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History and evolution of seepage meters for quantifying flow between groundwater and surface water: Part 2 – Marine settings and submarine groundwater discharge

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ABSTRACT

This review of studies that quantified fluxes with seepage meters in marine settings in the last decades shows the historical evolution of this device and the knowledge acquired during this period. Coastal environments are differentiated from freshwater settings due to water salinity and the effects of tides and waves that have important implications for the measurement approach and generated results. The framework in which seepage meters have been used in marine settings has evolved in parallel to the understanding of submarine groundwater discharge. This review of seepage meter research shows: an uneven distribution of studies in the world with some densely-studied regions and an absolute lack of data in other regions; a dominance of studies where only seepage meters were used compared to studies that combined seepage meter measurements with values determined with radioactive tracers or hydraulic calculations; and a variety of publication outlets with different focuses (hydrology, oceanography or multidisciplinary). The historical overview of the research conducted with seepage meters shows the wide range of seepage meter applications – from simply measuring fluxes at local scales to larger studies that extrapolate local results to estimate fluxes of water, nutrients, and other solutes at regional and global scales. A variety of automated seepage meters have been developed and used to better characterize short-term groundwater-seawater exchange, including the effects of waves and tides. We present recommendations and considerations to guide seepage meter deployment in marine settings, as seepage meters are still the only method that quantifies directly the interaction between groundwater and surface water.

1. Introduction

Seepage meters have been used in fresh-water settings since the 1940s, but the first mention of their use in a marine setting was on the east coast of North America in 1977 (Lee, 1977). Identical designs were used in both fresh and saline settings during the first decade of seepage-meter use in marine settings (e.g., Bokuniewicz, 1980; Vanek and Lee, 1991; Yelverton and Hackney, 1986). However, due to complexities with variable salinity and density, and intense hydrodynamic drivers in higher-energy coastal settings, seepage meters designed for marine use began to evolve on a separate path from freshwater instruments. Coastal areas are often exposed to tides and large waves, while in freshwater environments, with the exception of lakes that are large or have a long fetch, tides are non-existent or greatly reduced and waves are often a much smaller concern.

Dynamic marine settings provide additional challenges but also opportunities for characterizing fluxes. For example, salinity introduces the additional complexity of variable-density flow, but it can also aid determination of the origin of the water being studied. In coastal areas, freshwater is terrestrial in origin and driven by a land-to-sea hydraulic gradient, whereas saline water originates as surface water (e.g. estuaries, seas and oceans). Saline water is driven by a variety of mechanisms, such as density-driven circulation, waves, and currents (e.g. Santos et al., 2012), which are typically of minor importance or altogether absent in freshwater environments.

The interface between freshwater and saltwater has long been characterized for static (Drabbe and Badon Ghyjben, 1889; Herzberg, 1901) and dynamic (Cooper, 1959; Kohout, 1964) conditions, and so too has the relationship between freshwater discharge and offshore distance (Glover, 1959). Discharge from a coastal aquifer is fresh closest to the shoreline, then transitions to brackish with greater distance from shore, until at some point it acquires a salinity similar to the overlying

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marine surface water. The width of each zone (fresh, transitional, or saline) depends on hydrogeology, terrestrial hydraulic gradient, and surface-water characteristics (e.g. salinity, tidal range, depth). The need to quantify discharge of fresh water and associated solutes to marine settings has been one of the major drivers in the development and use of seepage meters in coastal zones—particularly for quantifying nutrients that can degrade valuable coastal ecosystems (Johannes, 1980; Slomp and Van Cappellen, 2004; Valiela et al., 1990; Wang et al., 2018). In light of this global interest, a new term was coined: submarine groundwater discharge (SGD). Initially, the exact meaning of SGD generated controversy due to a lack of consensus regarding the types and scales of fluxes related to variable research objectives (see replies between Moore and Church, 1996 and Younger, 1996). Additional descriptors were added to the SGD definition such as fresh, salty, marine, terrestrial or recirculated as the discussion in the literature extended for several years. Conversations regarding terms continue to appear frequently depending on the environment and field where SGD is considered.

This discussion led to a growing realization of the global importance of SGD, and the need to quantify these fluxes drove a coincident and substantial evolution of the seepage meter. Here, we present a chronological review to describe the major research findings and evolving methodologies of marine seepage meter studies. Thereafter, we present several recommendations for successful and accurate seepage meter deployments based on recommendations from the literature. We then describe the types and capabilities of several automated seepage meters and the current knowledge about the effect of tides and waves on all designs of seepage meters.

2. An overview of seepage meters studies in marine settings

We have identified 103 studies where seepage meters were used in the context of coastal environments. Most of these studies (47%) were conducted in bays or lagoons protected from wave action, 35% were conducted in coastal areas exposed to oceanic-scale processes, and 18% were conducted in laboratory or controlled settings (Fig. 1A). It is likely that the largest percentage of studies was conducted in protected environments because they are the most suitable for seepage-meter deployment. Studies located in North America are the most common (most conducted in the USA), followed by Asia and Europe, with only a few studies taking place in Oceania and Africa (Fig. 1B).

Studies using seepage meters as the only method to quantify flux were the most common but use of seepage meters in combination with radon or radium also were frequent, as was combining seepage meters with the gradient-driven Darcy method (Fig. 1C), which is calculated from local measurements of vertical hydraulic gradient and vertical hydraulic conductivity. In this classification, other methods, such as geophysical or numerical modelling, were not considered as they are usually verified with other indirect methods that quantify flux (i.e. tracers, water budget estimations).

The range in orientation of the journal where these studies were published is an indicator of the broad disciplinary appeal of the use of seepage meters for quantifying groundwater-surface-water exchange. This synthesis of the literature indicated that many seepage-meter studies conducted in marine settings were published in journals well outside of the marine science and oceanographic community, demonstrating the multidisciplinary importance of SGD and associated processes. Based on the 103 studies evaluated here, less than half (48%) were published in marine-focused journals, followed by an almost equal proportion of hydrology-focused journals (27%) and other multidisciplinary or other thematic journals (25%) (Fig. 1D). Differences in disciplines represented by journals can lead to use of different methodologies or even terminology for similar study designs and goals (i.e. Duque et al., 2020).

3. Historical review of studies using seepage meters in marine settings

3.1. 1970s and 80s: first usage in marine settings

Seepage meters were first deployed in a marine setting by David Lee (1977), who showed that fluxes were correlated to the tidal level. Several years later, Bokuniewicz (1980) attempted to quantify fresh groundwater discharge into Great South Bay on Long Island (NY, USA) to characterize the effect on the salinity of the bay and the local hard clam industry. Seepage meters were deployed in a series of cross-shore transects of 6–10 seepage meters up to 100 m offshore. The results showed that groundwater discharge decreased exponentially with distance from the shoreline (as previously noted for freshwater lakes by Lee, 1977 and McBride and Pfannkuch, 1975) and these exponential distributions were used to estimate the freshwater input at the bay scale. The effect of tides was documented, as well as the presence of erratic measurements not following any pattern. The lack of surficial streams discharging to the coastline further supported the predominance of fresh groundwater discharge that was responsible for the fresh-saline equilibrium of coastal waters (Bokuniewicz, 1980). Much of this early work focused on defining discharge patterns to accurately estimate regional groundwater discharge rates to coastal waters with the fewest measurements. This concept was also applied to large lakes. Cherkauer and Nader (1989) discussed the challenge of large spatial variability of seepage attributed to natural heterogeneity in hydraulic properties of near-shore sediments. Additional sources of uncertainty were identified including measurement duration and sampling frequency, and best practices were developed due to the lack of precedents (Lee, 1977; Shaw and Prepas, 1989). Early deployments of seepage meters also were made in estuaries (Zimmermann et al., 1985), coral reefs (Lewis, 1987), and salt marshes (Whiting and Childers, 1989).

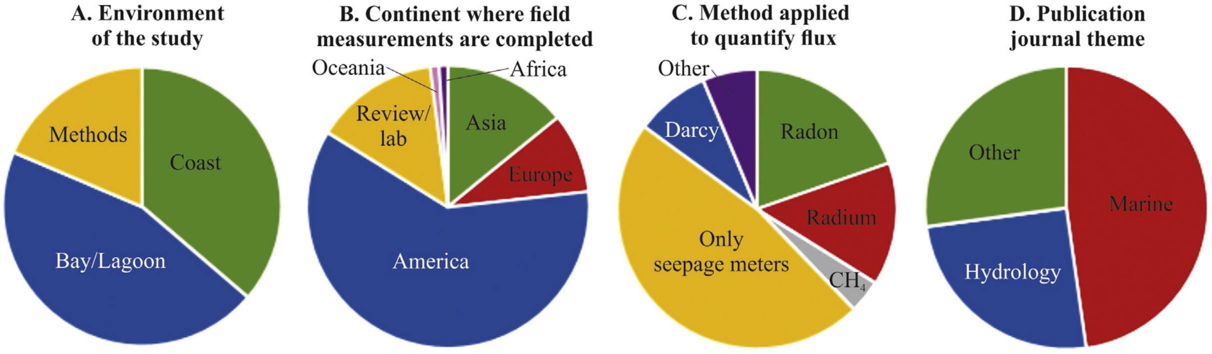

Fig. 1. Pie charts for different classifications in the 103 studies used in this review that applied seepage meters in marine settings.

3.2. 1990s: Interest in submarine groundwater discharge from the oceanography community

Continuing studies on Long Island focused on how salinity affected groundwater discharge and the generation of freshwater lenses in a barrier island (Bokuniewicz and Pavlik, 1990) and on defining groundwater-discharge patterns using analytical methods (Bokuniewicz, 1992). The lessons gained from lacustrine studies (spatial trends and distributions of seepage meters to identify water-exchange patterns) were applied in coastal environments to understand how groundwater discharge was controlled by morphology of the coastline (Cherkauer and Mckereghan, 1991). Studies also began to examine the role of groundwater as a carrier of nitrate and other nutrients and contaminants (Cherkauer et al., 1992; Gallagher et al., 1996; Giblin and Gaines, 1990; Reay et al., 1992). Parallel to these field investigations, new laboratory studies to characterize uncertainties related to seepage-meter measurements (flow field deflection, frictional resistance and head losses within the meter) suggested that caution should be applied when extrapolating seepage data for entire systems with limited data because of complex groundwater-surface water interaction (Belanger and Montgomery, 1992) and the effect of surficial currents in water bodies in which the seepage meters were installed (Libelo and MacIntyre, 1994).

Until the early 1990s, seepage-meter applications in fresh and marine settings followed parallel paths. Although coined much earlier (Zektzer et al., 1973), the term submarine groundwater discharge began appearing in published works with greater frequency (Johannes, 1980; Simmons, 1992), and for the first time was associated with seepage-meter investigations (Vanek and Lee, 1991). These studies included discussion of chemical and biological processes related to seepage in these near-shore marine settings, and the SGD phrase inspired a new line of research that grew rapidly during the following decades. When Zektzer et al. (1973) first used “submarine groundwater discharge” in an overview of the global effect of groundwater discharge to marine margins, they proposed several methods (coastal techniques, sea techniques, seawater methods and sea-bottom methods) to quantify that exchange. Seepage meters were not included in their listed methods because, at that time, seepage meters were almost exclusively applied to canal lining experiments (Israelson and Reeve, 1944; Rohwer and Stout, 1948) and had not yet been widely used in lake and wetland settings.

The recognition of the impact of SGD grew substantially in marine literature through the 1990s. Seepage meters were applied to both quantify fluxes and assess the spatial variability of those fluxes (Cable et al., 1997a) while, simultaneously, the errors associated with their use (seepage-bag issues, measurement duration, frequency of sampling) were being described and determined (Cable et al., 1997b). Robinson et al. (1998) highlighted the lack of studies in near-shore environments and differentiated the fluxes measured with seepage meters between total flux and freshwater flux based on electrical conductivity measurements of water collected in the seepage-meter bags. Separating freshwater flux from total flux was essential to better estimate nutrient and pesticide discharge originating from inland sources (Gallagher et al., 1996).

As larger seepage meter studies were undertaken to characterize the variability of SGD in space and time and over large areas, the high-labor requirements led researchers to develop alternative techniques for quantifying SGD. Automated seepage meters were invented that could be deployed for extended periods without a seepage bag or human intervention (see Section 5). Groundwater tracer methods were developed to provide regional estimates of SGD that integrated the impact of spatial variability that had widely been detected. Methane (CH4), ^{222}Rn, and Ra isotopes were proposed as tracers (Moore, 1999, 1996) due to their natural presence in groundwater and their relatively large groundwater concentrations compared with ocean water. Initial studies characterized SGD along the Florida Coast using a combination of tracers (^{222}Rn and CH_4) and seepage meters (Bugna et al., 1996; Cable et al., 1996a, 1996b) and applied a mass-balance approach for estimating regional SGD. Continuing work joined these methods with measured nutrient concentrations to estimate regional nutrients fluxes (Corbett et al., 1999, 2000). These studies validated the chemistry-based methods with seepage-meter measurements—this pairing has continued in many of the subsequent isotopic tracer studies.

3.3. Early 2000s: Drivers of SGD

The publication of SGD studies in high-impact journals (e.g. Moore, 1996) and the recognition from oceanographers of the importance of SGD as a source of fluids and solutes brought increased interest to oceanography that was strongly linked to seepage meters. For example, in a 2004 *Ground Water* special issue focused on the uncertainty of SGD fluxes and driving mechanisms, four of the twelve articles featured seepage meters. Paulsen et al. (2004) investigated the effect of tides on fluxes measured with an automated seepage meter. Bokuniewicz et al. (2004) compared seepage-meter data to data collected using other field methods. Martin et al. (2004) assessed mixing processes in the top centimeters of a seafloor aquifer. Cable et al. (2004) examined mechanisms beyond the terrestrial hydraulic gradients that drive SGD. Seepage meters served as the fundamental measurement method to investigate uncertainties about the processes, relevance, and approaches for studying SGD. Publications relied on seepage-meter measurements to: characterize coastal typology (Bokuniewicz, 2001; Bokuniewicz et al., 2003); provide context to quantified fluxes (Burnett et al., 2001; Loaiciga and Zektser, 2003); compare measured fluxes to numerical model and tracer approaches (Burnett et al., 2002; Garrison and Glenn, 2011); validate hydrogeological models that explained SGD (Smith and Zawadzki, 2003); and describe implications for dissolved-metal budgets (Spinelli et al., 2002).

The expansion of SGD studies with seepage meters triggered a discussion about the drivers of the exchange. Researchers observed that fluxes with variable salinities would have different origins. Although fresh-water seepage had a clear origin (fresh water is driven by the terrestrial gradient), the mechanisms that generated fluxes farther from the coastline, dominated by saltwater, would be more diverse. The differentiation between the different types of SGD (saline and fresh, recirculated and terrestrial) and the specific definition about the meaning of SGD were discussed in the first compilation paper on this subject (Taniguchi et al., 2002). A historical review of SGD (Burnett et al., 2003), partially based on previous investigations and replies presented by Li et al. (1999), Moore (1996), Moore and Church (1996) and Younger (1996), compared measured seepage with results from theoretical flow modelling and Ra mass balances. Still, the precise definition of SGD varied between papers (Martin et al., 2004) and required clarification of terms in each publication during this period.

The drivers of SGD remained a focus of interest, especially how SGD varied in response to tidal variation (Chanton et al., 2003; Michael et al., 2003; Taniguchi, 2002; Taniguchi et al., 2003) (see Section 6). The continuing development of automated seepage meters allowed quantification of SGD over shorter time scales (Paulsen et al., 2001; Taniguchi and Iwakawa, 2001; Tryon et al., 2001) to relate flux data with tidal oscillations (Sholkovitz et al., 2003; Taniguchi et al., 2005; Taniguchi and Iwakawa, 2004). The types and ranges of applications of automated seepage meters will be specifically explained later (see Section 5). Research also showed that surface-water currents, waves, and tides induce benthic exchange between surface water and groundwater in the seafloor aquifer. This recognition introduced additional sources of uncertainty to seepage meter measurements, which were quantified with a series of methodological studies (Murdoch and Kelly, 2003; Shinn et al., 2002) and discussed thoroughly (Corbett and Cable, 2003; Shinn et al., 2003) for marine settings.

Following the distinction between the different types of fluxes (driven by hydraulic gradient, density or tides and waves) and their association with salinity, Michael et al. (2003) characterized the spatial variability of fluxes and salinity distribution with a grid of seepage meters. Continuation of this research led to one of the most cited publications based on the use of seepage meters that showed that SGD varied in response to seasonal terrestrial recharge patterns, which added seasonality as a key factor in the study of fluxes and nutrients delivery to the coast (Michael et al., 2005).

3.4. Late 2000s: spreading SGD studies globally

An increased interest in quantifying SGD at the global scale brought an expansion of seepage-meter investigations from study areas that were located primarily along the east coast of the USA (and a few isolated studies in Sweden and Australia) to multiple locations in other continents. SGD was measured at a broad range of geological, hydrological and oceanic settings and compared with different methodologies—these included radioactive tracers (Rn and Ra) and automated seepage meters. These studies also considered short-term changes (tidal oscillations) and local hydrogeological or anthropogenic factors. Studies during this period were completed in Japan (Taniguchi et al., 2006c, 2006b), China (Peterson et al., 2008), Philippines (Taniguchi et al., 2008a), Israel (Weinstein et al., 2007), Portugal (Leote et al., 2008), Thailand (Taniguchi et al., 2007), Italy (Burnett and Dulaiova, 2006; Moore, 2006; Taniguchi et al., 2006a), Australia (Burnett et al., 2006), Brazil (Bokuniewicz et al., 2008; Taniguchi et al., 2008b), and Mauritius (Burnett et al., 2006). Studies conducted in the last 4 countries together with USA (New York) (Dulaiova et al., 2006; Stieglitz et al., 2007) were included in a joint initiative supported by UNESCO and the International Atomic Energy Agency (IAEA) (Burnett et al., 2006). The differentiation between fresh and saline sources of SGD and the quantification and impact of each of them are more frequently discussed in this period (i.e. Martin et al., 2007). During this time of rapid adoption of seepage meters, only a few reviews included information about seepage meters in marine settings (i.e. Brodie et al., 2009) or about SGD in general (i.e. for Japan by Gallardo and Marui, 2006).

Geophysical measurements were added as a complementary tool to better characterize the hydrogeology and salinity of the seabed aquifer and to guide the deployment of seepage meters. Electrical resistivity was used to facilitate monitoring of groundwater discharge (Simonds et al., 2008; Taniguchi et al., 2007) and detect heterogeneities in fractured environments difficult to capture by seepage meter installation (Stieglitz et al., 2008b). Bulk electrical conductivity was used to separate fresh and recirculated fluxes (Stieglitz et al., 2008a). A combination of radon and radium isotopes, electrical resistivity, and automated seepage meters was used to estimate nutrient delivery (Swarzenski et al., 2007). Improvements in methodology and resulting local knowledge increased confidence in the upscaling of fluxes estimated with seepage meters and the joint use with radioactive tracers allowed the quantification of biogeochemical transport (Swarzenski et al., 2006).

Investigations about the sources of uncertainty of using seepage meters brought a new element called bioirrigation into the discussion, following the observation of higher groundwater flow rates in shallow compared with deeper sediments (Martin et al., 2004), and the specific study of this phenomenon (Cable et al., 2006). Bioirrigation consists of flow through excavated tubes and shallow sediments generated by benthic organisms, roots, or crab burrows in the marine/bay bed sediments. Coastal areas are characterized by shallow water with high biological activity, and the presence of these types of structures can be assumed as frequent. Bioirrigation was suggested as a source of anomalous seepage meter measurements that could not be related to hydraulic properties (Cable et al., 2006).

By the late 2000s, the study of SGD was strongly associated with oceanographic studies while the “land hydrogeologist” in coastal areas focused primarily on saltwater intrusion with limited interest in SGD. Kazemi (2008) drew attention to the bias in this research line due to the disciplinary perspective and the lack of collaboration between land and ocean researchers. This observation can be also applied to the different ways that seepage meters were used among separate disciplines. Different seepage-meter designs, applications and uses evolved for lake-, river-, or land-based studies (see part 1, Rosenberry et al., 2020) compared to the marine studies emphasized herein, as well as the differences in publication outlet (Fig. 1).

3.5. Recent progress and trends

In the last 10 years, SGD has been increasingly recognized for delivering chemical loads to coastal areas with broad implications for nearshore marine ecosystems and for the understanding of chemical balances in the oceans. The drivers of SGD, the different types of fluxes that can be measured, and the existing methods for quantification are reasonably clear following numerous studies describing groundwater flow in coastal regions (Santos et al., 2012), introductory chapters in books and compilation studies (Moore, 2009), and intercomparison studies that apply seepage meters and other methodologies to improve characterization of SGD (Duque et al., 2019; Povinec et al., 2012; Tirado-Conde et al., 2019). Seepage-meter studies have focused on combining different methodologies for obtaining an integrated understanding of coastal systems (Swarzenski and Izbicki, 2009), developing methods to differentiate the contribution of fresh and saline SGD (Santos et al., 2009), or solving specific problems in a study area (Mwashote et al., 2013; Rapaglia et al., 2010; Rapaglia and Bokuniewicz, 2009; Weinstein et al., 2011). In each case, seepage meters were used to verify or establish the order of magnitude of SGD or to calibrate other methods.

Despite the variety of goals and locations, one characteristic is common among almost all these studies. While the variable nature of SGD precludes upscaling a limited number of seepage meter measurements to estimate regional scale SGD rates, seepage meter measurements can be used to validate other methods and minimize associated uncertainties. This measurement-scale problem has been recognized for decades but is still being mentioned in recent studies (e.g. Kao et al., 2013). A common consequence is that studies tend to use fewer seepage-meter measurements because they have a secondary role (i.e. to validate results obtained by other more scale-appropriate methods). A similar situation can be observed with the use of automatic seepage meters. While temporal changes in SGD can be quantified with great detail, the number of automated seepage meters is commonly small due to the cost of the device (Swarzenski and Izbicki, 2009; Taniguchi et al., 2014; Uddameri et al., 2014), which limits the comparison between high temporal and high spatial resolution in spite of the evidence of high variability in both temporal and spatial scales. Although very labor intensive, some studies have used large numbers of seepage-meter measurements to characterize discharging fluxes in connection with geological heterogeneity (Russoniello et al., 2013; Sawyer et al., 2014), differentiate the impacts of inland recharge due to monsoon on SGD (Debnath and Mukherjee, 2016), or propose conceptual discharge models to lagoons (Duque et al., 2018).

New data sources, techniques and tools are being used to quantify SGD at larger scales, but seepage-meter data remain essential to validate these new methods. Sawyer et al. (2016) estimated SGD for the contiguous USA and relied on seepage-meter measurements from 16 previous studies to demonstrate the reliability of this new approach. Seepage-meter studies in marine settings continue to spread to more countries and to applications in more challenging settings. Studies have been conducted in cold conditions where the operating characteristics of seepage meters are more difficult (Duque et al., 2018; Michael et al., 2005), in high-energy and deep-water settings, such as offshore of Antarctica (Uemura et al., 2011), and in extreme water depths up to 6 km (Tryon et al., 2001). Cold-water measurements also have been made in freshwater settings where seepage-meter measurements were made through holes cut in frozen lakes (Jones et al., 2016; Sebok et al., 2013).

The cost of data acquisition and the excessive labor requirements can make the utilization of seepage meters expensive despite the low cost of device construction. Still, the value of the measurements can be extended beyond the original intentions of the study by using data collected in previous studies with different aims where the knowledge about fluxes is needed (e.g., Bokuniewicz, 1992; Debnath et al., 2019; Michael et al., 2011; Sawyer et al., 2014; Smith et al., 2008). Also, the uncertainties about regional and global estimates of SGD are frequently driving the review of fluxes measured in previous studies (Taniguchi et al., 2002) or to calibrate new techniques. The re-utilization of fluxes measured with seepage meters can be applied in the calculation of transport of substances that were not considered in initial stages of research or in future circumstances as new contamination events are discovered. Hence, there is a big potential in the use of seepage meters not only for immediate purposes in unexplored areas or countries where there is a lack of knowledge but also for future application and understanding of potential contaminant processes associated with SGD.

4. Practical considerations for deployment of seepage meters in coastal areas

The review of the different studies using seepage meters in coastal areas provides advice or implicit recommendations when using them. In published studies, some researchers introduced a clear methodological message while others simply mention the approach in their specific application. A synthetic compilation of different recommendations (Table 1) has been made with a short analysis including the advantage of considering each technique or specific alteration along with potential challenges for its implementation. Some suggestions or recommendation may not apply to every setting due to local physical conditions (e.g., bedrock at the sediment-water interface), climatic conditions, or restrictions in personnel and budget.

5. Automated seepage meters

Automated seepage meters allow measurement of seepage over long deployment periods, in hazardous locations, and at much faster sampling rates than can be achieved with sampling bags on manual seepage meters—all without the human labor requirements of traditional seepage meters. However, automated designs are not as widely used because of the increased expense, fabrication complexity, and difficulty of deployment and retrieval. Most designs are similar to a manual seepage meter, but with an electronic flow meter or dye-dilution device replacing the seepage collection bag (Fig. 2). Some flow meters are commercially available (Mwashote et al., 2010; Rosenberry and Morin, 2004) whereas others are custom built (Sholkovitz et al., 2003; Zhu et al., 2015). Electronic flowmeters use heat-pulse, electromagnetic, or an ultrasonic theory to characterize flow. While each flow meter is only suitable for measurement of velocities within a certain range, slower velocities can be amplified by ganging seepage meters (Rosenberry, 2005) or varying the seepage chamber diameter (e. g. Sholkovitz et al., 2003). These devices permit a much faster sampling rate than Lee-type seepage meters, which allows characterization of short-duration processes such as seiches (Taniguchi and Fukuo, 1996), tides (Paulsen et al., 2004; Taniguchi and Iwakawa, 2001), and recharge events (Rosenberry and Morin, 2004). Automated flow meters do not require continuous monitoring during deployment, allowing longer-term deployments or measurements in locations with limited human access (Swarzenski and Izbicki, 2009). This also allows seepage measurements where human access might be costly, unpleasant or dangerous—for instance, deep water (Taniguchi and Fukuo, 1993; Tryon et al., 1999; Uemura et al., 2011) or in high latitudes where cold water can complicate manual measurements, as discussed by Duque et al. (2018) and Mwashote et al. (2010).

Like traditional seepage meters, water chemistry measurements may be collected during a deployment to further characterize seepage chemistry (e.g. Krupa et al., 1998) or chemical parameters may be automatically measured by collocated instruments such as conductivity-temperature sensors (Duque et al., 2019; Russoniello et al., 2013) or nutrient analyzers (Sholkovitz et al., 2003). An automatic seepage meter that allows the collection of samples is proposed by Lee et al. (2018) adapted to the tidal oscillations of coastal areas with a floating unit that oscillates with the bay/sea level. The seepage meter has an exit tube that allows outflowing of head water in the seepage meter chamber when exceeding the surface water head that facilitates sampling. Chemical sampling of reactive species from seepage meters may be problematic for two reasons. First, species may sorb to or desorb from seepage chamber interiors with changing redox conditions, especially if rusting steel is exposed. Second, the seepage chamber interior is generally anoxic, which may cause chemical reactions to alter species within the chamber (e.g. NO_3 reduction to NH_4, or formation of iron oxide in bed sediment or on the chamber wall, or dissolution releasing sorbed elements). Efforts have been made to construct seepage meters that maintain the same chemistry of the surface water within the seepage chamber by introduction of a permeable membrane or by circulating water through the seepage meter with a pump (Brooks, 2018). Burrowing organisms can also affect sampling, due to high H_2S emissions caused by preferential flowpaths, and bioirrigation processes (Cable et al., 2006).

Most automated seepage meters have several limitations in common—most notably, the high cost and complicated design. While automated designs are excellent for obtaining time series with high temporal resolution, cost has limited the number of simultaneously deployed seepage meters to characterize the spatial heterogeneity and uncertainty of SGD measurements. Most electronic flow meters require calibration, which may be accomplished in the laboratory before deployment, or by making measurements with collection bags simultaneously with automated measurements (Rosenberry et al., 2013). Automated flow meters frequently have low signal to noise ratio under turbulent conditions, and problems with zero-drift resulting from changing surface-water level (Zhu et al., 2015). Flow meters with narrow tube diameters may invoke head loss and decrease seepage-meter efficiency (Rosenberry and Morin, 2004; Russoniello and Michael, 2015). Finally, although most designs do not require the continual presence of an operator during a deployment, calibration and deployment are generally non-trivial (Mwashote et al., 2010; Sholkovitz et al., 2003; Zhu et al., 2015).

The first automated seepage meter logged the rate that seepage inflated a "bladder" of known volume (Reay and Walthall, 1994, 1991). The fully-inflated bladder tripped a switch that 1) logged the time and 2) started a pump to empty the bladder, which set up the seepage meter for the next measurement interval. This design had very low efficiency, capturing only 21–26% of actual seepage in laboratory calibration and the electromechanical mechanism was more complicated than the designs that would follow.

The most commonly deployed automated seepage meters rely on a flowmeter that consists of a heater and two-or-more thermistors separated by a known distance installed in the seepage meter outflow tube. "Heat pulse" seepage meters measure flow velocity as the time it takes for a pulse of water heated by the heating element to travel to a thermistor (Guaraglia and Pousa, 2014; Taniguchi and Fukuo, 1993; Taniguchi and Fukuo, 1996). Later designs improved on this initial study by adding thermistors to improve accuracy and allow measurement of both inflow and outflow (Krupa et al., 1998), or used thermocouples and moment analysis to improve accuracy (Lien, 2006). "Continuous heat" seepage meters are similar in design, but the heating element continuously warms water in the outflow tube and flux is calculated from the temperature gradient between downstream and upstream thermistors using the Granier method, which improves measurement accuracy (Taniguchi et al., 2003; Taniguchi and Iwakawa,

Table 1
Recommendations for the use of seepage meters in coastal areas based on suggestions from the literature and authors' experience.

Coastal area setting		
Action	Pros	Cons
Measure electrical conductivity (EC) in surface water, in water contained within the seepage cylinder during deployment, in water used to prefill seepage meter bag, and water in the bag following bag removal.	Determination of the seepage salinity and indication of flow origin	Need to wait for complete replacement by discharging groundwater before first bag attachment, assumes complete mixing of water inside the seepage cylinder, need to measure EC inside seepage cylinder and EC of seepage-bag water before and after attaching bag to seepage cylinder.
Use empty bags for chemical sampling	The sample is not mixed with other water type	May induce errors in discharge measurement due to bag elasticity, additional measurements of flux with prefilled bag might be needed
Use hemispherical chambers when waves are large	Decrease of error associated with flexing of the top part of the seepage meter	Requires more specialized seepage-meter construction
Deploy clusters of seepage meters	Provides a range of spatial variability at a meter scale for the assessment of spatial variability	Requires extra seepage meters and extra operators that could be used for covering a more extensive area
Construct conceptual salinity-based models to define the most likely SGD typology.	Define better the objectives of the seepage-meter measurements, allowing the number of measurements to be optimized	Requires exploratory preliminary campaigns or a priori knowledge of discharge patterns that is often the objective itself
Conduct seepage-meter measurements on calm days when waves/currents are low	Decrease the impact of wave setup and wave-induced measurement errors	Precludes data collection during windy periods
Record tide levels in sea/bay	Allows seepage measurements to be related to tidal changes	Requires additional equipment and maintenance
Characterize terrestrial hydraulic heads	Allows determination of fluxes that can be related to changes in recharge, lag times, or influences of storms and rain events	Requires installation of a monitoring well and monitoring equipment
Characterize wave conditions	Improves data interpretation	Requires additional equipment for quantifying waves size and frequency; waves can change during a measuring period
Characterize seabed hydrogeology to determine spatial distribution of hydraulic conductivity	Improves locating seepage meters to measure preferential flow	Not always possible or practical
Measure through a full tidal cycle	A tidally averaged flux value can be determined.	Requires multiple measurements and additional time and field work
Have numerous operators changing bags for campaigns with multiple seepage meters	Allows a better characterization of spatial and temporal variability	Requires a bigger team and increase in the cost of the campaign
Frequent maintenance of seepage meter chambers, including routine painting between deployments	Avoid settlement of organism in conduits affecting flow and prevent metal corrosion generating holes in seepage chamber walls.	Time consuming and increased cost in the short term
Add a floating buoy to seepage meter chamber	Aids location of seepage meters under high tide conditions	Extra work constructing the seepage meter. May introduce error due to float tugging on cylinder.
Use large diameter connections	Maximizes seepage meter efficiency and minimizes uncertainty due to waves	Extra cost for large diameter connections
Use of plastic seepage meters	Eliminates rusting. Reduces chemical alteration of water in the seepage chamber.	Plastic must be rigid to avoid wave-induced deformation. Plastic meters are buoyant, so a weight is required. Less resistant to physical impacts. Difficult to install in hard beds.

2001). Both heat-pulse and continuous-heat designs require a robust power source for the heater and computer logging, so power-supply cables are frequently run onshore (Taniguchi and Iwakawa, 2004) or to a vessel moored near the seepage meter (Mwashote et al., 2010), which may restrict possible deployment locations. Some designs are self-contained and do not require external power. While most studies only deployed one automated seepage meter for relatively short durations, up to five continuous-heat seepage meters have been deployed simultaneously to characterize the cross-shore flux gradient (Taniguchi et al., 2006b) and deployments have lasted up to 2 months (Taniguchi, 2002).

Automated dye-dilution seepage meters function similarly to the heat-based designs, except dye is released as a pulse and concentrations are measured upstream and downstream with a spectrophotometer (Sholkovitz et al., 2003). Whereas heat-pulse seepage meters require a unique heat pulse for each measurement, dye dilution seepage meters can use a single dye pulse release for many measurements of flux. Further advantages of the dye meter include a lack of need for calibration, it can be operated manually without submersible spectrophotometers, and it has a wide dynamic measurement range through simple adjustment of the mixing chamber volume or dye injection interval. Because dye behaves conservatively and does not decay (as heat does), problems can arise if dye that flowed into the seepage chamber later reverses and flows back out. An earlier tracer-based seepage meter for measurement of low-flow exchange at depth up to 6 km collected the dye history within a long coil of tube, so that fluxes could be determined by the concentration record within that tube following instrument retrieval (Spinelli et al., 2002; Tryon et al., 2001, 1999). The relatively low cost of this coil-type seepage meters allowed simultaneous deployment of up to 21 of these instruments. However, these instruments are restricted to measuring seepage velocities below 4 cm/d (Spinelli et al., 2002).

Ultrasonic and electromagnetic (EM) seepage meters allow direct measurement of water velocity in the outflow tube, require no moving parts or replenishment of dyes, and can maintain a high sampling rate. The ultrasonic seepage meter designed by Paulsen et al. (Paulsen et al., 2001) had two piezoelectric transducers facing each other in the outflow tube. The travel time of sound pulses traveling between the two transducers depended on the water velocity and salinity, so that flux could be calculated. Some head-loss was introduced by right angle bends in the outflow tube required by this design. Rosenberry and Morin (2004) designed an EM flow meter, which benefited by not requiring right angle bends in the outflow tube. EM flow meters consist of a non-ferrous flow tube surrounded by an electrical coil that produces a magnetic field. Fluids (fresh or saline) moving through this magnetic field induce a voltage that (according to Faraday's Law) is proportional to the velocity of the fluid and is measured by electrodes that are also mounted on the outflow tube. Both designs are capable of fast sampling rates which allow their application in measuring of fluxes that vary rapidly with changing drivers—the EM design can record

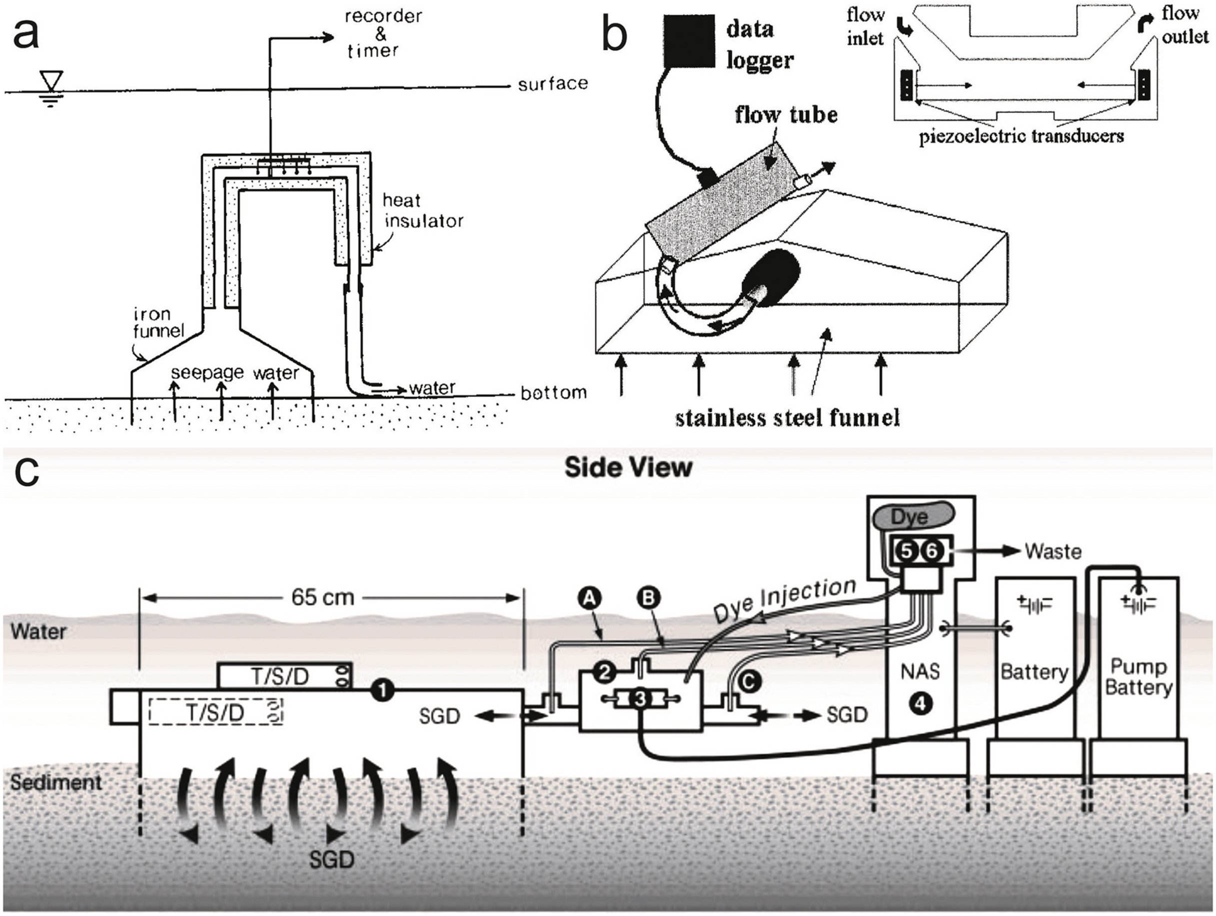

Fig. 2. Different models of automated seepage meters. a) Heal pulse seepage meter (Makoto Taniguchi and Fukuo, 1993). b) Ultrasonic seepage meter (Paulsen et al., 2001). c) Dye dilution seepage meter (Sholkovitz et al., 2003).

measurements at five-second intervals (Rosenberry et al., 2013), and the ultrasonic design is capable of rates higher than 1 per second (Paulsen et al., 2001).

6. Seepage meters functioning with tides

The first published marine deployments of seepage meters identified that tide level was correlated to the rate and direction of seepage flux in estuaries off the coasts of North Carolina and Nova Scotia (Lee, 1977) (Fig. 3). Lee determined that as tides rise and fall, the land-sea hydraulic gradient and resulting seepage also vary. Since then, additional research has characterized the tide-discharge relationship. Unlike fluxes driven by other hydrodynamic mechanisms (i.e. waves and currents), tide-induced flux may be measured with seepage meters because the flux direction and magnitude associated with tidal cycles (~12 h) are relativelyconsistent over the length of a typical seepage meter measurement (minutes to hours).

Tidally-driven fluxes can be attributed to two mechanisms, variation in the land-sea gradient, and variable loading of the seabed. The first mechanism, commonly known as *intertidal pumping*, occurs as surface-water levels vary over a tidal period while the terrestrial water remains relatively static (King et al., 2010; Robinson et al., 2007; Santos et al., 2012). This variation causes an elevated land-sea hydraulic gradient during low tide and a decreased gradient at high tide. Flux is correlated to the tidal amplitude, so discharge is greatest at low tide and lowest at high tide—and aquifer recharge will occur in cases when the high tide level rises above the terrestrial water table (Lee, 1977; Robinson et al., 1998). The discharge response frequently lags behind the tidal level (Taniguchi and Iwakawa, 2001). The second mechanism occurs because the increased load of surface water at high tide causes groundwater recharge, and discharge occurs when that load is removed at low tide (Russoniello et al., 2018; Sawyer et al., 2013; Wang and Davis, 1996). This second mechanism occurs farther from shorelines and at greater

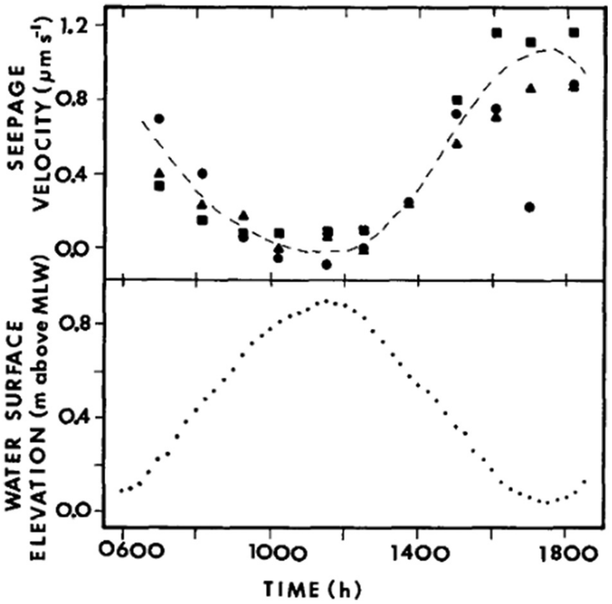

Fig. 3. Seepage velocity and tidal elevation in the first marine seepage meter study (from Lee, 1977).

depths (Fisher, 2005; Tryon et al., 2001).

Seepage is related to multiple constituents of the tidal signal. Several studies with automated seepage meters measured fluxes over periods of up to 2 months and found that discharge and recharge rates correlated to tidal amplitude over diurnal, daily, and spring-neap tidal cycles (Sholkovitz et al., 2003; Taniguchi, 2002; Taniguchi and Iwakawa, 2001). Michael et al. (2003) measured this flux-dependency on multiple tidal constituents with manual seepage meters, and also showed the effect of diurnal tide on SGD decrease with distance from shore.

Most seepage meter measurements are made in shallow, but fully submerged areas. However, several studies have examined seepage in the intertidal zone and in extremely deep ocean waters. Seepage rates and patterns in the intertidal zone are difficult to measure because changes can be rapid and large and occur where surface-water depth is very shallow. Groundwater discharges rapidly as the aquifer empties on the falling tide, and recharges the unsaturated aquifer rapidly on the rising tide (Michael et al., 2005; Rosenberry et al., 2013; Russoniello et al., 2016). These tidally-driven intertidal flux rates are positively correlated with shoreline slope (Rosenberry et al., 2013). Seepage-meter measurements of flux in the intertidal zone can only be made when the water is deep enough to fully submerge the seepage meter and associated collection bag. Michael et al. (2005) measured intertidal fluxes with intertidal seepage meters, which were tall cylinders with open tops that always remained above the water surface. When using these, in addition to the portion of flux caused by groundwater seepage, additional flux was caused by the variation of surface water elevation outside the seepage meter. The volume due to surface water variation was calculated as the product of surface water level change and the seepage meter area. Seepage in the intertidal zone was calculated by subtracting that volume from seepage measured with collection bags. Tidal energy dissipates with depth, so tidally-driven seepage is small but non-negligible in deep water (Tryon et al., 2001; Uemura et al., 2011).

7. Seepage meters functioning with waves

Seepage meters in coastal areas are frequently influenced by waves. Waves traveling over a flat seabed induce a net zero flux in both space and time—the non-zero groundwater recharge beneath the crest is equal to the discharge beneath the wave trough (King et al., 2009; Precht and Huettel, 2003; Riedl et al., 1972). The seabed pressure signal and resulting wave-induced fluxes are dampened and spatially averaged beneath seepage meters compared to a bare seabed (Russoniello and Michael, 2015). Wave-induced flux rates cannot be characterized with manual seepage meters because wave periods are much shorter than manual seepage meter measurement periods.

Many studies have noted and suspected that wave-pumping added uncertainty to seepage-meter measurement (Cable et al., 1996a, 1996b; Libelo and MacIntyre, 1994; Shinn et al., 2002) and several studies have attempted to understand and quantify this uncertainty. Cable et al. (2006) measured wave conditions during seepage meter deployments but found no correlations between wave energy and seepage rates. Smith et al. (2009) found that waves can flex seepage meter chambers and generate fluxes up to 100 cm d^{-1}. The study recommended the use of hemispherical chambers to reduce flexing inherent to Lee-type chambers in areas with high wave energy. Seepage cylinders made of steel, although subject to rust in marine settings, may resist flexing to a greater extent than cylinders made from plastic. However, all meters installed in environments with high enough energy to flex seepage cylinders are subject to large measurement error, including the possibility of being completely removed from the bed. Generally, both plastic and metal cylinders are sufficiently stiff that flexing is a minimal concern in most installations. If measurements in high-energy environments are required, a low-profile, hemispherical, and sufficiently strong cylinder would help minimize errors. If seepage meter efficiency differs between recharge and discharge, waves will introduce a net flux through the seepage meter. Several studies have found that seepage meter efficiency is consistent between recharge and discharge under low steady flow conditions when the connection diameter between the bag and chamber are large (Rosenberry and Menheer, 2006; Russoniello and Michael, 2015). Efficiency may vary between recharge and discharge if fluxes are high, waves are asymmetric (typical in shallow high-energy conditions), or if the collection bag inlet is pinched by wave energy (e.g. Russoniello and Michael, 2015). Maximizing the diameter of connections between the collection bag and seepage chamber, and placing the seepage bag inside of a bag shelter, should minimize associated uncertainty (Rosenberry and Morin, 2004). While these sources of error are possible, wave tank experiments show that wave-induced seepage meter uncertainty is negligible under low-wave intensity conditions (Russoniello and Michael, 2015). A frequent solution and recommendation to deal with this is the use of a shelter (discussed extensively in Rosenberry et al., this issue) for the collection bag to minimize hydrodynamic disturbance (Libelo and MacIntyre, 1994; Rosenberry, 2008).

8. Future perspectives

Seepage meter measurements in coastal settings have been a continuous research activity for the last several decades and have contributed to an improved understanding and ability to quantify submarine groundwater discharge over a wide range of scales and locations. Still, regional and global estimates of SGD remain highly uncertain because of a lack of studies in multiple regions and the substantial challenges associated with these environments. Field seepage meter studies will continue to help reduce uncertainties and produce better estimates of fluid and solute fluxes to global oceans.

The use of seepage meters has presented multiple local adaptations that optimize their utility for a broad range of physical settings and a variety of goals. The establishment of common guidelines would help in the intercomparison of studies at different locations, and to verify methodological improvements. For example, results should be presented in units of distance per time, which would normalize seepage data regarding the area of the seepage cylinder and allow ready comparison of results between sites and studies. An agreement to assign a positive or negative sign for upward or downward flow would also reduce ambiguity. An initial idea would be to implement the best practices presented in this review to the extent that the natural conditions, time constrains and project goals allow. Continuing improvements in measurement technique and modifications to the measuring system should be clearly described and presented in publication outlets globally accessible that emphasize methods development. In the course of conducting this literature review, details about modifications to either the device or the standard measurement method have too often been omitted, hindering the exchange of useful information.

In marine settings, the distinction between fresh and saline fluxes is essential for interpreting results as they have different water sources and are generated by different mechanisms. This can be challenging because transitions from freshwater to saltwater along a transect or across a bed area are generally variable in space and time. All interpretations of seepage-meter fluxes in marine settings should be framed from this mixed-source perspective. A general understanding of the processes that can take place either inland, at the shoreline interface, or out to sea should always be considered when making this distinction. To favor inter-site comparisons of results and methods, studies should describe the location of the study area relative to freshwater, transition zone or saline water, at least from a conceptual perspective.

Given that seepage-meter measurements are essentially point measurements, development of innovative ways of upscaling these discrete data to scales more applicable to resource management is a high priority. Aspects such as heterogeneity, comparison between modelled and direct measurements, and seasonal/time-series data analysis based on the local hydrological and marine characteristics would be especially beneficial.

Coastal settings are one of the most dynamic environments in which seepage meters can be used. Studies conducted in these environments must collect data at a time resolution capable of relating changes in measured fluxes with applicable environmental conditions, which may include tidal oscillations, terrestrial water-table changes affecting fresh flux, waves, and currents. Substantial additional improvements in sensor technology and application are required to achieve these goals.

Automated seepage meters have been essential for both understanding the exchange of fluxes in coastal areas and in the assessment of chemical fluxes and ocean composition. Nevertheless, the cost of these devices has prevented studies that simultaneously address spatial and temporal variability. The development of low-cost devices would be a solution that could increase the number of installations to help address concerns about spatial heterogeneity and scaling of results.

Seepage meters have most often served to validate other methodologies (i.e. numerical modelling, tracers, hydraulic calculations). But the opposite strategy has also proven beneficial and effective; select locations for seepage-meter deployments based on output from numerical models, tracer based studies, geophysical surveys, or hydraulic-gradient calculations designed to optimize the use of seepage meters (i.e Duque et al., 2019; Russoniello et al., 2013). Another useful approach would be to find optimal combinations with other methods that can be “standardized” to favor comparison of studies or help to design monitoring nets in new study areas.

The compartmentalization between publication outlets and seepage meter study objectives for land or marine settings has resulted in differences instead of synergies. Recently, publications have increased incorporation of cross-disciplinary findings, but additional work towards a collaborative understanding is necessary. The interdisciplinary collaboration is essential to advance future challenges in coastal areas to better characterize fluid and chemical fluxes to the ocean and understand stresses on global water resources that accompany a changing climate.

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