Investigation of Submarine Groundwater Discharge under Drought Conditions in Northwestern Coastal Taiwan

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Abstract

Submarine groundwater discharge (SGD) plays a vital role as a source of water, nutrients, and solutes from land to sea, serving as a crucial freshwater resource, particularly during drought conditions. The northwestern coast of Taiwan, known for its strong SGD, features several coastal flowing artesian wells (FAWs) that become prominent under such conditions. This coastal area presents a dynamic and complex environment where tidal variation, density-driven seawater circulation, and seasonal seawater exchange create intricate hydrological interactions between seawater and freshwater. This study integrates physical modeling and geochemical analysis to investigate the mechanisms driving FAWs and seasonal variations in SGD, with a particular focus on extreme drought conditions.

Hydraulic head data from coastal FAWs and onshore wells were analyzed alongside tidal observations to elucidate the mechanisms driving coastal FAWs. Multi-phase groundwater modeling revealed that coastal FAWs are driven by upward flow caused by a sharp freshwater-seawater interface, which acts as a barrier and deviates from conventional geological concepts. The daily SGD volume was estimated from this model to sustain the local population's water needs for approximately 23.18 days. Complementing this, radium isotope tracers (^{223}Ra, ^{224}Ra$_{ex}$, and ^{228}Ra) provided valuable insights into seasonal variations in SGD. The result of SGD during the wet season (841.47 ± 156.61 cm d^{-1}) were 2.7 times higher than those in the dry season (391.34 ± 79.59 cm d^{-1}), with deep aquifers likely contributing to SGD during droughts, as evidenced by stable isotope (δ^{18}O, δD) and radium activity ratio analyses. These findings enhance our understanding of SGD under contrasting hydrological conditions, underscore its role in mitigating drought impacts, and highlight the importance of coastal FAWs as key tools for investigating SGD dynamics.

1. Introduction

Fig: The map shows the history of Taoyuan-Chungli tableland including six different major sub-tablelands in the order Hokou, Fukang, Yangmei, Talun, Chungli, and Taoyuan.

*Observation data

Fig: Photographs shows the dried up Sun Moon Lake in Taiwan turn into the grassland under the historical drought 2021. (*Photo by Zhangxin Zheng*)

Fig: Photographs of coastal FAWs O1, O2, and O3 in 2021 at TaiCOAST site. The groundwater in these wells is freshwater.

*Scientific questions

What is the mechanism of coastal FAWs ?

Where is the source of SGD in the northwestern coastal zone of Taiwan ?

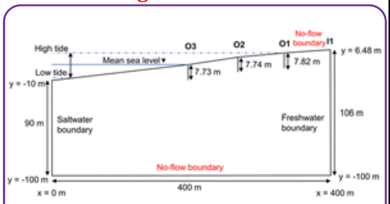
What is the variation in the quantity of SGD under drought conditions compared to the wet and dry seasons in the northwestern coastal zone of Taiwan?

*Objectives

1. Explaining the mechanism of coastal FAWs in this study area
2. Identifying the source of groundwater in this study area.
3. Quantifying the total volume of SGD under the drought conditions in the wet and dry season

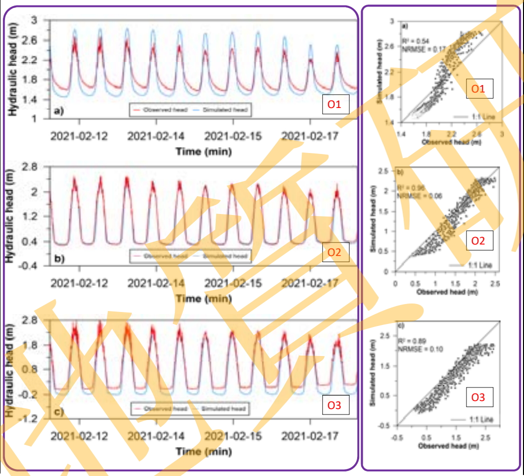
2. Physical approach

*Model settings

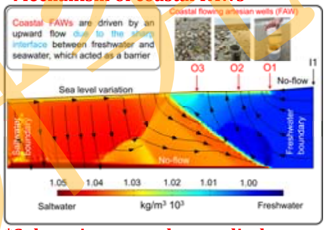


Parameter	Unit	Value
Porosity	–	0.35
Permeability	m^2	1.02 × 10^{-11}
Freshwater density	kg/m^3	1000
Saltwater density	kg/m^3	1035
Fresh dynamic viscosity	Pa·s	9.11 × 10^{-4}
Saltwater dynamic viscosity	Pa·s	9.81 × 10^{-4}
Gravity	m/s^2	9.81

*Model calibration and validation results



*Mechanism of coastal FAWs



*Submarine groundwater discharge

$Q = A \times v_D$ $A = coastal\ line \times well\ depth$

The assumption that the Xinwu coastal aquifer is homogeneous.

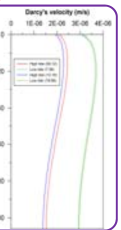
Coastline line = 11,203 m

Well depth = 106 m

$v_D = (2.96 \pm 0.61) \times 10^{-6}\ m/s$

$Q = (3.05.24 \pm 62.90) \times 10^3\ m^3$

Xinwu District had a population of about 48,063 people in 2020 and daily water consumption per capita in Taiwan is about 274 liters (Juan et al., 2016). Therefore, this means that the total volume of SGD on February 13, 2021 could supply water for 23.18 days for the whole Xinwu District (Dang et al., 2024a).



3. Chemical approach

*Study area and field work

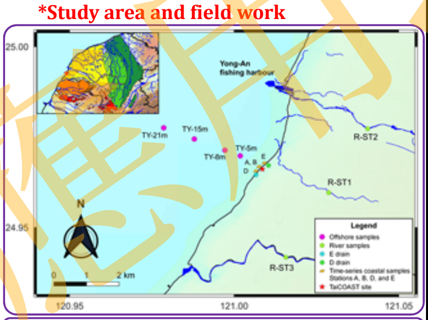


Fig: Distribution of sample locations of offshore, river, drain E, drain D, and the time-series coastal seawater samples (stations A, B, D, and E).

*The radium apparent age of coastal seawater

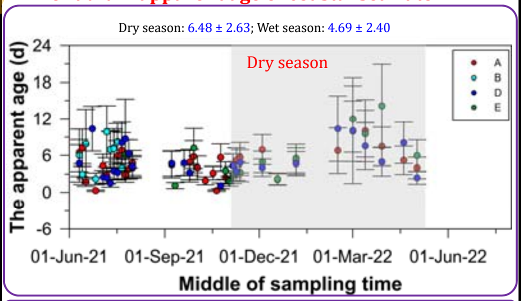


Fig: The radium apparent time in the middle of sampling time.

*Submarine groundwater discharge

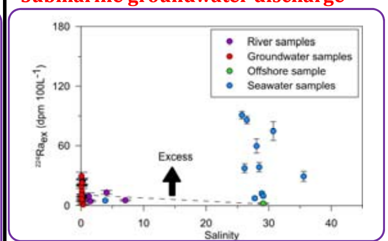


Fig: The salinity versus ^{224}Ra^{ex} in river samples, groundwater, offshore seawater, and seawater samples. The dash line indicates the expectation of radium activity between the discharge of surface water (river and drain) and the offshore seawater.

*The source of groundwater

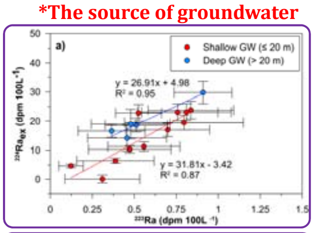
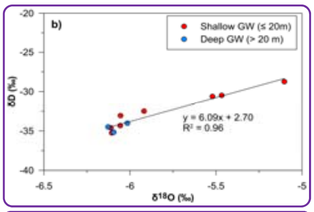


Fig: The δ^{18}O versus δD for all samples at TaiCOAST site.



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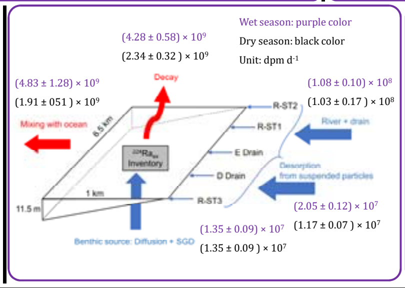

$$J_{riv} + J_{drain} + J_{diff} + J_{des} + J_{SGD} = J_{mix} + J_{decay}$$

J_{SGD} = (8.97 ± 1.41) × 10^8 dpm d^{-1}; (4.12 ± 0.60) × 10^8 dpm d^{-1}

$Q_{SGD} = \frac{J_{SGD}}{Ra_{GW}}$ = (5.52 ± 1.18) × 10^7 m^3 d^{-1}; (2.04 ± 0.45) × 10^{7}m^3 d^{-1}

SGD = 848.85 ± 181.74 cm d^{-1}; 314.16 ± 69.09 cm d^{-1}

Ra$_{GW}$ represents ^{224}Ra$_{ex}$ end-member value of GW (16.25 ± 2.37, 20.18 ± 3.32 dpm 100L^{-1})

(Dang et al., 2024b)

4. Conclusions

- The mechanism of coastal FAWs are caused by a sharp interface between freshwater and seawater
- Average Darcy's velocity obtained from multi-phase groundwater model for SGD at TaiCOAST site is (2.96 ± 0.61) × 10^{-6} m/s
- Based on mass balance model of ^{224}Ra, SGD in wet season [(9.85 ± 2.15) × 10^{-5} m/s] and was 2.7 times that in dry season [(3.65 ± 0.81) × 10^{-5} m/s].
- Isotope analyses with high correlation (R^2= 0.96) show that shallow and deep water were from consistent sources
- Deep groundwater is important freshwater source of discharging in drought period

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