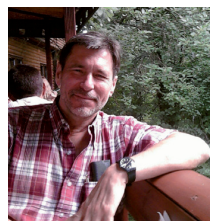


As was recognized recently, the submarine groundwater (SG) could transport a significant amount of hazardous contaminants to the coastal ocean. Among them are onland chemicals, trace metals, radioactive isotopes, fertilizers, sewage and many others, concentrations of which in SG are often very high. An assessment of impact of intruded pollutants on ecosystems requires a complex, including experimental study and numerical modeling. Until now, the latter was focused on contaminant distributions inside aquifers and only a few works were focused on the processes in near-seepage zones. In this book, therefore, we propose a 3-D Eulerian-Lagrangian model for predicting the transport and dispersal of pollution-containing SG discharging into the coastal environment. The generalized model is configured for the coastal zone of the southwestern Taiwan, and its initialization is based on observation data collected in two high-resolution hydrographic surveys of the region. The proposed approach should be useful for both students and professionals, or someone else who are interesting in problems of coastal water quality and, particularly, its sensitivity to discharges of pollutant-containing SG.



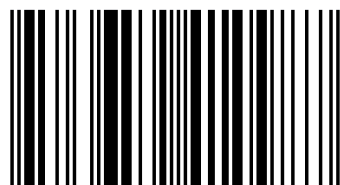
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Submarine Groundwater and Coastal Ocean Pollution

Case Study in the Southwestern Coastal Zone of
Taiwan: Observations and Modeling



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Foreword

As was recognized, the submarine groundwater transports a significant amount of hazardous contaminants to the coastal ocean. An assessment of the impact of intruded pollutants on the coastal ecosystems requires understanding fate of the pollutants and processes of their dispersal in ambient waters. In this book, we present recent observations of hydrophysical fields and contaminants allowed identifying locations of submarine groundwater discharge on the shelf the southwestern Taiwan and propose a 3-D coupled circulation/particle-tracking model for predicting the transport and dispersal of pollution-containing groundwater discharging into a coastal environment.

Model scenarios of pollution release were set up on base field observations. For this, two high-resolution hydrographic surveys of the region, including water and bottom sediment sampling campaigns, were accomplished in February and October of 2009. Water samples were also collected from the neighbouring on-land groundwater wells. At some locations in the study regions, the vertical profiles exhibited a slight but detectable decrease of salinity manifested in the near-bottom portion of the water column. Although convectively unstable, this feature appeared robust and persisted through the 8 months separating the two surveys. As was found, the salinity anomalies, in the near-bottom layer, were often accompanied by peaks of fluorescence, chlorophyll, silica, nitrate, and iron concentrations, as well as the minima of turbidity.

During simulations, the Lagrangian particle-tracking model takes currents and turbulent diffusivities predetermined by the ocean circulation model and uses the Lagrangian approach to predict the motion of individual droplets, the sum of which constitutes a contaminant plume in result of discharge of contaminant-rich submarine groundwater. The ocean circulation model was forced by tides and historical seasonal favourable winds for the southwestern coast of Taiwan. The initialisation of the coupled model was set using field data obtained in 2009 on the Pingtung shelf where

shallow aquifer seepages were discovered. Several types of numerical experiment scenarios were set up to elucidate the transport and dispersal of conservative and nonconservative (nitrate) contaminants in the shallow coastal zone. The comparison of obtained numerical results with observations performed by other researches was discussed.

Chapter 1. Introduction

Submarine groundwater discharge (hereinafter SGD) has been recognized as a potentially significant contributor of various contaminants to the coastal ocean [1-11]. Although not as obvious as river discharge, groundwaters can also discharge directly into the coastal ocean [12-14]. Like surface water, groundwater flows down gradient. Therefore, groundwater flows directly into the coastal ocean wherever a coastal aquifer is connected to the sea. Furthermore, artesian aquifers can extend for considerable distances from shore, underneath the continental shelf with discharge to the coastal ocean at their points of outcrop. In some cases, these deeper aquifers may have fractures or other breaches in the overlying confining layers, allowing groundwater to flow into the sea **Figure 1** schematically illustrates shallow and deep aquifers and processes associates with SGD.

It is very important that groundwater discharge might be an important pathway for diffuse pollution to enter the coastal zone where coastal aquifers have become contaminated by septic systems or other pollution sources [1].

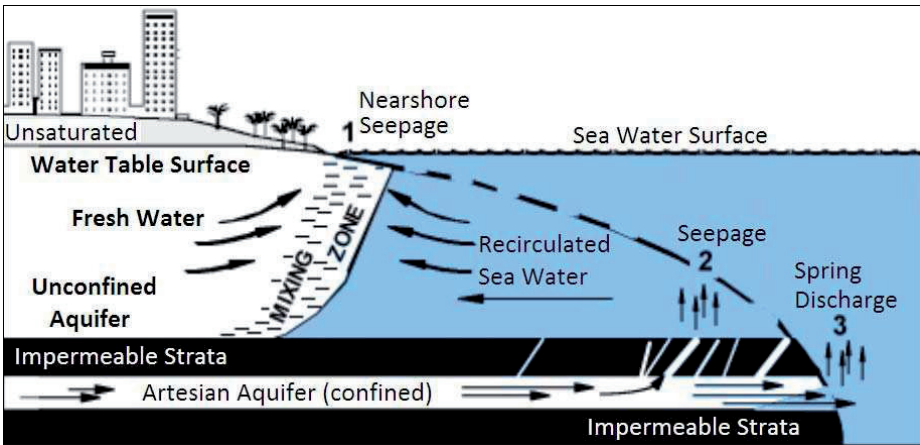


Figure 1. Diagrammatic view of the relationships between coastal aquifers, seawater, and groundwater discharge. Three types of submarine groundwater discharge are illustrated: (1) Nearshore seepage; (2) Offshore seepage; and (3) Submarine springs (Modified from [13]).

Despite SGD contribution in the ocean's water budget is generally small, it represents an important source of nutrients and other contaminants that affect the ecology of the estuaries and coastal fresh water bodies [1-5, 9, 10, 15-18]. There are reports that SGD may also be an important source of alkalinity and carbon to shelf waters [7].

Submarine groundwater coming from coastal aquifers into the coastal ocean carries dissolved contaminants, concentration and type of which considerably varied from region to region. Multiple studies indicate that the concentration of groundwater contaminants increases with increasing housing density and agriculture activity. Expanding residential and commercial near-shore development is leading to increased nutrient inputs to groundwater that eventually migrate into coastal waters. Several-decades long research shows that nitrogen inputs via non-point sources over large coastline areas cause decline of ecological health and may support harmful algal blooms [8].

In Taiwan, investigations of the offshore discharge of groundwater, for many years, were largely motivated by water resource related issues. As was noted in [19], there were at least two reasons why scientific studies have developed so slowly in this field. First, the SGD process is inherently very difficult to measure and monitor, which tended to discourage serious investigations. Nearshore seepages around Taiwan typically have very diffuse and highly variable unit fluxes although the cumulative discharge can be very significant when it occurs over a wide area. Second, SGD is a process that occurs across a land-sea interface that spans different scientific disciplines as well as environments. Unfortunately, there are distinct cultural and structural differences that separate terrestrial and marine scientists. Literally, hydrologists and coastal oceanographers are looking at the same problem from different ends.

For the last decade, intensive field investigations of coastal environment pollution associated with SGD are undertaken in coastal zone of Taiwan including its southwestern part (**Figure 2**).

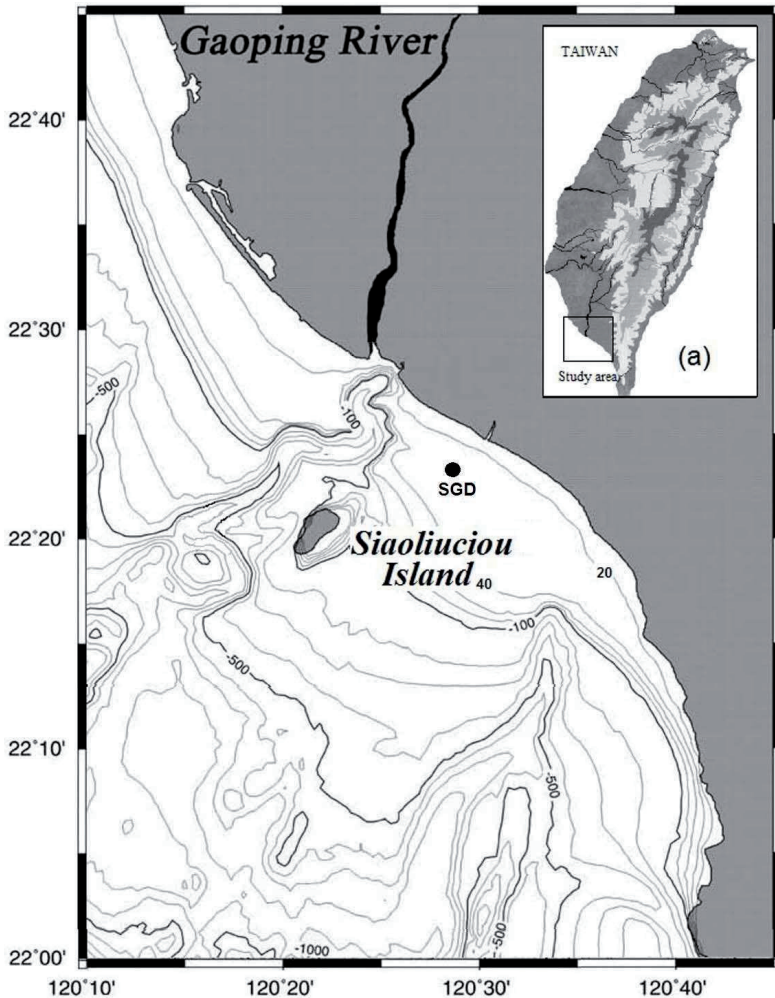


Figure 2. Map of the Pingtung coastal zone showing the bathymetry off southwestern Taiwan and stations of hydrographical observations (marked by solid circles) in the area of the shallow SGD well (marked by the solid square). (Modified from [20]).

The coastal waters of the Pingtung Plain are ground for fisheries, and also recreational area, therefore, it is important to estimate the rates of SGD in the area and evaluate the impact on the seawater column. Until 2004, no attempts to quantify SGD in Pingtung shelf based on an observational data have been undertaken, although some indirect evidence pointing on its existence has been reported (e.g., [21, 22]). Virtually the only direct measurements of SGD in the inner shelf were carried out in 2004 by C.-T.A. Chen and his co-workers [23]. They deployed SGD collecting devices buried in the bottom sands at 5 sampling sites (Kaohsiung city, Kaoping River mouth, Fangsan, Jinshawan, and Yaniliao townships). The collected samples were analyzed for salinity, pH, and nutrients (nitrate, nitrite, phosphate, and silicate).

At two locations, namely, Xiziwan within Kaohsiung city limits, and Fangsan township, distinct SGD signatures were observed, manifested in significantly reduced salinity and pH, and elevated concentrations of nutrients, as compared with the surrounding ocean waters. The freshening was particularly dramatic at a station named “Eureca” by these researchers, situated 300 m from the Fangshan coast at the depth 7.8 m, where the bottom water sample reportedly had salinity of only 0.2 psu (!), i.e., was essentially fresh.

These published observations yielded enlightening results. However, they were restricted to the very inner part of the shelf immediately adjacent to the coast (0-300 m from the shoreline, 0-8 m depth), and focused on the groundwater within the bottom sands and sediments. In the present study, we attempted to detect the SGD signatures in the area by means of oceanographic measurements, and also quantify the SGD influence on the seawater column.

R.-M. Wang and his co-workers [15] were found out that Gaoping River and aquifers are significant sources of trace elements and other chemical constituents to the southwestern coastal waters of Taiwan where onland chemicals as NH_4 , SO_4 , NO_3 , PO_4 and SiO_2 , hydrocarbons, trace metals (Ni, Cu, Cd), NaOH, fertilizers, and sewage were. Reference [15] also reported the exploratory discovery of SGD by

using salinity in Taiwan for the first time in the coastal area and point out that SGD may occur near the Kaoping River estuary. Recently [16, 17] have shown that submarine groundwaters are also clearly indicated by tracers of oxygen, strontium isotopes and barium content. They noted that the concentration of many contaminants in groundwater is typically several times higher than in seawater. Usually with distance from seepage the concentration of contaminants decreased rapidly. As observations of nitrate (NO_3) plumes near shallow seepages have shown [6, 9], the flux of nitrate towards the marine environment was highly variable even over a short distance from the coast. In addition, greater dispersion near the seepage face due to movement of water masses in response of tides and to seasonal cycles of recharge to the fresh aquifer. Outside an aquifer, nitrate diminished substantially in concentration so that horizontal and vertical sizes of a detectable inclined nitrate plume did not exceed 6 and 4 m, respectively [6].

In the coastal ocean, processes of spreading and fate of contaminants coming from SG aquifers are governed by ocean dynamics and depend on many factors as seepage zone, discharge rate and type of contaminants. Mathematically, predicting such processes is very a complicated task that requires developing numerical models for reproducing/predicting the ocean circulation and transport of contaminants. Until now, numerical modeling directed to the solution of problems associated with pollution inputs from SGD is mostly focused on modeling the transport and biogeochemical processes [8, 10, 24] inside aquifers. Some works have been dedicated to analysis and modeling an influence of tides on oscillation of groundwater discharge rate [1, 11, 25]. By theoretical model for SGD and the associated chemical transfer to the ocean, [1] have demonstrated that wave setup and tidal pumping may be the processes largely responsible for the high rate of SDG and, in turn, a considerable intensification of the transport of chemicals to the ocean. Despite wide spectra of models and approaches that were built for the solution of various problems associated with contamination of coastal zone due to SDGs, yet, no

attempt has been made on the development of a complex approach for predicting the regional circulation and its effect on the transport and mixing of pollutants coming into seawater from submarine seepages. Therefore the objective of this work is to fill this gap and develop a pollution transport model coupled with an ocean circulation model. In the work, we will focus on the shelf zone of the southwestern Taiwan, however, based on the generalized approach, the model can be adapted easily for any region of interest.