

Yau, V.M., Schiff, K.C., Arnold, B.F., Griffith, J.F., Gruber, J.S., Wright, C.C., Wade, T.J., Burns, S., Hayes, J.M., McGee, C., Gold, M., Cao, Y., Boehm, A.B., Weisberg, S.B., Colford, J.M., 2014. Effect of submarine groundwater discharge on bacterial indicators and swimmer health at Avalon Beach, CA, USA. Water Res. 59, 23–36. https://doi.org/10.1016/j.watres.2014.03.050.

Yeakley, J.A., Ervin, D., Chang, H., Granek, E.F., Dujon, V., Shandas, V., Brown, D., 2016. Ecosystem services of streams and rivers. In: River Science: Research and Management for the 21st Century, pp. 335–352.

Yoshioka, R.M., Kim, C.J.S., Tracy, A.M., Most, R., Harvell, C.D., 2016. Linking sewage pollution and water quality to spatial patterns of Porites lobata growth anomalies in Puako, Hawaii. Mar. Pollut. Bull. 104, 313–321. https://doi.org/10.1016/j.marpolbul.2016.01.002.

Zektser, I.S., Loaiciga, H.A., 1993. Groundwater fluxes in the global hydrologic cycle: past, present and future. J. Hydrol. 144, 405–427.

Zektser, I.S., Ivanov, V.A., Meskheteli, A.V., 1973. The problem of direct groundwater discharge to the seas. J. Hydrol. 20, 1–36. https://doi.org/10.1016/0022-1694(73)90042-5.

Zhang, W., Ricketts, T.H., Kremen, C., Carney, K., Swinton, S.M., 2007. Ecosystem services and dis-services to agriculture. Ecol. Econ. 64, 253–260. https://doi.org/10.1016/j.ecolecon.2007.02.024.

Zhou, Y.Q., Sawyer, A.H., David, C.H., Famiglietti, J.S., 2019. Fresh submarine groundwater discharge to the near-global coast. Geophys. Res. Lett. 46, 5855–5863. https://doi.org/10.1029/2019GL082749.