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Confidential manuscript submitted to Water Resources Research

The subterranean estuary: Technical term, simple analogy, or source of confusion?

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Key Points:

- Since its definition in 1999, the term “subterranean estuary” has been expanding in scientific literature
- It may enhance communications between the communities of hydrogeology and ocean sciences, but does also carry an element of confusion?
- We open a discussion within the coastal research community about the use and meaning of terminology in future studies

This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the [Version of Record](#). Please cite this article as doi: [10.1029/2019WR026554](https://doi.org/10.1029/2019WR026554)

Abstract

Twenty years ago, the term *subterranean estuary* was proposed by Moore (1999) as a call of attention to the ocean sciences community about the importance of coastal groundwater systems, which can compete in relevance and impact to oceans with fresh runoff coming from the continent. Coastal aquifers were presented as an analogy to surface estuaries in that water of different density comes together and establishes a saline wedge underlying fresher water. In the past two decades, the use of this term has expanded. Initially limited to studies with an oceanographic viewpoint considering the impact of groundwater on the ocean, it is now common in the literature, competing with classical hydrogeological terminology such as *coastal aquifer* or *seawater intrusion*, and reaching publications with a traditional hydrogeological focus. The popularity of this terminology suggests that it fills a need not met by existing coastal hydrogeological terms, although these classical terms have their roots in a long history of study of coastal groundwater. This term may serve to enhance communications between the traditionally disparate communities of hydrogeology and ocean sciences - imbricating saltwater intrusion studies with marine sciences and bringing an opportunity to enhance interactions. But does the term also carry an element of confusion? This essay is intended to open a discussion within the coastal research community about the use and meaning of terminology in future studies of coastal and offshore groundwater systems.

1 Introduction

The study of groundwater in coastal areas has been approached from two separate traditions, marine science and hydrogeology. From the land-hydrology perspective, the traditional focus has been on the freshwater as a water supply resource, and saltwater is treated as a pollutant to be avoided; thus, processes beyond the coastline are often ignored. As an example, most hydrogeologists have seen groundwater models that end near the coastline, with the precise location dictated more by a lack of offshore hydrostratigraphic data and to avoid computational difficulties of simulating variable-density flow than by a scientific principle. In marine science, understanding ocean processes is the main goal, and the aquifer may be considered a contributor of chemical components. Similar to hydrogeologists who neglect flow beyond the coastline, marine-focused work has sometimes taken a very limited view of the aquifer. As an example, studies using natural radioactive tracers to quantify submarine groundwater discharge (SGD) commonly present extensive and detailed characterization of the tracer distribution in seawater, but measurements of the groundwater endmember may be sparse (Duque et al., 2019). In reality the processes of interest to the two disciplines are not physically distinct, and they occur in the same place - coastal aquifers at the intersection of land and sea – and at the same time. Better communication between the two disciplines is clearly desirable (Destouni and Prieto, 2010, 2003; Kazemi, 2008; Werner et al., 2013), but barriers remain, going even so far as the terminology used for the most basic element, the name of the system under study.

For at least a century, since the time of Drabbe and Badon Ghyjben, (1889) and (Herzberg, 1901), hydrogeologists have used the terms *coastal aquifer* to describe a groundwater system at the interface of land and sea, *freshwater-saltwater interface* to describe the subsurface fresh-salt mixing zone, and *seawater intrusion* to describe the process of inland movement of saline groundwater. The term *subterranean estuary* was put forward in the marine literature (Marine Chemistry; Moore, 1999) to describe coastal aquifers as analogous to surface estuaries where mixing of fresh water and seawater is taking place, along with associated density-driven flow and biogeochemical processes. While the term *subterranean estuary* has been widely adopted in the marine science community in place of the more traditional hydrogeological terms, it is less used, and even unrecognized, in the hydrology community. For this reason, the objectives of this work are to (1) re-examine current coastal hydrogeological terminology, (2) assess compatibility and possible conflicts between the two sets of terms, and (3) open a discussion about the requirement (or not) for consensus on terminology in light of the need for greater collaboration and integration to solve the pressing natural and anthropogenic challenges facing coastal systems.

1.1. Subterranean estuary

A subterranean estuary was defined as “a coastal aquifer where ground water derived from land drainage measurably dilutes sea water that has invaded the aquifer through a free connection to the sea” (Moore, 1999). At the time, many hydrogeologists and oceanographers normally thought of groundwater as being exclusively fresh, so this term was purposely designed to draw attention to the importance of flow and reaction in brackish and saline groundwater systems. Thus, although the definition is physical, the implication is biogeochemical, “to emphasize the importance of mixing and chemical reaction in these coastal aquifers” (Moore, 1999). The reactions resulting from mixing of waters of different origin have important implications for processes of particular interest to the marine community, including nutrient sources and attenuation (Couturier et al., 2017), temporal and spatial variability of biochemical conditions (Santos et al., 2012), and the impact of coastal groundwater discharge on global chemical fluxes (Moore, 2010).

The definition on which the estuary analogy is based was proposed by Pritchard (1967): “a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage”. Other estuary definitions do not explicitly require the presence of freshwater runoff, although the salinity must differ from seawater. For example Tomczak and Godfrey (2003) define an estuary as “A narrow semiclosed water body which has a free connection with the open sea (at least, periodical) and whose water salinity is to an extent different from that in the open ocean.” From these definitions it can be generally derived that the term estuary refers to geographic features such as rivers, lagoons, bays, and other inlets.

To oceanographers, the concept of an estuary also includes significant biogeochemical processes, including salinity-dependent desorption, nutrient cycling, and carbon export to the

ocean. The important biogeochemical implications of the surface estuary are not, in our experience, widely known beyond the marine community, but they explain why the subterranean estuary concept, with its own set of biogeochemical implications, has been so powerful among oceanographers. The slow movement of groundwater and the mixing of water with different properties (salinity, oxygen level, organic matter content), make coastal aquifers prone to chemical and biochemical reactions with associated implications for the delivery of nutrients to coastal areas (Valiela et al., 1990) or chemical budgets of oceans (Milliman, 1993).

1.2. Coastal aquifers, freshwater-saltwater interface, and saltwater intrusion

Before defining the term *coastal aquifer*, we note that aquifers in general have commonly been defined in terms of use to humans (“permeable enough to yield economic quantities of water to wells”; (Freeze and Cherry, 1979), bringing water-supply overtones to any discussion of aquifers. But another definition, which has become increasingly common as hydrogeologists (and oceanographers) investigate an ever broadening array of scientific questions, describes aquifers simply as permeable units that can transmit significant fluxes of water. Coastal aquifers are then defined by a connection with the sea. Coastal aquifers have long served as a source of high-quality water for human and agricultural use, but this resource is at risk of saltwater contamination. Of particular concern is the location of the subsurface zone where fresh and saline groundwater mix, commonly referred to as the freshwater-saltwater interface or transition zone. This is a diffuse boundary for which the spatial extent and location depend on the aquifer properties (i.e. hydraulic conductivity and its distribution) and hydrological (hydraulic head oscillations) and marine (tidal and wave) processes. The displacement of this interface inland due to natural processes or anthropogenic activities is termed *seawater intrusion* or *saltwater intrusion*.

The basic quantitative understanding of density equilibrium between fresh and saline groundwater under static conditions was established almost simultaneously by Drabbe and Badon Ghyjben (1889) and Herzberg (1901), generating the seed of a new field of study focused on seawater intrusion. This was the starting point for USGS studies on the coast of Florida, which considered mixing of water with different properties and density-driven saline groundwater convection (Cooper, 1959; Kohout, 1964). Other processes, such as freshwater discharge to the sea (Glover, 1959), and the generation of tide-driven intertidal circulation cells (Lebbe, 1981; Michael et al., 2005; Robinson et al., 2006), have been widely explored through field measurements and/or model simulations. Management strategies for seawater intrusion prevention have been the subject of decades of research, particularly in areas that rely heavily on coastal aquifers for water supply (e.g., Barlow and Reichard, 2010; Mantoglou, 2003; Park and Aral, 2004).

1.3. Terminology usage

Since the term *subterranean estuary* was established in 1999, its use has increased rapidly. A simple analysis was performed using the Scopus database to count the number of

publications with the keyword *subterranean estuary* versus *coastal aquifer* and *saltwater intrusion/seawater intrusion/saltwater-freshwater interface* – these terms will be referred to here as *coastal aquifer** - in abstracts, titles and keywords. In spite of being a more specific term than *coastal aquifer* and only used for the last 20 years, *subterranean estuary* appears in 16 % of the publications (Fig. 1). Of the 157 publications found referring to *subterranean estuary*, 38 % also used classical hydrogeological terms such as *coastal aquifer* or *saltwater-freshwater interface* (Fig 1).

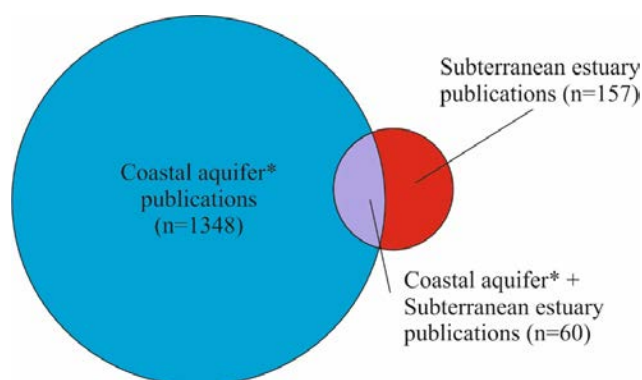


Figure 1. Number of publications using the term *coastal aquifer** (including *coastal aquifer* and *saltwater intrusion/seawater intrusion/saltwater-freshwater interface*) compared with *subterranean estuary*, and coincidence of both.

The presence of different terminology in particular journals indicates the tendencies of the hydrological and marine science communities. Papers in which *coastal aquifer** is used exclusively dominate in journals related to hydrological sciences (i.e. Journal of Hydrology, Water Resources Research, Hydrogeology Journal, Advances in Water Resources, Environmental Earth Sciences) (Fig. 2). Publications exclusively using *subterranean estuary* are split between marine science journals (i.e. Marine Chemistry, Estuarine Coastal and Shelf Science, Limnology and Oceanography) and “Others”, which we consider to have a broader multidisciplinary focus (i.e. Geochimica et Cosmochimica Acta, Geophysical Research Letters, Science of the Total Environment, Biogeochemistry).

Analyzing the publications using the term *subterranean estuary* exclusively, only 14% are in hydrological sciences journals (Fig. 2) while the same analysis combining both *subterranean estuary* and *coastal aquifer** increases this number to 27% (Fig. 2). In the analysis of the publications with the term *coastal aquifer** it is clear that it is much more frequent in hydrological sciences journals (73%) than in marine sciences journals (3%) (Fig. 2). Even if publications using *subterranean estuary* are a minority, most have been published in recent years, pointing to a potential new trend in terminology within the scientific community to which the publication is directed (for example, the ratio of publications using *subterranean estuary* to

those using *coastal aquifer** increased from 7% in the period 2000-2004 (7/91) to 15% for 2014-2019 (72/485).

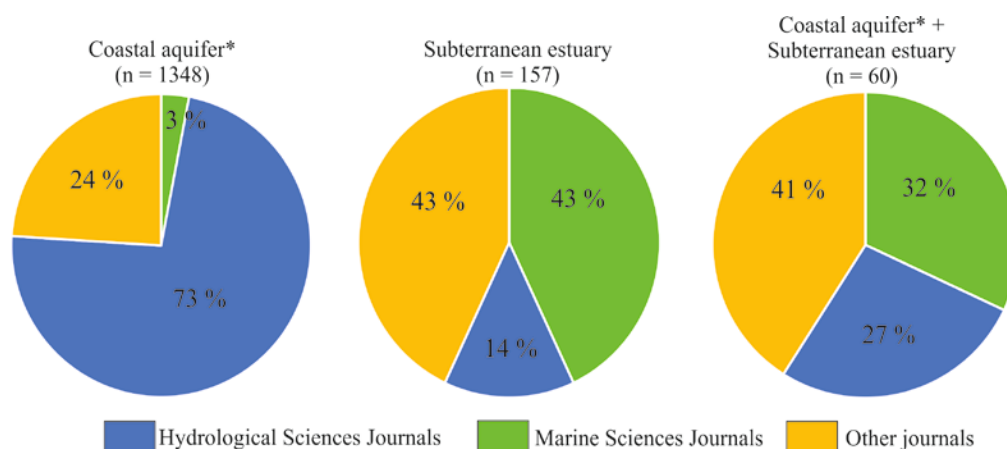


Figure 2. Percentage of publication type using different terminologies,

2 Discussion

The differences in terminology can cause problems in communication between different researchers and communities, potentially creating a barrier to knowledge sharing. Since the term *subterranean estuary* has been developed relatively recently, it is worth comparing its characteristics with those of existing terms.

We first explore the limits of the estuary analogy. One of the main sources of confusion with use of the term is the word *estuary*. From a geological viewpoint, a *subterranean estuary* could be envisioned as a paleoestuary located in the stratigraphic record or possibly as the aquifer beneath a surficial estuary. It could even, in a worst case scenario, reinforce old public misperceptions that groundwater flows as underground rivers. An estuary is also often considered a geographical feature involving an embayment and a confined exchange with the ocean, whereas a *subterranean estuary* is fully extensive along coastlines. The boundaries of coastal aquifers are usually defined by hydrostratigraphic features (the extent of permeable sediments or rocks), while the *subterranean estuary*, particularly if defined primarily as the mixing zone between fresh and saline groundwater, could migrate in response to saltwater intrusion or changes in rainfall. Finally, it is not clear how deep the *subterranean estuary* extends in multilayered systems (multiple stacked aquifers separated by confining units), which are common in coastal areas. The term *subterranean estuary* is usually applied for shallow processes with strong interactions with surface water that may not occur in deeper strata.

The term *subterranean estuary* has also been used in different ways by different researchers. In the published literature, *subterranean estuary* is frequently used as a substitute for *coastal aquifer* (i.e. the geologic system in which coastal groundwater is located, whether fresh, brackish, or saline). In other cases, it can be easily replaced by *saltwater-freshwater interface*, referring to just the mixing zone itself, particularly when the focus is on chemical reactions. In these cases, it tends to be presented as a physical system or location (unless explicitly expressed as dynamic). However, sometimes the term is used to describe interactions with surface water (which in this case is seawater or estuarine water), perhaps more synonymous with coastal *groundwater-surface water interaction* processes. One of the major elements that support the use of *subterranean estuary* is the biochemical connotation, but that aspect is commonly the least prominent aspect of the estuary analogy for those beyond the chemical oceanographic community.

From this analysis it can be inferred that the main conflict of the term is that it fits very well for the oceanographic community due to their knowledge about estuaries, biochemical reactions, and freshwater and saltwater fluxes in coastal areas. But it may be a source of confusion (Duque and Michael, 2018; Jiao and Post, 2019) for those who are less familiar with estuaries, including many within the hydrology community. As a result of this potential confusion and the broad and varied usage of *subterranean estuary*, its meaning can appear poorly defined, generating uncertainty even when used by authors who know the term well.

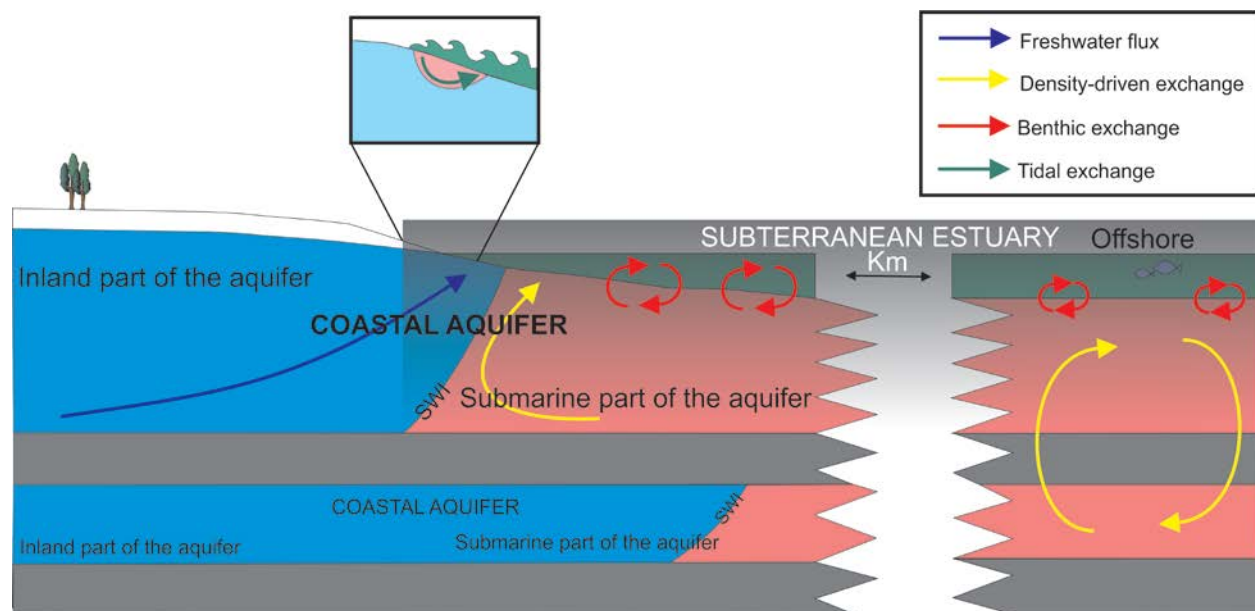


Figure 3. Schematic view of the part of a coastal aquifer interacting with the sea. SWI means saltwater-freshwater interface and divides the areas dominated by freshwater (in blue) and

saltwater (in red). Primary flow mechanisms and proposed subterranean estuary extent are presented, including benthic exchange following the definition of Huettel et al. (2014) and the intertidal circulation cell (Robinson et al., 2006). Figure not to scale.

To resolve these sources of confusion, we propose an addition to the original definition in which the subterranean estuary is defined as the part of the coastal aquifer that interacts actively with the ocean. This definition includes fresh groundwater that is influenced by tides or that could discharge to the ocean; the zone of mixing between fresh and saline groundwater; and entirely saline groundwater that may exchange with the ocean far offshore (see George et al., this issue). The analogy with surface estuaries breaks down somewhat with this definition, because, although surface estuaries commonly include freshwater tidal systems, they typically do not extend to purely saline systems. However, given the importance of purely saline exchange in coastal systems (Huettel et al, 2014; Moore, 2010), this may be a compromise worth making.

With this new definition in mind, we ask again what exactly a subterranean estuary is and whether it is distinct from features and processes described by traditional terms. We suggest that subterranean estuaries, together with the mixing and reaction implied by that term, would be located within coastal aquifers. Our questions about whether subterranean estuaries are confined to shallow depths, or whether they include deep, confined aquifer layers then depend on the scale of interest. For example, the significant volumes of freshwater stored below continental shelves (e.g., Post et al., 2013) may not be part of the subterranean estuary if they are not actively exchanging with seawater, but for systems with more active offshore exchange or for those studying the impact of variations in sea level over 100 ky time scales (e.g., Cohen et al., 2010), the entire system may be included.

We can then consider the juxtaposition of our current set of terms. Using the above definition, the subterranean estuary probably would not move, or intrude, inland over short time scales, because the position of the saltwater-freshwater interface would not measurably affect the zone influenced by tidal fluctuations. Over longer time scales, sea-level rise or fall will certainly cause surface estuaries and subterranean estuaries to migrate with the shoreline, while the rock or sediments that comprise coastal aquifers will remain stationary. In our usage here, the *freshwater-saltwater interface* and *saltwater intrusion* are well defined terms that apply to portions of or processes within the *subterranean estuary*, which itself occupies key portions of *coastal aquifers*. We could still ask whether the mixing and reaction of a subterranean estuary could instead be described by *groundwater-surface water interactions*, but in coastal zones this introduces several other examples of terminology that differs by discipline (e.g., Wilson et al., 2016). For now, let us observe that saltwater intrusion and submarine groundwater discharge pull in opposite directions, even if they occur contemporaneously, and whether these processes are associated with coastal aquifers and subterranean estuaries is likely to remain a matter of individual preference.

Although some might like to see both communities converge on the term *coastal aquifer*, the loss of the term *subterranean estuary* would mean the loss of the connotations that have played a part in spurring the interdisciplinary science that is redefining our understanding of the functioning of the subsurface interface between land and sea, encompassing complex physical, chemical, and biological processes. And while confusing for some, it is a synthetic and practical term for others. It is also a reminder of the need to work together, from both sides of the coastline, to tackle the scientific questions that will advance our ability to manage groundwater resources, protect coastal ecosystems, and close chemical ocean budgets.

3 Final thoughts

We propose two ideas moving forward. 1- *Subterranean estuary* as a concept. Retain the traditional hydrogeological terms when referring to particular aspects of a coastal groundwater system (i.e., *coastal aquifer*, *freshwater-saltwater interface*, *saltwater intrusion*) and use subterranean estuary when referring to the complex zone of subsurface land-sea interactions as defined above - the system that conceptually includes all of the relevant physical, chemical, and biological aspects that excite researchers working at the land-sea intersection; 2- Adopt a new term – *subterranean mixing and reaction field*. This term is more specific than subterranean estuary, with less confusion related to the analogy, and it preserves the concept that these zones are hydrobiogeochemically dynamic. We acknowledge that this new term would add several syllables and retain the word most likely to be mis-spelled, but perhaps these disadvantages would be offset by the acronym, SMRF (Pronounced “smurf,” a widely recognized Dutch term. For readers not familiar with this term, a smurf is a small blue cartoon character). Certainly these are not the only two options, and another is to carry on with current usage. We intend this essay to catalyze dialogue between researchers and communities in order to broaden awareness, promote understanding, and create new cross-disciplinary interactions.

Acknowledgments

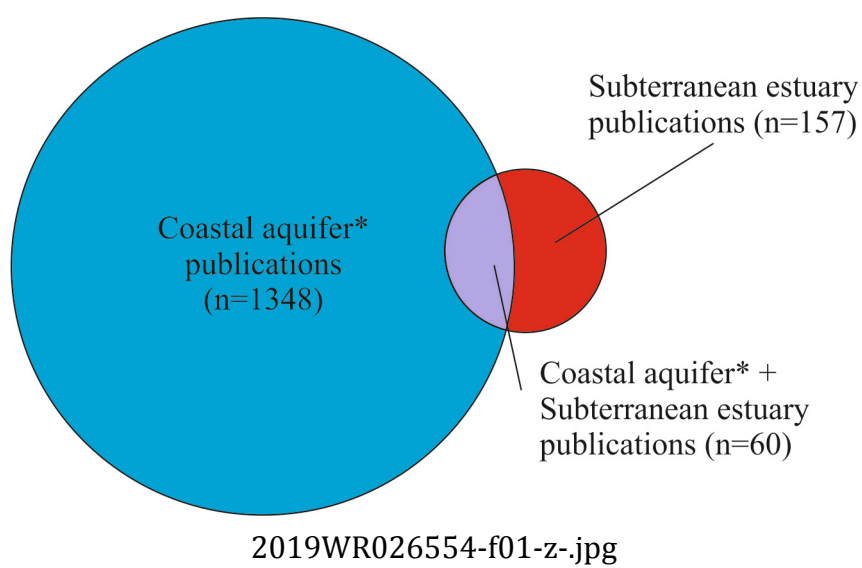
The research leading to this work has received funding from the European Union Seventh Framework Programme [FP7/2007-2013] under grant agreement number [624496] and the US National Science Foundation: NSF EAR-1151733 and OIA-1757353. We thank the SWIM community for fruitful discussions about the topic covered in this publication. This work was carried out as part of the activities of the Aarhus University Centre for Water Technology, WATEC.

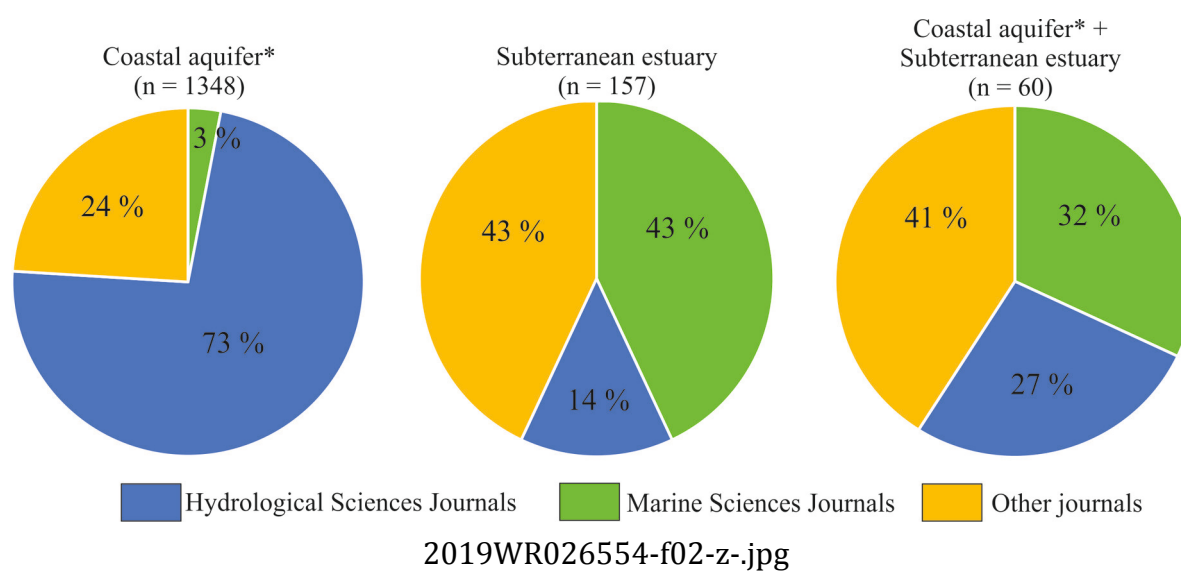
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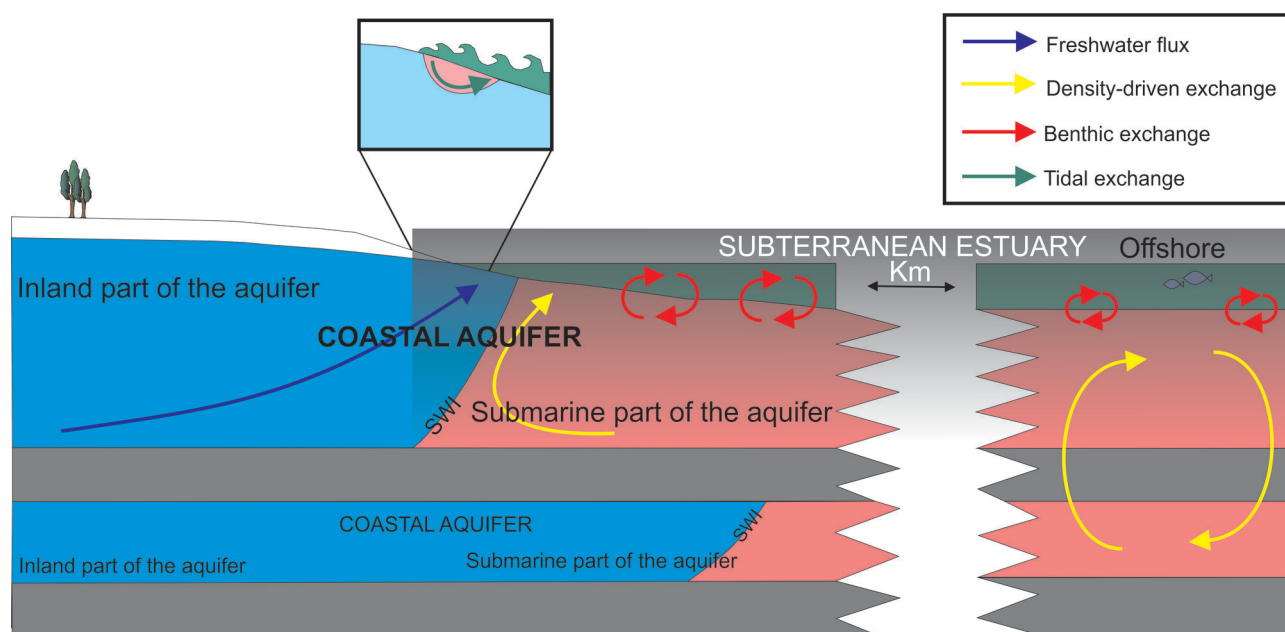
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