

# **A Non-Instrumental Method to Determine Hydraulic Heads on Low-Lying Coastal Aquifer**

**Mohd Azraai Kassim, Ph.D**  
**Muhammad Nassir Hanapi, M.Sc**  
Faculty of Civil Engineering  
Universiti Teknologi Malaysia

**Mohd Harun Abdullah, M.Sc**  
School of Science and Technology  
Universiti Malaysia Sabah

## **ABSTRACT**

The technique introduced in this paper is to provide an alternative method to determine hydraulic heads in an unconfined coastal aquifer. The heads could be established within a study area without the needs to use any instrument, such as a theodolite. Instead, a less costly small-diameter transparent tube is used to produce a horizontal plane, formed by a balanced water level in it. Such planes are used as reference levels between two wells on an area, which is relatively flat. Current tidal heights are required in order to calibrate the measurements obtained from the reference levels to the mean sea level. The application of this method at field as a case study has revealed the reduction and critical condition of  $h$  in the phreatic aquifer of a small island, due to the frequent pumping of the wells.

## **INTRODUCTION**

Hydraulic heads or total head ( $h$ ), as defined in fluid mechanics, is composed of the elevation head, the pressure head, and the velocity head. It is also known as the total mechanical energy, derived from the sum of those three factors [1]. But, due to relatively slow movement of groundwater, the velocity head is often ignored [2]. Therefore, the total head in a well involves only two components, i.e., the elevation head ( $z$ ) and the pressure head ( $\psi$ ). In groundwater hydrodynamic studies, the state of the  $h$  is associated with the groundwater flow. Generally, it is determined indirectly based on the observation of the water level in a well, which is one of the common measurements in groundwater investigations. The inclination of two levels or more indeed validate the flow properties and laws related to the water movement from a recharge to a discharge area.

The determination of  $h$  is needed to define changes in water levels over time, groundwater flow directions, and effects of pumping. In an unconfined aquifer,  $h$  coincides with the actual groundwater surface and therefore it is called groundwater table [3]. A report has indicated that the depth to the water table has an important effect on the use of the land surface and on the development of water supply from unconfined aquifers [4]. The land may become "waterlogged" during wet weather and unsuitable for domestic usage where the water table is found at a shallow depth. As for water table at a great depth, the cost of constructing wells and pumping water for domestic needs may be expensive.

On the other hand, the direction of the slope of the  $h$  is also important because it indicates the direction of groundwater movement. Geological, topographical, and hydrological features determine the regional variations in the piezometric level and hydraulic head changes along different directions [3]. When there is a change in the head per unit horizontal distance, the relationship between any two  $h$  forms a hydraulic gradient. Such a concept is generally expressed as,

$$Q = kiA \quad (1)$$

where  $Q$  is the groundwater flow,  $k$  is the coefficient of permeability,  $A$  is the cross-sectional area of the aquifer, and  $i$  is the hydraulic gradient. With the difference in heads, then the groundwater tends to move in the direction of low potential. The position and the slope of the water table are determined by measuring the position of the water level in wells from a fixed point. To utilize these measurements in order to determine the hydraulic gradient, the position of the water table at each well must be determined relative to a datum plane that is common to all the wells. In order to determine  $h$ , normally one may do leveling based on a temporary benchmark (TBM) constructed on site using a theodolite. However, in a situation where such an instrument is not available for such a purpose, an alternative method is illustrated and discussed in this paper.

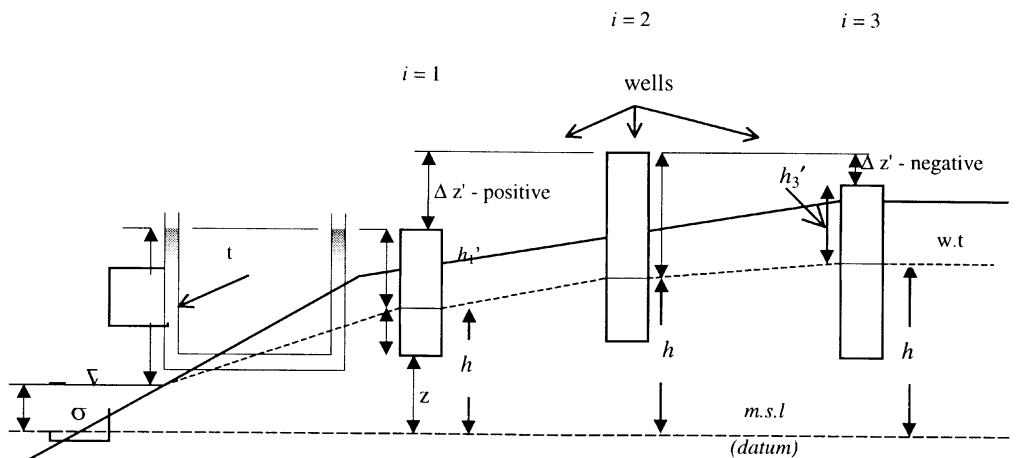
Hence, the purpose of this paper is to introduce a simple concept of water leveling application in the determination of  $h$  of phreatic water in a coastal aquifer. A case study is also put forward as an example of such an application.

## **METHODOLOGY AND LIMITATIONS**

The materials needed for this technique are a small-diameter transparent tube, a measuring stake (or any long stick and measuring tape), tidal chart, and a string and a chalk. To proceed with the method, the tube filled with water is placed between the current tidal height mark and the first well to be measured (Figure 1). The heights of the water level in the tube at both ends, from the ground and the reference levels at the shore and the wells are determined, respectively.

The technique is repeated for the other locations by referring to its previous measured reference site for each measurement. The water level depths in the wells from the reference point can be simply determined using a string attached with a chalk. In order to determine the current tidal height during the setting up of a reference level, a standard tidal chart is also essentially required.

The method employed is specifically for the determination of  $h$  in a shallow unconfined coastal aquifer, particularly on small islands with a flat land feature. The distances between wells, and from the coast to the wells are preferably localized or roughly 50 m for each measurement to be carried out (depending on the maximum length of the leveling tube).



**Figure 1** Determination of hydraulic head,  $h$  in a shallow phreatic aquifer.

## THEORETICAL CONCEPTS

Basically, fresh groundwater moves seaward continuously at a rate that is related to hydraulic gradient in an aquifer. The consequence of man's withdrawal of water from the landward parts of an aquifer may have far-reaching effects on the heads. Thus, the concept of this approach to determine the current head potential at several locations in such condition is discussed. As depicted in Figure 1, the height of a well located at location  $i = 1$  from the current tidal height is represented by  $B$ . With that, a reference level is set at the top of the well, from where the measurement of water level depth in the well ( $h_1'$ ) is to be undertaken too.

At location 1 ( $i = 1$ ), where the first reference level is obtained, the relationship of the measured parameters can be presented as follows,

$$h = \xi - h_1' \quad (2)$$

where  $h$  consists of the pressure head and the elevation head. The sum of the tidal amplitude from the mean sea level (*msl*) recorded at a particular time and a projected height of B implies the current reference level from *msl*. Therefore, the subtraction of the phreatic depth from the height of well from, *msl*, represents  $h$ . The fluid leveling in the tube employs the Bernoulli's theorem.

A similar technique is applied in determination of the head in another well, by using the first measured well ( $i = 1$ ) as a point of reference. In Figure 1, the location of the second well is shown as  $i = 2$ . The level difference between the well and the previous measured well at  $i = 1$ , is indicated as  $\Delta z$ , where in this case,  $\Delta z$  is positive. Such a positive value is valid as long as the following subject well is higher than the reference well. A reference well in this concept is defined as a well where its  $h$  has been determined using the same technique. A subject well then refers to the well to be measured. When such well is lower than the reference well, then  $\Delta z$  is negative. Again,  $\Delta z$  is obtained based on the balanced level of fluid in the tube.

In general, the phreatic  $h$  leveling can be formulated as follows,

$$h_i = \xi - h_i' + \Delta z' \quad (3)$$

where,  $h_i$  = hydraulic head at location  $i$

$\xi$  = (B +  $\sigma$ )

B = a location reference level (LRL) above current tidal height

$\sigma$  = current tidal height

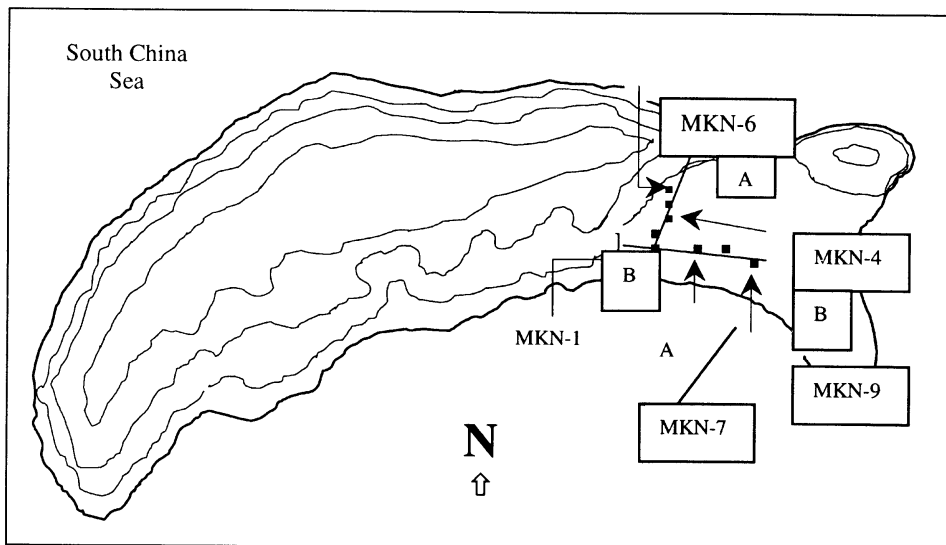
$h_i'$  = LRL from water level in the well

$\Delta z'$  = difference of height between a subject well and a reference well,  
LRL is based on the height of top of the well at location  $i$

## FIELD APPLICATION

A case study has been carried out at field to determine  $h$  in production wells of Manukan Island. This small island is situated on the north-west coast of Sabah. Currently, there are nine partially penetrating dug wells on the low-lying area as shown by Figure 2. The pumping rate at wells MKN-1 to MKN-6, and MKN-7 to MKN-9 are 180 litres/min and 40 litres/min, respectively. Groundwater tends to be the main source of freshwater all year round since there is no surface water on the island. It is understood that over-pumping of wells may lead to the lowering of water table. The determination of heads in the production wells of Manukan Island have revealed that all the wells might have been over-extracted, as indicated by Table 1. The decreasing values of  $h$  calculated at wells MKN1 to MKN-9 implies that the water levels in the wells were declining towards the *msl*. Such situation may potentially lead to seawater intrusion into the aquifer due to the hydraulic pressure exerted by the aquifer.

When pumping was done, the maximum  $s_w$  that can be achieved were not more than the depth of each well. Since the wells are of the partially penetrated, the shallow depths limit the extent of  $s_w$ . However, frequent pumping increases the extraction quantity of the groundwater, which eventually decline the water table of the island. Table 1 shows that the wells located further inland experienced a relatively greater impact of the pumping. The wells were pumped relatively heavier by the operator to cater the daily water supply demand on the island. As a result, it creates a significant reduction of head in the wells such as in wells MKN-3, MKN-4, MKN-5, and MKN-6 which have dropped to 0.18 - 0.21 m above msl. Such condition is worsened since the aquifer has limited recharge of freshwater.



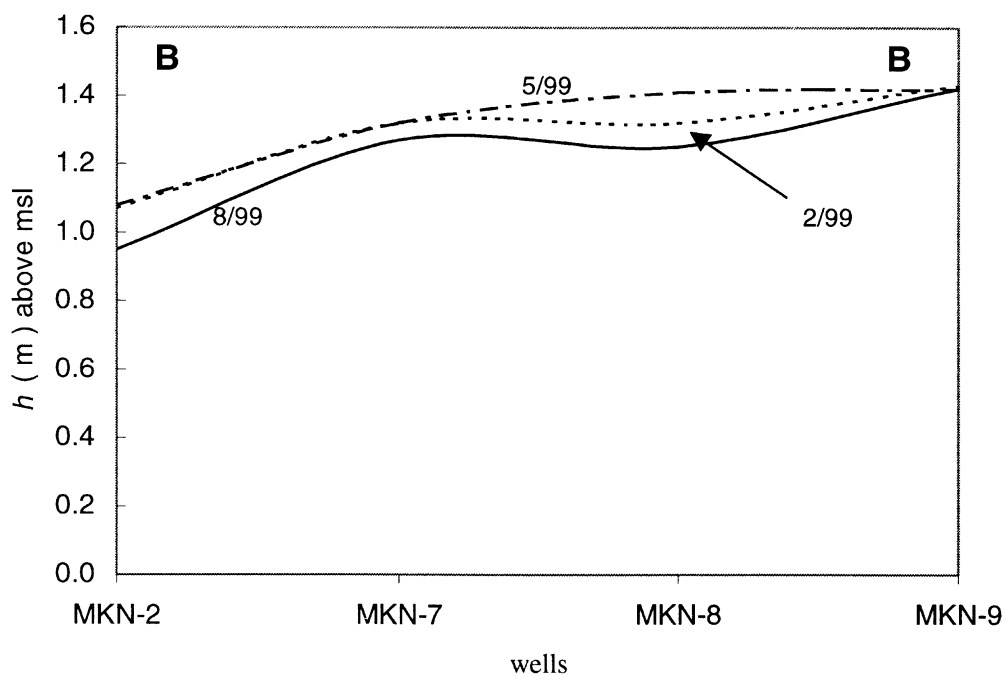
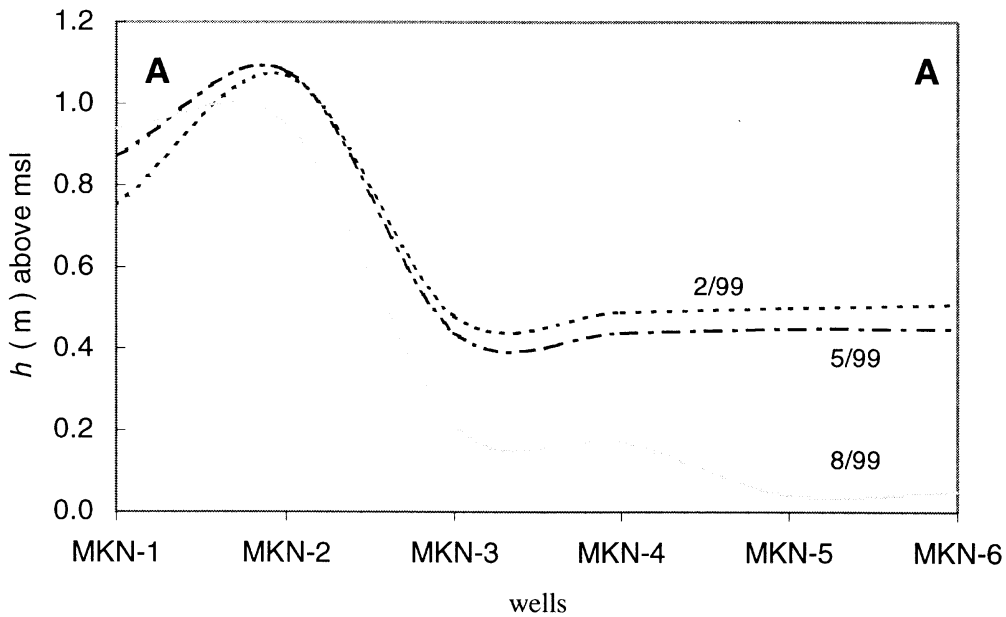
**Figure 2** Locations of the wells on Manukan Island, Sabah.

**Table 1** The  $h$  values of water in the production wells on Manukan Island.

Well code	Date of measurement	B (m)	(B+ $\sigma$ ) (m)	$h'$ (m)	$h$ (m)
MKN-1	2/99	1.45	2.85	2.10	0.75
	5/99			1.98	0.87
	8/99			1.91	0.94
MKN-2	2/99	1.52	2.92	1.85	1.07
	5/99			1.84	1.08
	8/99			1.97	0.95
MKN-3	2/99	1.16	2.56	2.08	0.48
	5/99			2.12	0.44
	8/99			2.35	0.21
MKN-4	2/99	1.16	2.56	2.07	0.49
	5/99			2.12	0.44
	8/99			2.39	0.17
MKN-5	2/99	1.14	2.54	2.04	0.5
	5/99			2.09	0.45
	8/99			2.50	0.04
MKN-6	2/99	1.15	2.55	2.04	0.51
	5/99			2.10	0.45
	8/99			2.50	0.05
MKN-7	2/99	1.65	3.05	1.73	1.32
	5/99			1.73	1.32
	8/99			1.78	1.27
MKN-8	2/99	1.65	3.05	1.73	1.32
	5/99			1.64	1.41
	8/99			1.80	1.25
MKN-9	2/99	1.69	3.09	1.66	1.43
	5/99			1.67	1.42
	8/99			1.67	1.42

The highest  $h$  at wells MKN-1, MKN-2, MKN-3, MKN-4, MKN-5, and MKN-6 ever recorded in previous studies were 1.22 m, 1.06 m, 0.42 m, 0.44 m, 0.44 m and 0.46 m above msl, respectively [5]. Based on those figures, apparently there was a drop in the water table.

The three wells MKN-7, MKN-8 and MKN-9, which were pumped daily at a slower rate compared to the six wells discussed earlier, presents a higher  $h$ . Such condition reflects the natural movement of groundwater in the aquifer is directed towards the sea. This at least minimizes the possible inward movement of the saltwater interface due to negative hydraulic gradient. Since MKN-7 is located near to the area where pumping were done at higher rate (Figure 2), the impact of pumping of those wells can be noticed on its lower  $h$  compared to MKN-8 and MKN-9. Figure 3 shows the cross-section of A-A and B-B (in Figure 2) with respect to the water level in the existing dug wells on the island.



**Figure 3** The water level in the dug wells.

## CONCLUSIONS

The method introduced in this paper would be of assistance in the determination of water table especially in a small area of low-relief topography in the absence of standard instrumentation. The balanced water level in a tube between two locations provides a horizontal line as a basis for the measurement of different heights from current reference points. The case study done on an island suggested that the method has shown a useful contribution to research methodology, using a tool that is simple and incurring less cost. Besides, it provides a means for monitoring critical levels of  $h$  that can cause saline water intrusion into a phreatic coastal aquifer.

## ACKNOWLEDGEMENT

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