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Societal use of fresh submarine groundwater discharge: An overlooked water resource

N. Moosdorf*, T. Oehler

Leibniz Centre for Tropical Marine Research (ZMT), Fahrenheitstrasse 6, 28359 Bremen, Germany

ABSTRACT

Terrestrial groundwater discharging directly into the sea ("fresh submarine groundwater discharge", fresh SGD) is increasingly recognized as nutrient and pollutant pathway from land to coastal oceans. However, its active use by coastal populations and its role for coastal societies is nearly entirely neglected. Here we present examples from a variety of places and from all available sources around the world to highlight that fresh submarine groundwater discharge is widely valued as a water resource for drinking, hygiene, agriculture, fishing, tourism, culture, or ship navigation. In Peru, fresh SGD is used for drinking, on Tahiti for bathing, in Greece for irrigation, in Bali for blessing, and already Alexander von Humboldt noted the danger for smaller vessels from a submarine spring off Cuba, but at which Manatees gathered and were hunted by fishermen. These are just a few of the presented examples, which document the complex value fresh submarine groundwater discharge has for coastal communities. Because global change will strongly affect this water resource we should assess and understand that value, before the phenomenon will disappear at many locations due to terrestrial groundwater extraction or sea level increase.

1. Introduction

1.1. General introduction

Submarine groundwater discharge (SGD), the direct discharge of groundwater to the sea, is a ubiquitous phenomenon around the world. While SGD is defined as "any and all flow of water on continental margins" (Burnett et al., 2003; Moore, 2010), this review focuses on the terrestrial fraction ("fresh SGD"). At global scale, recirculated seawater is estimated to 90% of the total SGD, and fresh SGD only attributes to 10% of the discharge volume (Kwon et al., 2014). Compared to rivers, fresh SGD is estimated to discharge 0.01–10% of the water volume (Garrels and Mackenzie, 1971; Zektser and Loaiciga, 1993; Church, 1996; Taniguchi et al., 2002).

SGD has received significant scientific attention only since about 20 years ago (Zektser and Loaiciga, 1993; Church, 1996; Taniguchi et al., 2002; Burnett et al., 2003), with only a few scattered publications describing it previously (e.g. Fischer et al., 1964; Kohout, 1966; Manheim, 1967; Zektzer et al., 1973). The naming of the phenomenon varies depending on the community background of the describing scientists. The term "submarine groundwater discharge" was mentioned first in the 1970′s (Zektzer et al., 1973; Johannes, 1980) and early on adopted by scientists of the marine community (Simmons and Netherton, 1987; Cuet et al., 1988; Lapointe et al., 1990). Others, focusing on karstic environments with their conduits called the discharging water "submarine springs" (Kohout, 1966; Stefanon, 1972; Fleury et al., 2007), or "vrulja" (after a spring in Croatia) (Bögli, 1980; Sekulic and Vertacnik, 1996). Again others use the terminology "coastal seepage" or "groundwater seepage" (Kay et al., 1977; Marsh, 1977; Perissinotto et al., 2014). This diversity and lack of clear definitions complicates a comprehensive study of the phenomenon. Nevertheless, scientific interest, both at local and larger scale, recently has strongly increased while the significant contributions of SGD to coastal nutrient budgets became clearer (Moore, 2010; Moosdorf et al., 2015). Recently, the potential relevance of SGD for coastal ecology (Paytan et al., 2006), global water budget (Burnett et al., 2003; Kwon et al., 2014) or biogeochemical matter cycles (Slomp and Van Cappellen, 2004; Cole et al., 2007; Beusen et al., 2013) was highlighted.

One of the most important roles of fresh SGD could be that of a water resource. It is traditionally known to the local population at many coastal places around the world. Scholarly efforts of previous authors show that fresh SGD was used in ancient times by the romans (noted by Strabo and Pliny the elder), who took water from submarine springs from boats and used it as drinking water supply (Taniguchi et al., 2002). The resource use exceeds pure drinking. Fishermen and divers profit from fresh SGD e.g. in Australia (Phillips, 2015). In addition,

* Corresponding author.
E-mail address: nils_sci@moosdorf.de (N. Moosdorf).

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fresh SGD is culturally important for many coastal societies around the world, documented by horse offerings to Poseidon 2000 years ago at a fresh submarine spring (Leake, 1830) or by the blessing of scores of pilgrims and tourists at the Hindu temple Tanah Lot which is built on an intertidal spring (Lubis and Bakti, 2013). However, reports of current usage of SGD are rare and scattered. Only a single economic study assesses the value of SGD at the example of Obama, Japan (Burnett et al., 2015).

This study aims to raise awareness of the relevance of fresh SGD to society, while in addition highlighting future risks for fresh SGD use, such as coastal groundwater pumping and groundwater pollution. The societal relevance of fresh SGD and its vulnerabilities should be recognized in order to take fully informed decisions on coastal and groundwater management.

1.2. Physical background and occurrence of fresh submarine groundwater discharge

Fresh SGD, terrestrial groundwater discharging into the sea, is controlled by hydraulic gradient and aquifer attributes. The controls have been analyzed in theoretical models (Kaleris, 2006), and local field studies (e.g. Michael et al., 2005; Holliday et al., 2007; Viso et al., 2010). While the main controls a qualitatively known, their quantification remains a challenge. A main controlling factor is aquifer permeability, which controls, together with the hydraulic gradient, the amount of water that can be transported through the aquifer (e.g. Russoniello et al., 2013). In particular in areas with high permeability, groundwater recharge is another main control from the terrestrial side (e.g. Michael et al., 2013). From the marine side, tidal cycles change the hydraulic gradient temporarily, which impacts seawater recirculation and freshwater flow (Greskowiak, 2014). Marine forcing factors on fresh SGD are subject to strong temporal variations through e.g. seasonal and tidal cycles, while from the terrestrial side aquifer permeability has a very strong local variability. This leads to an intense variability of fresh SGD both in time and space, which complicates its estimation and extrapolation.

Fresh SGD occurs as diffuse discharge through the pores of coastal sediments, and as conduit flow resulting in submarine springs, which are often visual as a blurred zone in the ocean (examples shown in Fig. 1). Conduits may follow existing rock structures, e.g. karstic caves (Maksimovic, 1957; Evans, 2003; Fleury, 2005; Mejias et al., 2012; Stieglitz et al., 2013) or lava tubes (Peterson et al., 2009; Dimova et al., 2012; Povinec et al., 2012), but can also develop in muddy confining layers above aquifers (Holliday et al., 2007). Per definition, groundwater seepage and springs in the intertidal region are also included in SGD, although they are only submarine during high tides.

2. Societal use of fresh SGD

Fresh SGD has been used as a resource for long time, and is still used, particularly in more remote communities around the globe. The main part of this review is dedicated to highlighting the worldwide use of fresh SGD as a water resource, which was mostly overlooked by scientific publications. We distinguish five different use categories: drinking, hygiene, agriculture, fishing/diving, and spiritual use. In total, this review presents 41 examples of fresh SGD use worldwide. Fig. 2 shows the location and category of the examples and Table 1 provides literature references and a short description. The examples which have not yet been described in any published literature are presented in the appendix.

2.1.1. Fresh SGD as drinking water source

Fresh SGD has been used as drinking water resource for centuries. Strabo (63 BCE to 21 CE) reported the use of a submarine spring at the city Aradus (now Arvad), 4 km offshore Latakia, Syria. Fresh SGD was collected from boats and transported to the city. In Chekka (Lebanon), plastic tubing over a funnel shaped dome was used at least until 1963 to transport water from a submarine spring to the coast (Kohout, 1966).

An example of the importance of submarine groundwater discharge as water resource is the island nation of Bahrein, whose drinking water needs traditionally were sustained to a substantial proportion by

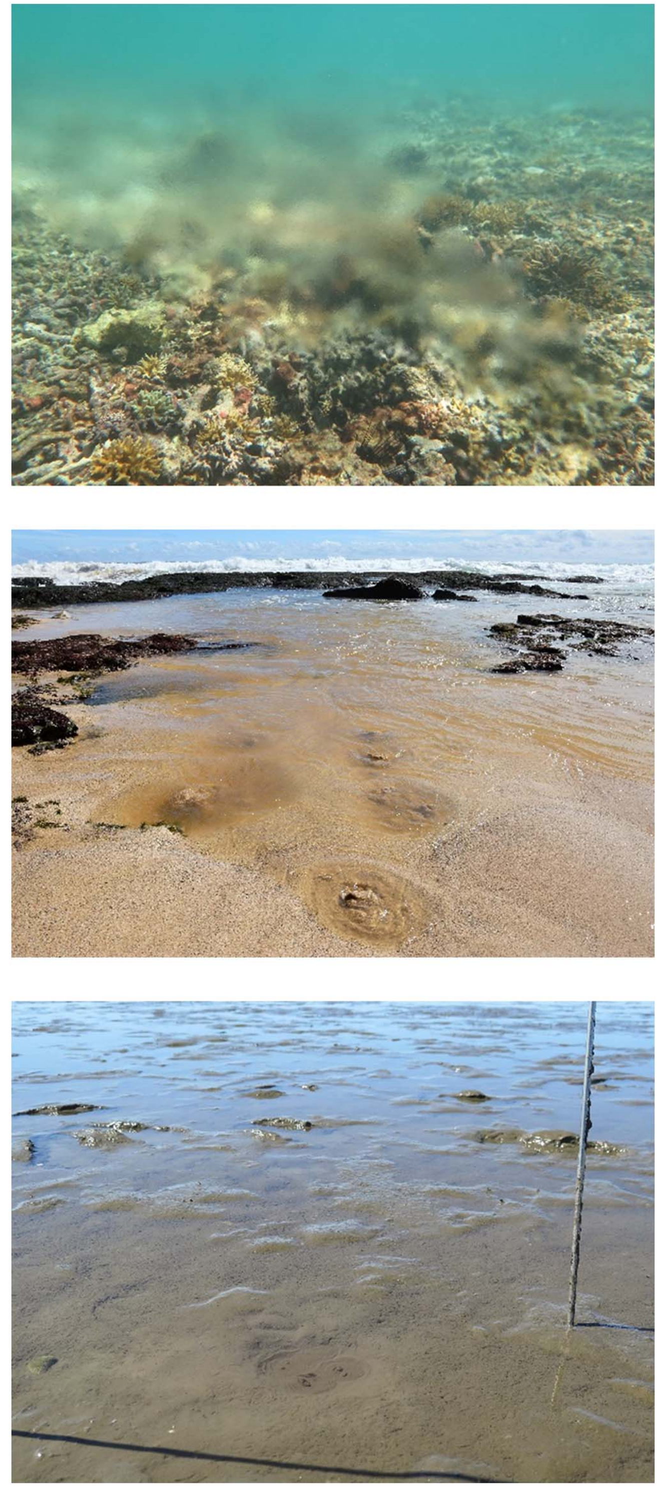

Fig. 1. Examples for a karstic submarine spring in Lombok, Indonesia (top: Site #31 in Fig. 2, image credit: Imke Podbielski), a karstic intertidal spring in Gunung Kidul, Indonesia (middle: Site #8 in Fig. 2, Image credit: Nils Moosdorf), and an intertidal spring in a muddy environment (bottom: Sahlenburg, Germany – no known societal use, thus not represented in Fig. 2, image credit: Nils Moosdorf).