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Land–sea interface identification and submarine groundwater exchange (SGE) estimation

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ABSTRACT

In this article we consider the problem of estimating submarine groundwater exchange quantities as an inverse problem in which the unknown is the location of the interface between the land and the sea, whereas overspecified boundary conditions are available on another part of the domain boundary. A data completion problem on a fictitious domain, which can be rather larger or smaller than the real one, is analyzed and the land–sea interface at the null hydraulic head isovalue is identified. Examples are given for different dimensions of the domain for a case of sea water intrusion and one of land water discharge. The sensitivity of the identification process to noisy data is considered.

1. Introduction

Most of the world's usable freshwater lies underground and exchange occurs between freshwater and seawater wherever aquifers are hydraulically connected to the ocean [1,2]. This exchange of water between the sea and coastal aquifers is now recognized as being an important parameter for near shore marine water and groundwater systems. The oceanographic community divides this exchange into a submarine groundwater discharge (SGD), the flux of fresh water from the continent to the ocean, and a submarine groundwater recharge (SGR), the flux of seawater from the ocean to the aquifer. The net flux is therefore the difference between these parameters, known as submarine groundwater exchange (SGE) [3,4].

For a long time, coastal groundwater studies focused on the SGR phenomenon, which is known as marine intrusion because of its direct consequences on groundwater salinisation and thus on water use. However, little attention was paid to submarine groundwater discharge (SGD), as it was considered to be insignificant compared to discharge from rivers and other surface waters.

However, in recent years, SGD has received more attention as it appears that it is more than just a simple exchange of water between land and sea. In fact, the flow of groundwater into the ocean is critical since this water often carries dissolved nutrients and pollutants. Therefore it is now recognized that SGD can influence coastal-water and geochemical budgets and drive ecosystem change.

Estimating the magnitude of SGE is a real challenge due to the difficulties of localizing SGE areas, estimating the water and solute fluxes in both directions, and distinguishing between the fresh groundwater discharge and the discharge of seawater re-circulation. As described in [4], different methods are used to measure SGE. Mention can be made of direct and indirect field measurements by using seepage meters, piezometers and geochemical tracers such as radium isotopes and radon. The application of these methods involves considerable financial and investment efforts, leading scientists to resort to numerical methods like the water balance approach and computational simulations.

The numerical models and software used in SGE simulations vary in complexity, but all of them have in common the solution of a forward well-posed problem with a given land–sea interface [5–9]. Two-dimensional horizontal domains and flows are considered in large scale and regional models and for groundwater resource management purposes. In addition, studies focusing on coastal zones, vertical sections and three dimensional domains have been modeled and density-dependent flow and salt transport simulated. In the latter cases, the computed water and salt fluxes strongly depend on the position of the zero piezometric level or line. However, many deep coastal aquifers extend far under the sea-bed and, generally, little is known about the extension of these

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aquifers beyond the shoreline. When studying and modeling these aquifers, researchers are often led to fixing an arbitrary limit to which a null piezometric level is assigned. This statement represents the hydraulic contact between the aquifer and the ocean. It is clear that the position of this limit influences the piezometric distribution of the entire aquifer as well as the exchanges of water between the aquifer and the ocean.

Many methods are used for identification geometry problems, among them the well known Level Set Method (LSM) that was originally developed by Osher and Sethian [10]. The LSM tracks the motion of an interface by embedding the interface as the zero level set of a signed distance function. This method is widely used in several disciplines including geometric inverse problems, see [11,12]. The advantage of level set methods is their ability to handle topology changes easily. Another method based on the reciprocity principle was used by Hariga et al. [13] to identify an interface separating two hydrogeological domains with different hydraulic transmissivities. The reciprocity principle is derived from mechanics and establishes for flow problems a relationship between different sets of forcing terms, including sources, sinks and boundary conditions, and the resulting head fields. The interest of the reciprocity principles lies in the simplicity of the resulting identification process, and its main drawback is the large amount of data required, which are generally not available.

In this paper we consider the problem of estimating SGE quantities as an **inverse problem** in which the unknown is the location of the interface between the land and the sea, whereas overspecified boundary conditions are available on another part of the domain boundary. This inverse problem can be stated as follows: *Given observed* ***flux*** *and* ***head*** *measurements on a part of the domain boundary, find the* ***land–sea interface*** *which is another part of the domain.*

We consider a fictitious domain Ω_f larger than the real one Ω. Ω_f has the same overspecified and prescribed boundaries as Ω, but is extended beyond the zone where the unknown interface could be located. The aim is to solve a data completion problem for Ω_f, by exploiting the over-specified data [14]. Then, the land–sea interface is located where the zero hydraulic head isovalue line occurs. From the practical standpoint and in order to obtain this overspecified boundary, it is easy to calculate the normal derivative even on an internal part of the domain and close to the boundary isopiezometric line [15,16] since the known piezometric levels correspond to measured values in boreholes and are presented as interpolated isolines.

The method and numerical tools used in this paper have already been presented in [14,17–19], our contribution in this work is based on the applicational aspect.

After a mathematical presentation of the model and the method used to identify the interface between the coastal aquifer and the sea (Sections 2 and 3), we illustrate the methodology by providing several numerical examples (Section 4) and then conclude the paper with remarks and perspectives.

2. Land–sea interface identification

In the groundwater for which the sea is the natural outlet, a mixing zone occurs along the coastal margin between the freshwater and salt water. The position and extension of this mixing zone depend on several factors including the flow rate of the groundwater, the density of the salt water, the hydrodynamic characteristics of the reservoir, the tide, etc.

The full mathematical formulation of this problem of intrusion of salt water into coastal aquifers leads to a coupled problem of density flow and transport [20]. The practical nature of this subject has led to a large number of works that have focused on giving more or less complete solutions. Mention can be made of the Ghyben–Hersberg approximation dating from the beginning of the century [21] which considers that the salt water is immobile, with the freshwater flowing above it without any mixing. It resulted in the well-known formula bearing the same name ($z = -40h$, where z is the depth of the interface below sea level and h the peizometric height in the groundwater). This approximation of an abrupt interface was the basis of models that calculated the position of the interface for different limit conditions and characteristics of the reservoir [22]. However, it is insufficient to permit a precise description of the problem.

Indeed, on the one hand, the movement of seawater in the coastal margin is never negligible, and on the other hand, freshwater and seawater are not non miscible fluids. In reality, a more or less large mixing zone develops in which concentrations in salt vary between that of the seawater and that of the freshwater. This is the solution of Henry [20] which introduces the processes of mechanical dispersion and chemical diffusion of salts into this problem. This semi-analytical solution in the vertical plane uses double Fourrier–Galerkin series to solve the coupled flow and transport equations in steady state. Although developed in the case of low convection, this solution has the advantage of confirming the re-circulation of salt water from the bottom to the top of the aquifer following dispersion processes. It also constitutes the obligatory test of the numerical models developed to simulate density flows and transport [23,24].

3D models have recently been built using currently available calculation tools for real coastal groundwater and by considering coupled density and transport processes [25].

The first question that arises before building these more or less sophisticated direct models concerns the extension of the domain to be modeled and its limit conditions. For the density flow problem, the upstream limit of a coastal aquifer is often determined according to the geological information and piezometric map available for the site studied. The downstream limit of a coastal aquifer is therefore the coastline. However, for confined coastal aquifers, this downstream limit is difficult to ascertain a priori, as the geological formation containing it can stretch far out to sea, with unknown discharges and inflows and without any precise geological information available on this extension. In studies of these aquifers, hydrogeologists often have no other choice but to set an arbitrary limit downstream where the piezometric height is null, corresponding to that of the sea and deduced by extrapolating the piezometric data. For the associated salt transport problem and due to density processes, the downstream frontier of a coastal aquifer is subdivided into two parts: a low part where the seawater enters the aquifer and mixes with the freshwater and an upper part where the salt mixture exits into the sea. The net exchange flux is therefore the algebraic sum of these two flows. The limit conditions in terms of transport in this limit are therefore written as a consequence and as a function of the tests on the direction of the flow, from the groundwater to the sea or from the sea to the groundwater.

The method developed in this paper is aimed at identifying the downstream limit of a deep coastal aquifer which is information necessary prior to any complete modeling of the system and coupled density and transport processes. It also permits estimating the net exchange flux between the groundwater and the ocean which is valuable information for aquifer freshwater resource management and for marine hydroecology.

From the hydrogeological standpoint, exchanges of water between the ocean and coastal aquifers can be analyzed in the geometric plan of the aquiferous formation. These flows then take place at outcrops of the aquifer formation in the ocean floor as a function of the value of the piezometric gradient between these outcrops and the ocean. In this study a two-dimensional horizontal