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Using Freshwater Heads to Analyze Flow Directions in Saline Aquifers of the Pingtung Plain, Taiwan

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Abstract: The hydraulic head is the most important parameter for the study of groundwater. However, a head measured from observation wells containing groundwater of variable density should be corrected to a reference density (e.g., a freshwater head). Some previous case studies have used unknown density hydraulic heads for calibrating flow models. Errors arising from the use of observed hydraulic head data of unknown density are, therefore, likely one of the most overlooked issues in flow simulations of seawater intrusion. Here, we present a case study that uses the freshwater head, instead of the observed hydraulic head, to analyze the flow paths of saline groundwater in the coastal region of the Pingtung Plain, Taiwan. Out of a total of 134 observation wells within the Pingtung Plain, 19 wells have been determined to be saline, with Electric Conductivity (EC) values higher than 1500 µS/cm during 2012. The misuse of observed hydraulic heads causes misinterpretation of the flow direction of saline groundwater. For such saline aquifers, the determination of a freshwater head requires density information obtained from an observation well. Instead of the purging and sampling method, we recommend EC logging using a month interval. Our research indicates that EC values within an observation well within saline aquifers vary not only vertically but also by season.

Keywords: variable-density groundwater; freshwater head; Pingtung Plain; Taiwan

Citation: Chiu, Y.-C.; Chen, C.-H.; Cheng, Y.-T.; Chen, W. Using Freshwater Heads to Analyze Flow Directions in Saline Aquifers of the Pingtung Plain, Taiwan. *Water* **2021**, *13*, 3491. https://doi.org/10.3390/w13243491

Academic Editors: Fulin Li and Longcang Shu

Received: 25 October 2021
Accepted: 2 December 2021
Published: 7 December 2021

1. Introduction

Seawater intrusion is one of the most concerning issues for groundwater resources management within coastal aquifers. Using hydraulic head observations to infer groundwater flow directions is a basic procedure in seawater intrusion studies [1–3]. Organizations such as the USGS, The Geological Survey of Denmark and Greenland (GEUS), and the Taiwan Water Resources Agency collect long-term hydraulic head (water-level) data and maintain observation well nets (Table 1). A hydraulic head is obtained by measuring water level in an observation well where level refers to mean sea level.

Numerical models such as SEAWAT are used to simulate variable-density transient groundwater flow in porous media, using freshwater as a reference fluid [4]. SEAWAT is a public domain computer program. The source code and software are distributed free of charge by the U.S. Geological Survey (USGS). However, no density information data for observed hydraulic heads (or water levels) is available within databases. Table 1 provides case studies using unknown density observed hydraulic heads for calibrating (or evaluating) flow models [5–13]. Errors arising from the use of observed hydraulic head data of unknown density are, therefore, likely one of the most overlooked issues in flow simulations of seawater intrusion [14–16].

Table 1. Studies on the simulation of groundwater-level within saline aquifers.

	Case 1	Case 2	Case 3
Location	Eastern Shore, Virginia, USA	Danish–German border	Pingtung, Taiwan
Number of observation wells	51	22	134
Well depth (m below the land surface)	6–113	18–345	18–270
Electrical conductivity (μS/cm)	104–7906	334–13,590	195–51,900
Sources of observed groundwater levels	Virginia observation- well network	Danish national database	Taiwan Water Resources Agency
Numerical Model	SEAWAT	SEAWAT	SEAWAT FEFLOW
References	[6,7]	[8,11,12]	[10,13]

As an alternative to the hydraulic head (H_i), previous studies have suggested using an equivalent freshwater head (H_{fi}) for analyzing flow components within a variable-density groundwater aquifer. A freshwater head (H_{fi}) can be calculated from point water head measurements using the following formula [17–19] (Figure 1):

$$H_{fi} = H_i \times D_i/D_f - Z_i \times (D_i - D_f)/D_f \tag{1}$$

where H_i is the hydraulic head, D_i is the density of water within the observation well, D_f is the freshwater density, and Z_i of the elevation head represents the mean level of the well screen.

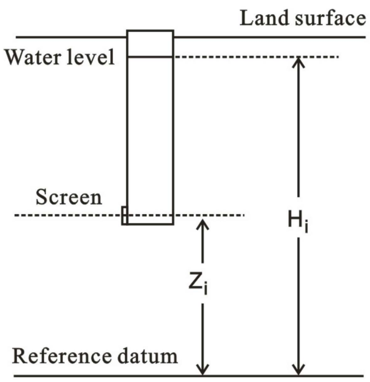

Figure 1. A schematic representation of a hydraulic head (H_i) and an elevation head (Z_i). Definitions are provided in Equation (1).

Here, we present a case study for using the "equivalent freshwater head (H_{fi})" instead of an "observed hydraulic head" for analyzing the flow paths of saline groundwater within the coastal Pingtung Plain, Taiwan. We also provide recommendations for water level data collection from a saline groundwater area.

2. Study Area and Hydrogeology

The Pingtung Plain is located in southwestern Taiwan, where the southern border is in contact with the South China Sea (Figure 2). Geologically, the Pingtung Plain consists of rivers, deltas, and estuary of unconsolidated deposits surrounded by mountains and hills composed of pre-Holocene rock [20,21]. From 1995–1998, a total of 134 new observation wells were constructed by the Taiwan Water Resources Agency (WRA). The staff of WRA maintains and collects water level data, and offers data through its website [22–24]. Water level data are automatically recoded at one-hour intervals using a pressure transducer within the observation well. However, groundwater chemistry data, including Electric Conductivity (EC), are only collected once a year by water purging and sampling with a pump.

Four aquifers (F1 to F3-2), down to 300 m in depth, were identified and, at most, four observation wells were installed at one site (Figure 3). Lengths of screens, ranging from 12 to 30 m, were placed on the bottom of observation wells. Aquifers in the area are composed of gravel and sand, and are separated by fine-grain, clay-rich aquitards (T1 to T3). A total of eight sites, all at the coastal location, presenting saline groundwaters with EC's higher than 1500 μS/cm (at 25 °C), were first noted in WRA reports during investigations conducted from 1995–1998.

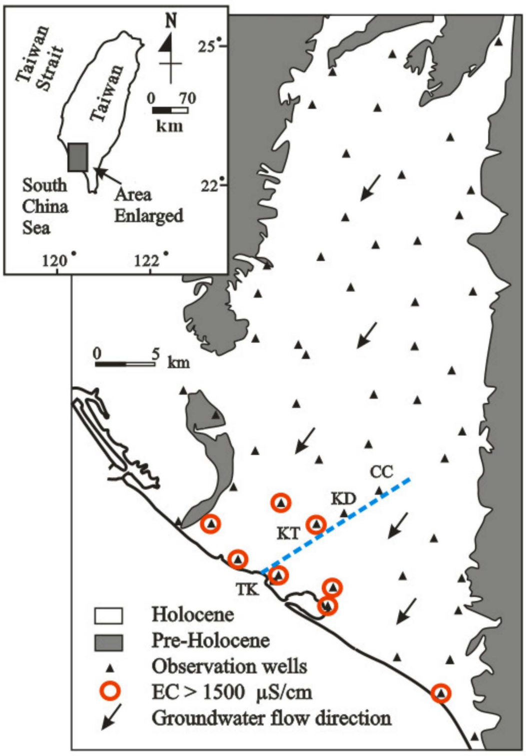

Figure 2. The locations of saline groundwater having an EC > 1500 μS/cm (at 25 °C), as well as observation wells within the Pingtung Plain, Taiwan. Hydrogeological profiles are marked with a blue dashed line (Please see Figure 3).

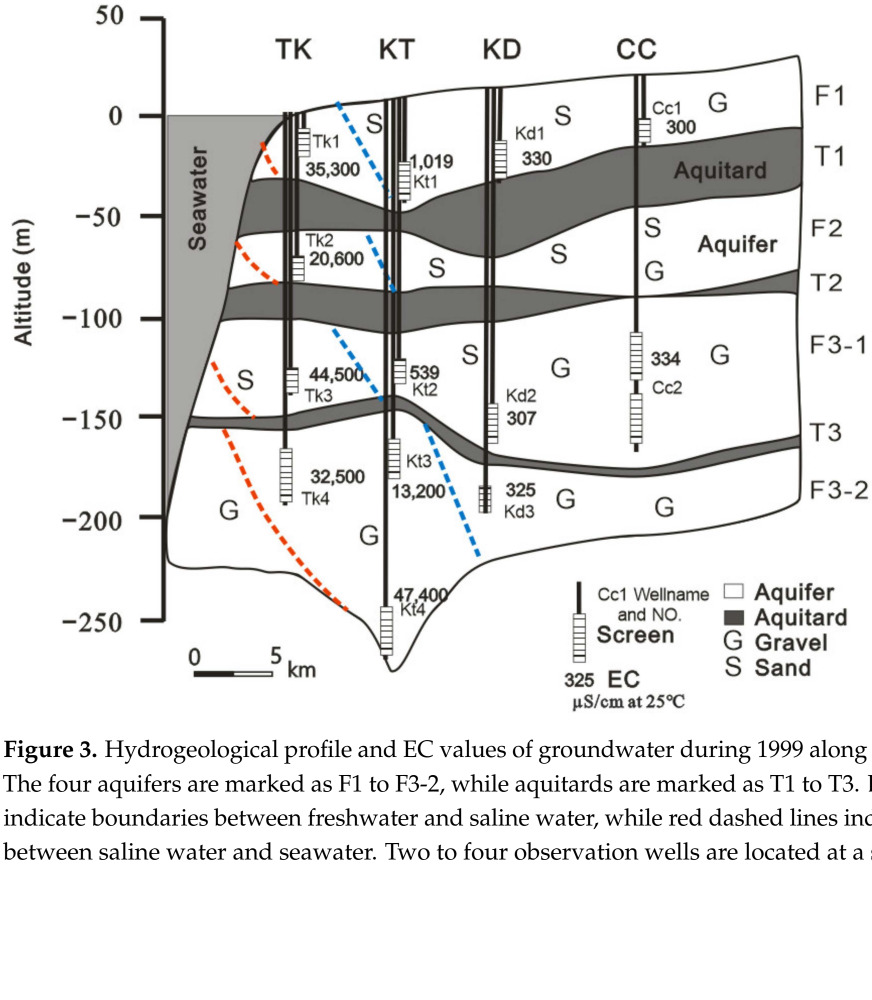

Figure 3. Hydrogeological profile and EC values of groundwater during 1999 along the TK–CC wells. The four aquifers are marked as F1 to F3-2, while aquitards are marked as T1 to T3. Blue dashed lines indicate boundaries between freshwater and saline water, while red dashed lines indicate boundaries between saline water and seawater. Two to four observation wells are located at a single site.

3. Distribution of Saline Groundwater

Groundwater EC and the mean level of the screen (the elevation head) for the 134 observation wells are provided in Figure 4. In 2012, 19 observation wells displayed EC's higher than 1500 μS/cm (Table 2). An EC of seawater of 52,000 μS/cm, with a density of 1026 kg/m^3, and a density of freshwater (EC < 1500 μS/cm) of 1000 kg/m^3 can be assumed. The densities of saline water (D_i) within observation wells can be calculated using the following formula [25]:

$$D_i = 0.000515\ EC + 999.277 \tag{2}$$

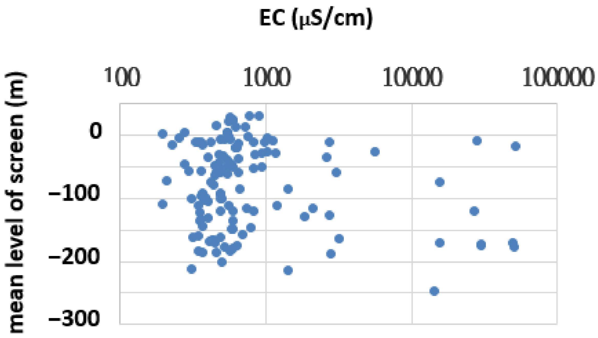

Figure 4. Groundwater EC and the mean level of the screen (elevation head) for the 134 total observation wells within the Pingtung Plain (2012 data from [21]).

Table 2. The freshwater heads of observation wells with EC >1500 μS/cm during 2012.

Observation Well	EC (μS/cm)	Density (kg/m^3)	Mean Level of Screen (m)	Annual Hydraulic Head in 2012 (m)	Freshwater Head in 2012 (m)	Difference in Head (m)
1. CF1	51,900	1026.0	−16.53	−0.78	−0.37	0.41
2. TK4	50,900	1025.5	−177	−0.43	4.07	4.50
3. SY2	49,800	1024.9	−171.02	−0.96	3.28	4.24
4. KT3	30,300	1014.9	−172.63	0.2	2.77	2.57
5. LY3	30,000	1014.7	−174.96	2.53	5.14	2.61
6. DS1	28,100	1013.7	−8.42	−0.01	0.11	0.12
7. LY2	26,900	1013.1	−120.96	2.41	4.03	1.62
8. TK2	15,800	1007.4	−75	1.4	1.97	0.57
9. DT2	15,500	1007.3	−171.08	3.04	4.30	1.26
10. KT4	14,200	1006.6	−247.63	1.8	3.44	1.64
11. SH1	5610	1002.2	−25.51	−0.19	−0.14	0.05
12. DS3	3210	1000.9	−164.42	−5.91	−5.76	0.15
13. CF2	3050	1000.8	−58.03	−3.97	−3.92	0.05
14. CF4	2780	1000.7	−188.03	1.8	1.93	0.13
15. KT2	2720	1000.7	−127.63	1.82	1.91	0.09
16. TK1	2700	1000.7	−10.5	0.16	0.17	0.01
17. KT1	2620	1000.6	−34.63	0.48	0.50	0.02
18. DS2	2111	1000.4	−114.92	−15	−14.96	0.04
19. TK3	1860	1000.2	−129	0.34	0.37	0.03

Density is known, as well as the mean level of a screen. Therefore, by using Equation (1); freshwater heads can be determined as shown in Table 2 and Figure 5. A difference in the head by as much as 4.5 m occurred for well TK4, a freshwater head at 4.07 m, while the observed annual hydraulic head was only −0.43 m. According to Equation (1), differences between an observed hydraulic head and a freshwater head increase with increasing depth within a water column and the density within an observation well. Within the TK4 well, the mean level of the screen was −177 m, and the density of water was 1025 kg/m^3.

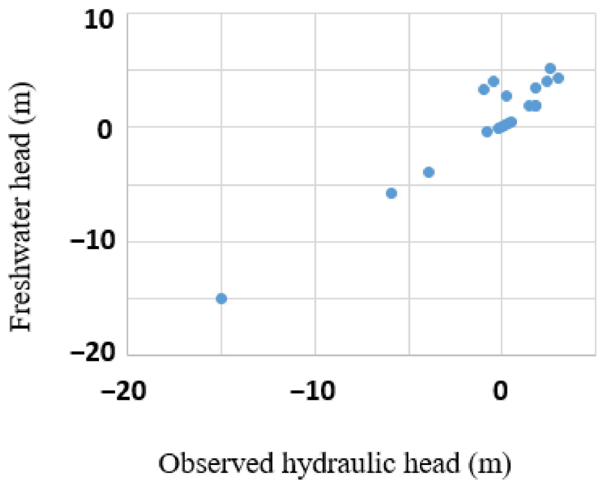

Figure 5. Freshwater heads and observed hydraulic heads for saline groundwaters during 2012.

The misuse of observed hydraulic heads causes a misinterpretation of the flow direction of saline groundwater [2,26]. For example, Figure 6A displays the distributions of observed hydraulic heads (m) within aquifer F3-2 during 2012. The direction of groundwater flow was from the KT site to the TK site, from land to sea, according to the observed hydraulic heads. However, according to the freshwater heads (Figure 6B), the flow direction should be the opposite (from sea to land).

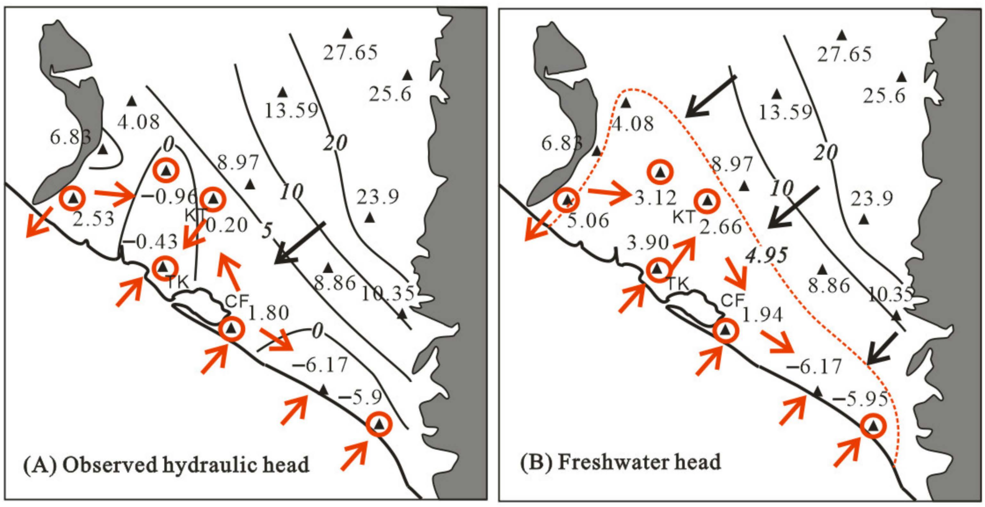

Figure 6. (**A**) Observed annual hydraulic heads (m) within aquifer F3-2 during 2012. (**B**) Freshwater heads were calculated based on observed annual hydraulic heads, EC, and mean screen level. Observation wells marked with a red circle were saline groundwaters with an EC > 1500 µS/cm, which represent a potential seawater intrusion area. Black arrows indicate the flow directions of fresh groundwater, while the flow directions of saline groundwater are marked by red arrows. The depth of aquifer F3-2 is approximately 150–230 m, with an average depth of 190 m. The freshwater head of seawater at a depth of 190 m is approximately 4.95 m (red dashed line).

A potential area of seawater intrusion may also be indicated by the equivalent freshwater head of seawater. The depths of aquifer F3-2 were 150–230 m, with an average of 190 m. The freshwater head of seawater at a depth of 190 m was approximately 4.95 m. The coastal portion of aquifer F3-2, with a freshwater head less than 4.95 m, was potentially impacted by seawater intrusion (the red dashed line in Figure 6B). Figure 7 shows groundwater EC in the F3-2 aquifer during 2004–2019. The saline groundwater area in which ECs were > 1500 μS/cm is consistent with the potential seawater intrusion area in Figure 6B.

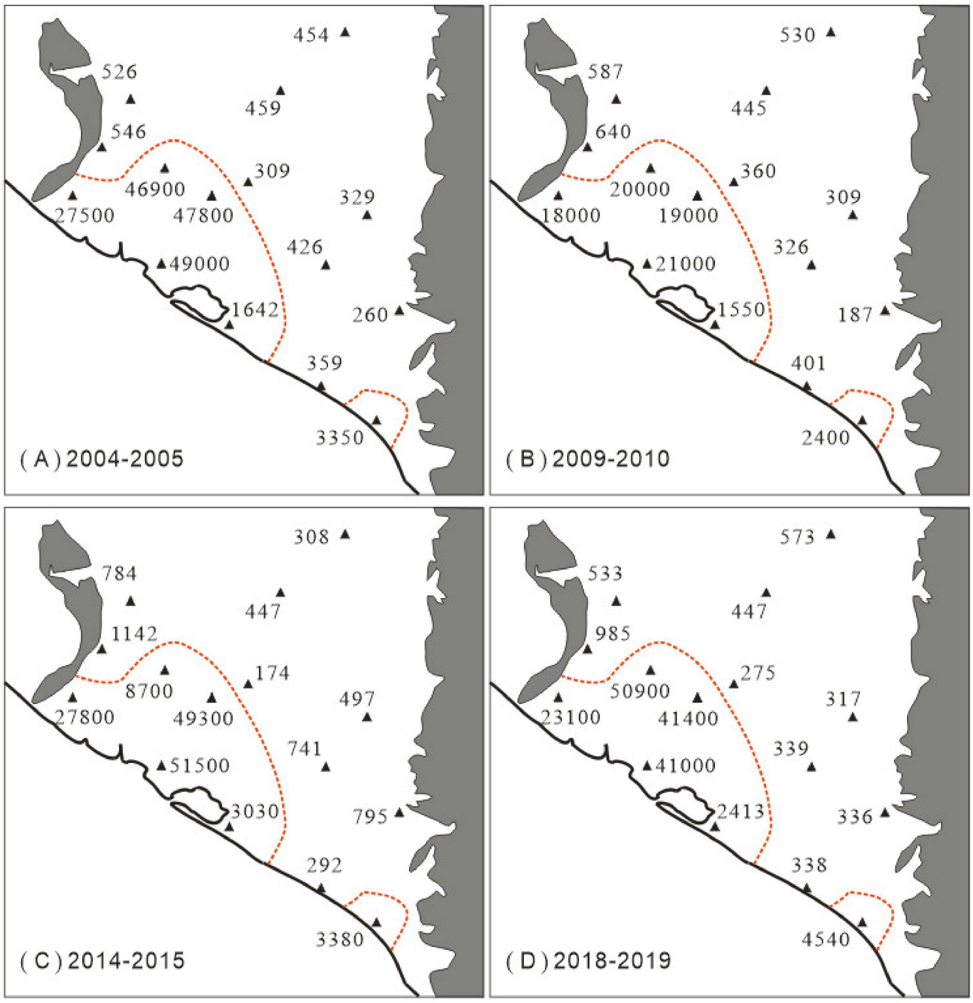

Figure 7. The groundwater EC (μS/cm at 25 °C) in the F3-2 during 2004–2019. The area marked by a red dashed line represents a saline area in which ECs were > 1500 μS/cm. (**A**) 2004–2005; (**B**) 2009–2010; (**C**) 2014–2015; (**D**) 2018–2019.

Figures 6 and 8 show freshwater heads and the flow directions of groundwater from the four aquifers within the Pingtung Plain during 2012. The depth of aquifer F1 ranged from 0 to 50 m in depth below the land surface, with an average of 25 m. The freshwater head of seawater, at an average depth of 25 m, was 0.65 m. In Figure 8, the potential seawater intrusion area for aquifer F1 is marked by a red dashed line where freshwater heads were <0.65 m.

Averaged depths were 75, 125, and 190 m, and the freshwater heads of seawater at those depths were 1.95, 3.26, and 4.95 m for aquifers F2, F3-1, and F3-2, respectively. In Figures 6 and 8, potential seawater intrusion areas are shown with red dashed lines. The deepest aquifer, F3-2, displayed the largest area of potential seawater intrusion, approximately 7 km towards land.

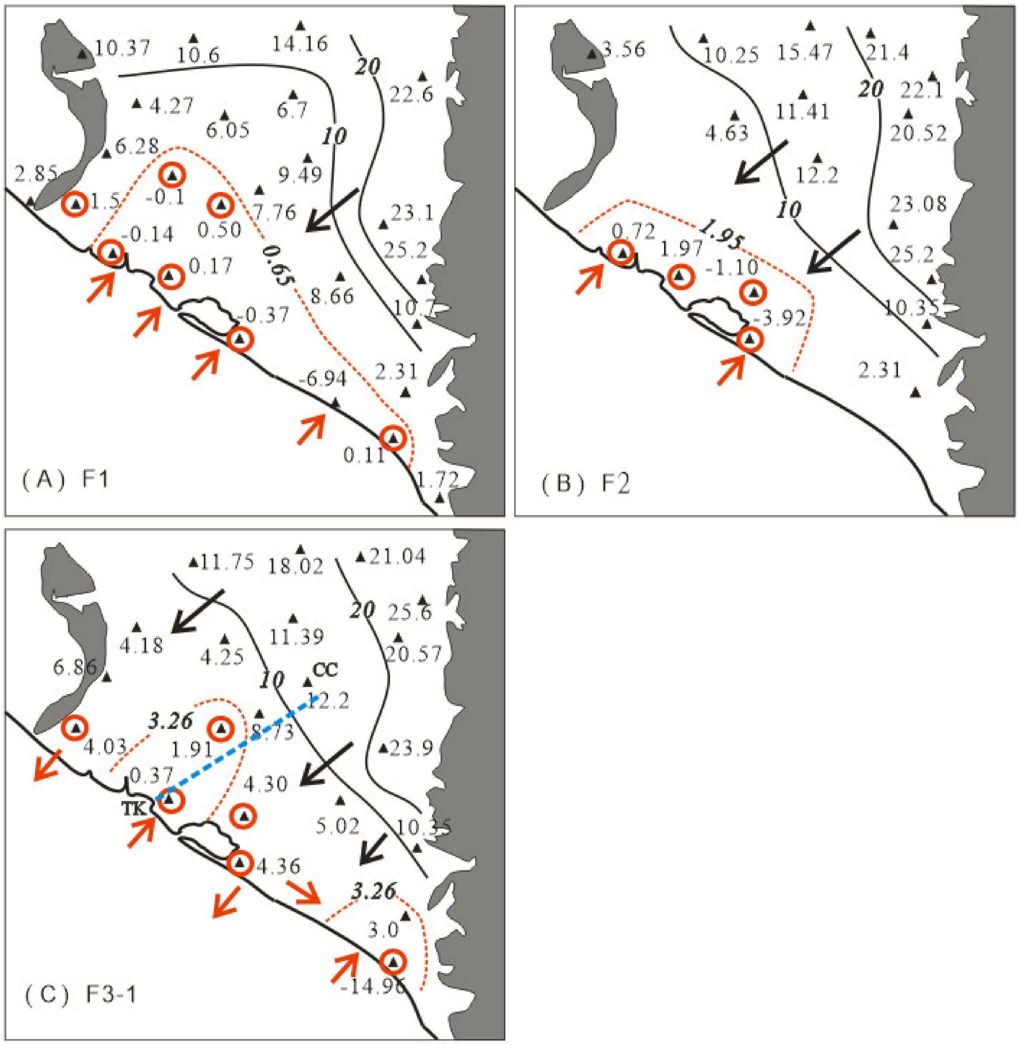

Figure 8. (**A**) The freshwater heads and flow directions of groundwater for the four aquifers within the Pingtung Plain during 2012. (**A**) The depth of aquifer F1 ranges from 0 to 50 m below the land surface, with an average depth of 25 m. The fresh head is 0.65 m, with an average depth of 25 m of seawater. The area marked by a red dashed line represents a potential seawater intrusion area in which freshwater heads were <0.65 m. (**B**) Aquifer F2 is 50–100 m in depth, with an average of 75 m. The freshwater head for 75 m seawater depth is 1.95 m. (**C**) Aquifer F3-1 is 100–150 m in depth, with an average of 125 m.

4. Flow History along the Profile TK–CC

We used a flow path along profile TK–CC to represent the flow history of aquifer F3-1 from 1999–2018 (Figure 8C). EC values of groundwater for the four observation wells within aquifer F3-1 along the TK–CC profile are provided in Table 3. Annual observed hydraulic heads and freshwater heads of those wells are shown in Figure 9.

During the period from 1999–2018, the flow direction was from CC2 to TK3, that is, from land to coast, according to the observed hydraulic heads. However, after 2015, a completely different explanation is explained by the freshwater heads of saline water within observation wells TK3 and KT2. According to the freshwater heads (Figure 9), the flow direction between TK3 and KT2 changed in 2015 (i.e., from coast to land).

Due to saline water flow to the landside since 2015, freshwater heads for July 2020 were 3.07 m and 1.79 m for wells TK3 and KT2, respectively. We predict that the EC in wells TK3 and KT2 will increase. Water sampling on 19 July 2020 indicated that EC within TK3 increased to 42,600 μS/cm from 21,700 μS/cm (2018), and increased to 9545 μS/cm from 3280 μS/cm within KT2.

Table 3. The EC (μS/cm at 25 °C) of four wells within aquifer F3-1 along the TK–CC profile from 1999–2018.

Year	TK3	KT2	KD2	CC2
1999	44,500	539	307	334
2000	1114	1003	305	330
2001	1041	1336	341	353
2002	27,328	2520	378	418
2003	11,140	3080	309	341
2004	18,300	3410	317	347
2005	18,870	2190	322	347
2006	19,200	2430	309	341
2007	11,960	1801	311	364
2008	1534	2660	320	346
2009	-	-	-	-
2010	1334	2000	386	-
2011	-	-	-	-
2012	1860	2720	369	360
2013	-	-	-	-
2014	756	593	785	321
2015	23,700	4820	-	-
2016	24,500	3570	-	-
2017	23,300	3840	-	-
2018	21,700	3280	292	375

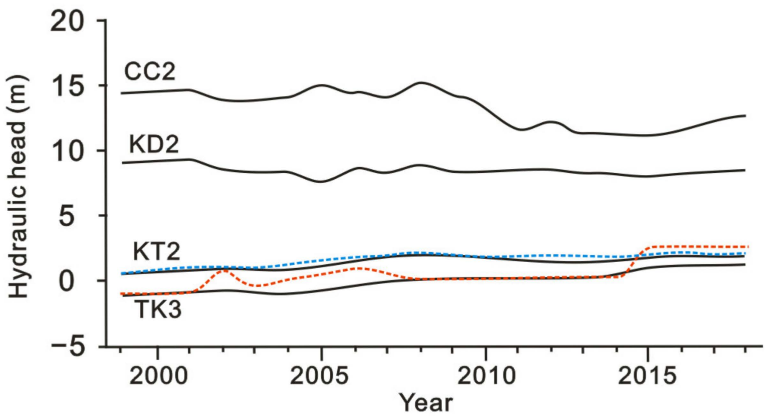

Figure 9. The annual observed hydraulic heads (black lines) of the four observation wells that screen aquifer F3-1 along the TK–CC profile. The freshwater heads (dash lines) of observation wells TK3 (red) and KT2 (blue). The flow direction between TK3 and KT2 changed during 2015, according to the freshwater heads, while an interpretation of no change was found when using the observed hydraulic heads.

5. EC Values within Observation Wells

The determination of a freshwater head requires density information within the observation well. Compared to water-level data, density information is not easy to obtain. Water density is not directly routinely measured by the Taiwan Water Resources Agency (WRA). Density-related measurements such as EC and TDS (total dissolved solids) are only determined once per year. The WRA's current measurement method, which is regulated by the Taiwan Environmental Protection Agency (NIEA W103.56B) for water sampling, consists of purging and sampling. However, the purging and sampling method is quite time-consuming, labor-intensive, and expensive. The method may also result in the mixing of different layers of groundwater from outside an observation well.

We suggest that EC logging is a robust and inexpensive method for collecting density information for the water column within an observation well. New EC logging data are generally vertically varied within observation wells for saline aquifers of the Pingtung Plain.

On 19 July 2021 (Figure 10), vertical EC values by logging ranged from 4452 to 15,319 µS/cm and 14,346 to 31,341 µS/cm within wells KT2 and TK3, respectively. Calculations for the density of the water column should use an average value rather than just one value at any depth.

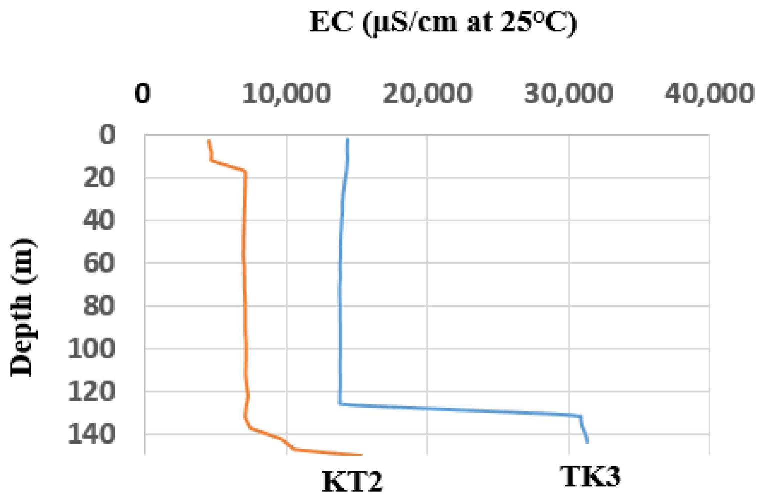

Figure 10. Vertical EC logging values within wells KT2 and TK3 on 19 July 2021.

EC logging values within an observation well were not only vertically varied but also varied with season. Figure 11 shows vertical EC logging values within well TK4 from 2020–2021. EC values ranged from 35,000 to 55,000 µS/cm. Values were higher during the dry season (February 2021) and lowered during the rainy season (September 2020). In summary, for collecting density information within observation wells in saline aquifers, we recommend EC logging using a monthly sampling interval instead of the purging and sampling method.

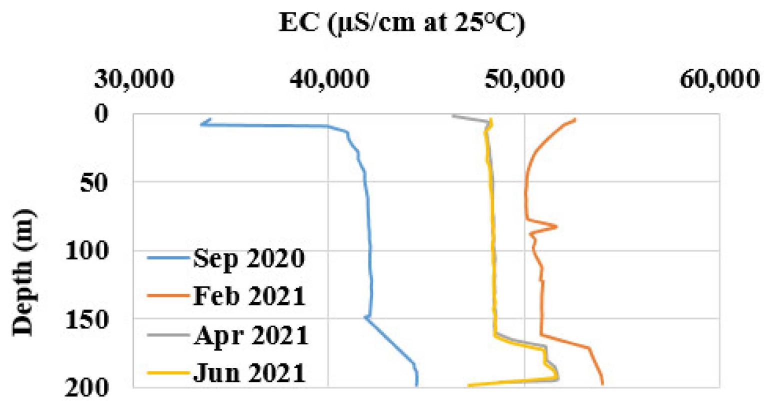

Figure 11. Vertical EC logging values within well TK4 during 2020–2021.

6. Conclusions

Instead of an observed hydraulic head, we used an equivalent freshwater head to analyze flow components in variable-density groundwater aquifers within the Pingtung Plain, Taiwan. Out of the total 134 observation wells, during 2012, 19 wells were saline with EC values higher than 1500 µS/cm. The misuse of observed hydraulic heads causes a misinterpretation of the flow direction of saline groundwater.

For saline aquifers, the determination of a freshwater head requires density information within the observation well. We recommend using EC logging with a month measurement interval instead of the purging and sampling method. Our research indicates that EC values within an observation well within saline aquifers vary not only vertically but also by season.

Author Contributions: Conceptualization and methodology, Y.-C.C. and W.C.; investigation, resources, and data curation, C.-H.C. and Y.-T.C.; writing—original draft preparation, W.C.; writing—review and editing, Y.-C.C. All authors have read and agreed to the published version of the manuscript.

Funding: We thank the Ministry of Science and Technology of Taiwan, the Central Geological Survey, and the Water Resources Agency for research funding and support.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study is available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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