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A Case Study of the Depth of Fresh/Salt Water Interface Using Values of Freshwater Heads in Groundwater of Variable Density

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ABSTRACT

Almost two thirds of the world's population lives within 400 km of the ocean shoreline; just over half live within 200 km, an area only taking up 10% of the earth's surface. As the world's population continues to grow at an alarming rate, fresh water supplies are constantly being depleted, bringing with it issues such as saltwater intrusion and increasing the importance of groundwater monitoring, management, and conservation. Constant monitoring of the fresh/salt water interface is necessary for proper management of ground water resources. This work studies the variation in the depth of fresh/salt water interface using different values of freshwater heads extracted from heads in coastal groundwater system near The Hague, Netherlands along sections P-DD. Results showed that high density difference between freshwater and saltwater has little effect on the depth of fresh/saltwater interface.

KEYWORDS: Groundwater, Saltwater, Freshwater, Saltwater/freshwater interface

INTRODUCTION

Salt water intrusion is a key issue in dealing with exploitation, restoration and management of fresh ground water in coastal aquifers (Kim et al. 2007). In coastal areas, fresh groundwater systems are in contact with saline water. When fresh water is withdrawn at a faster rate than it can be replenished, a draw-down of the water table occurs with a resulting decrease in the overall hydrostatic pressure. When this happens near an ocean coastal area, salt water from the ocean intrudes into the fresh water aquifer. The result is that fresh water supplies become contaminated with salt water as is happening to communities along the Atlantic and Gulf coasts.

To prevent this, more and more countries adopt extensive monitoring schemes and numerical models to assess how much water can be pumped without causing such effects.

In coastal aquifers, density differences allow sea water to intrude underneath the fresh water and form a fresh/salt water interface. This interface may either be sharp or have a thick dispersion zone, depending upon several factors, including density difference between fresh water and salt water, aquifer geometry, hydraulic properties, discharge rate to the sea and dispersion parameters of the aquifer (Sakr, 1999).

Due to the difficulty of measuring the fresh/saltwater interface depth in the field, only few studies have been done on the variations in the depth of the interface. Izuka and Gingerich (1998) proposed a method using the vertical head gradient measured in a partially penetrating well to estimate the depth of the fresh/saltwater interface below the well. Also, Kim et al. (2007) presented a method to estimate the depth of the fresh/saltwater interface in coastal aquifers using two sets of pressure data obtained from the fresh and saline zones within a single borehole.

THEORETICAL BACKGROUND

Baydon-Ghyben (1888, 1889) and Herzberg (1901) derived analytical solutions to approximate the salt water intrusion behavior, which are based on a number of assumptions that do not hold in all field cases. The Ghyben-Herzberg ratio states, for every foot of fresh water in an unconfined aquifer above sea level, there will be forty feet of fresh water in the aquifer below sea level.

In the Ghyben-Herzberg equation,

$$z = \frac{\rho_f}{\rho_s - \rho_f} h$$

The thickness of the freshwater zone above sea level is represented as h and that below sea level is represented as z. The two thicknesses h and z, are related by ρ_f and ρ_s where ρ_f is the density of freshwater and ρ_s is the density of saltwater. Freshwater has a density of about 1.000g/cm^3 at 20 °C, whereas that of seawater is about 1.025 g/cm^3.

The hydraulic head is the driving force behind groundwater movement. It is given as:

$$H = Z + \frac{P}{\rho g}$$

$$\rho H = Z\rho + \frac{P}{g} \qquad (1)$$

P is the fluid pressure, ρ the fluid density while Z is the elevation, measured positively upwards

Point water head and freshwater head are key concepts when studying movement of groundwater of variable density. Point-water head at a point i in groundwater of variable density is defined as the water level, referred to a given datum, in a well filled sufficiently with the water of the type at i to balance the existing pressure at i. Freshwater head at any point i in groundwater of variable density is defined as the water level in a well filled with fresh water from i to a level high enough to balance the existing pressure at i. (1) can now be re-written as:

$$\rho_i H_{ip} = Z_i \rho_i + \frac{P_i}{g} \tag{2}$$

and

$$\rho_f H_{if} = Z_i \rho_f + \frac{P_f}{g} \tag{3}$$

for point water head H_{ip} and fresh water head H_{if} respectively at any point in groundwater of variable density. Solving for P_i and P_f and equating them gives:

$$\rho_i g(H_{ip} - Z_i) = \rho_f g(H_{if} - Z_i)$$

$$\rho_i gH_{ip} - \rho_i gZ_i = \rho_f gH_{if} - \rho_f gZ_i$$

$$\rho_f gH_{if} = \rho_i gH_{ip} + \rho_f gZ_i - \rho_i gZ_i$$

$$\rho_f H_{if} = \rho_i H_{ip} - Z_i[\rho_i - \rho_f] \tag{4}$$

$\rightarrow$

$$\rho_i = \frac{\rho_f H_{if} - Z_i \rho_f}{H_{ip} - Z_i} \tag{5}$$

ρ_i and ρ_f are the density of water at i and the density of freshwater respectively.

Using the terms in (Lusczynski, 1961), the Ghyben-Herzberg equation can be re-written as:

$$Z'_d = -\frac{\rho_1 H_{1p}}{\rho_2 - \rho_1} \tag{6}$$

Z'_d is the depth of the freshwater/salt water interface, $\rho_1 = \rho_i$ is the density at a point in freshwater, $\rho_2 = \rho_s$ is the density at a point in saltwater and H_{1p} is the Point water head in freshwater.

The negative sign points to the fact that all depths considered in the text are below sea level.

RESULTS AND DISCUSSIONS

The data used in this study were extracted from Section P-DD, The Hague, Netherlands (Lusczynski, 1961).

Three observation and sampling stations were considered, Station N, MN and DC, their freshwater head (H_{if}) and point-water head (H_{ip}) values were extracted and their corresponding densities (ρ_i) were calculated from (5). For each station, a value of H_{if} and its corresponding density ρ_i was chosen at a particular depth (Table 1). An assumed value was also chosen for salt water density ρ_s such that it is higher than the fresh water density calculated. ρ_i was then kept constant whilst ρ_s was gradually increased (by a step of 1.000kg/m^3) and the corresponding depth of the fresh/salt water interface (Z'_d) was calculated from equation (6). These values of Z'_d were then plotted against the density difference between fresh water and salt water for the three stations.

Figure 1 shows the effect of density difference on the interface depth. This shows that there is an abrupt rise in the depth of the fresh/saltwater interface at density difference values 0.5kg/m3 up till 3.0kg/m3 for the three stations, N, MN and DC after which it now maintains a steady position. In order words, the depth of the interface rarely changes where the density difference between the freshwater and saltwater is relatively high.

Table 1: Freshwater density (ρ_f), freshwater heads (H_{if}), depths (Z_i), point-water heads (H_{ip}) and calculated densities (ρ_i) for the three stations

Station	ρ_f	H_{if}	Z_i	H_{ip}	ρ_i
N	1000	1.14	56	0.58	989.9
MN	1000	1.01	64	0.35	989.6
DC	1000	0.64	55	0.28	993.4

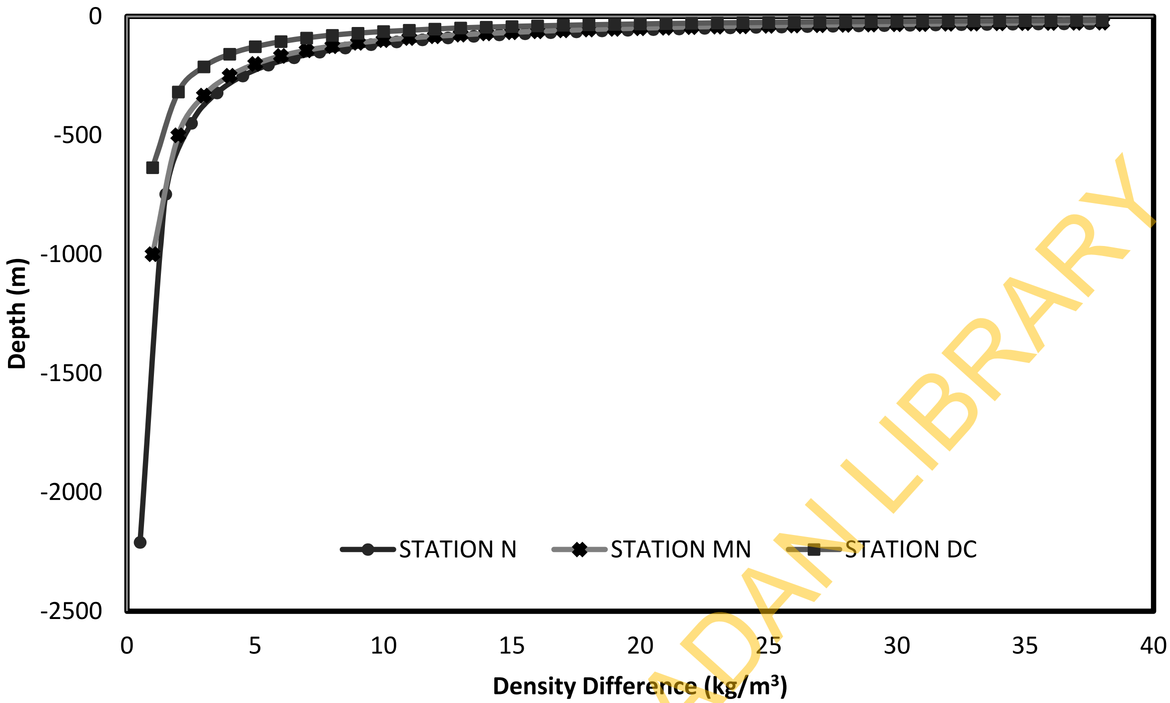

Figure 1: Depth of freshwater/saltwater interface versus density difference between freshwater and saltwater for stations N, MN and DC

In reality, the movement of the fresh/saltwater interface depth is uncommon due to its slow response to changing stress conditions. Masterson, J.P. (2004) in his work stated that the slow response of the fresh/saltwater interface to changes in pumping makes it impractical to measure the change its position in response to changes in pumping the field. As a result, analytical equations and numerical flow models that incorporate the available information on the subsurface hydrogeology must be used to predict the future effects of pumping on the movement of the freshwater/saltwater interface.

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