

Assessment of Ground water Quality and Seawater Intrusion Potential in the Klang River Basin, Malaysia Using Hydro-chemical Analysis and MODFLOW Simulation

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Abstract. The study assessed the groundwater quality and seawater intrusion possibility based on the long-term hydro-chemical monitoring data and the numerical groundwater flow models. Klang River Basin in Malaysia was assessed choosing monitoring well S9 with regards to groundwater under the historical records (1998-2018) and physical parameter; pH, temperature, electrical conductivity (EC), total dissolved solids (TDS) and chemical parameters (major ions and selected trace metals). The electrical conductivity (EC=193.66 μ S/cm) and the TDS (range: 270-600 mg/L) are indicative that the groundwater is mostly fresh. The chloride levels were between 68 and 100 mg/L, which is much lower than the seawater intrusion level of 250 mg/L, indicating that there was not much impact of the sea. The trace metals of arsenic (\approx 0.0046 mg/L) and mercury (\approx 0.00035 mg/L) were systematically less than EPA guideline values but iron concentration levels remained high (mean 9.45mg/L), probably because of geogenic sources or borehole material. The MODFLOW model assumed a confined to unconfined aquifer system with constant-head boundary conditions along the coastal margin, no-flow boundaries from mean annual rainfall (2,420 mm/yr), Hydraulic conductivity and storage coefficient were derived from JMG pumping test records. A three-dimensional Visual MODFLOW model with data on pumping tests indicated that the drawdown (<0.01 m) of well S9 was negligible currently. The outcomes suggested equilibrium ground water situations with minimal seawater intrusion potential whereas revealing the necessity to monitor the iron concentration and ground water extraction at the most urbanised basin.

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1 Introduction

Groundwater constitutes a major freshwater resource and plays a critical role in sustaining domestic, industrial and agricultural water demands worldwide [1,2]. On the coasts and in regions that are highly urbanised, the groundwater systems are also facing threats of pollution and intrusion of seawater because of excessive abstraction, land-use change and poor waste management [3,4]. Malaysia is facing localised water stress problem despite the presence of surface water resources due to uneven distribution of rainfall and rapid urbanisation which forces the government to use groundwater resources [5]. Recent studies across Southeast Asia have highlighted growing concerns over groundwater quality degradation driven by urban expansion, agricultural intensification and inadequate sanitation infrastructure, with particular emphasis on coastal aquifer vulnerability to salinisation and trace metal contamination [6, 7].

Klang River Basin is among the more urbanised catchment areas in Malaysia and is highly developed industrial and commercial and residential. Earlier researchers have pointed out how coastal alluvial aquifers in Peninsular Malaysia are prone to the effects of salinisation and reduction in the quality of groundwater when over pumped [68]. The quality of groundwater in this basin should therefore be monitored to protect the water security and human health.

The seawater intrusion is of special interest in coastal aquifers where the excessive abstraction can disrupt the natural freshwater, saltwater balance [9]. Hydro-chemical indicators such as chloride concentration, electrical conductivity and total dissolved solids, combined with numerical groundwater flow modelling, are widely used to assess intrusion potential and abstraction impacts [10,11]. This study aims to (i) assess long-term groundwater quality trends at monitoring well S9, (ii) evaluate the potential for seawater intrusion using hydro-chemical indicators, and (iii) simulate groundwater drawdown behaviour under existing abstraction conditions using a three-dimensional MODFLOW model.

2 Literature Review

In this study, the literature review synthesises key findings related to groundwater quality assessment, coastal aquifer seawater intrusion, and numerical groundwater modelling relevant to tropical and urbanised basins.

2.1 Groundwater Quality Assessment in Coastal and Urban Basins

Groundwater quality deterioration in rapidly urbanising regions has been widely reported, particularly in coastal aquifers where anthropogenic pressure and natural hydrogeological conditions interact [1] & [2]. Hydro-chemical indicators such as pH, electrical conductivity (EC), total dissolved solids (TDS) and major ion concentrations are commonly used to characterise groundwater suitability for domestic and industrial use [1] & [3]. Tropical studies have demonstrated that EC and TDS are good predictors of salinisation and anthropogenic effects whereas trace metals can be useful in reflection of both geogenic and human-made activities [4]. Study of the groundwater quality in Malaysia has revealed that

high levels of iron have often been found in alluvial aquifers, and this has been mostly as a result of reductive dissolution of iron bearing minerals and corrosion of the well components [5], [6], & [7]. Seawater intrusion indicators encompass hydro-chemical parameters primarily chloride concentration, EC/ TDS ratios, and ionic ratios such as Cl/HCO₃ that signal the mixing of saline and freshwater in coastal aquifers [10, 13]. Intrusion of seawater is a significant issue of the coastal groundwater system under the influence of intensive abstraction [8] & [9]. The most popular conservative tracer used as an indicator of saline intrusion is the chloride concentration and the threshold of 250 mg/L is usually taken to be the standard threshold of potable ground water [10]. The same has been observed in coastal aquifers in Southeast Asia and the need to monitor over extensive periods of time to be able to differentiate between natural levels of background and one associated with pollution [11] & [12]. Electrical Conductivity (EC), Total Dissolved Solids (TDS) and ionic ratios have also been used in conjunction with chloride as the measure of mixing between fresh water and seawater [13]. The localised seawater intrusion has been reported to be caused by excessive pumping and the lack of recharge, especially in shallow alluvial aquifers located in the west coast of Peninsular Malaysia. Nevertheless, the spatial extent of intrusion is dependent on aquifer characteristics, rate of abstraction and its closeness to the coastline which explains the importance of site-based evaluation integrating chemical indices and groundwater flow model.

2.3 Numerical Groundwater modelling

There are also common numerical groundwater flow models like MODFLOW which are used to forecast the behaviour of the aquifer in various situations involving abstraction, as well as the likelihood of seawater intrusion [14]. Successful implementations of MODFLOW in the global coastal aquifers have been used to estimate the drawdown, evaluate the hydraulic gradients and aid in the decisions taken in ground water management [15]. In Malaysia, the studies carried using MODFLOW have been shown to be useful in assessing the effects of abstraction in urban and industrial environments [16].

Seawater intrusion (SWI) in coastal aquifers continues to be a major global concern due to its impacts on freshwater availability, aquifer sustainability, and groundwater quality in coastal regions. Previous studies have established that SWI is driven by interacting natural and anthropogenic factors, including sea-level rise, climate variability, excessive groundwater abstraction, and complex hydrogeological conditions, which collectively influence saline–freshwater dynamics in coastal aquifers [17, 20, 21]. Recent review studies further indicate that research on seawater intrusion has expanded significantly over the past two decades, reflecting increasing scientific attention to coastal groundwater vulnerability and management challenges [18, 21].

Geophysical methods have become increasingly important for monitoring and characterizing seawater intrusion in coastal aquifers. Systematic reviews highlight the effectiveness of electrical resistivity, electromagnetic, and seismic techniques in delineating freshwater–saltwater interfaces and identifying intrusion pathways with high spatial resolution [18]. In high-quality coastal aquifers, particularly in India, geophysical investigations have proven valuable for assessing salinization trends and supporting sustainable groundwater management [19].

Advances in understanding SWI processes have been supported by both observational studies and numerical modeling approaches. Density-dependent groundwater flow and transport models have been widely applied to investigate the landward migration of saline

fronts under sea-level rise and climate change scenarios, demonstrating that intrusion dynamics are strongly controlled by recharge conditions, pumping stresses, and aquifer properties [19, 20]. These findings suggest that climate-driven changes may substantially exacerbate seawater intrusion in vulnerable coastal aquifers if adaptive management measures are not implemented.

Management strategies for mitigating seawater intrusion typically integrate engineered solutions, such as hydraulic barriers and artificial recharge, with sustainable groundwater abstraction and regulatory frameworks. Recent studies emphasize that long-term mitigation of SWI requires integrated approaches that account for hydrogeological heterogeneity, projected climate change impacts, and socioeconomic constraints to ensure the resilience of coastal aquifer systems [20-21]. Despite the advances reviewed above, a clear research gap remains: few studies have simultaneously integrated multi-decadal hydro-chemical monitoring records with three-dimensional numerical groundwater flow modelling to quantify seawater intrusion risk in highly urbanised tropical coastal basins. The Klang river basin with its rapid urbanisation and proximity to the Straits of Malacca, represents an ideal yet understudied case. This study addresses that gap by combining 20 years of hydrochemical data from monitoring well S9 with a calibrated three-dimensional MODFLOW simulation to provide a comprehensive assessment of groundwater sustainability and intrusion potential.

3 Materials and Methods

3.1 Study Area

Klang River Basin is situated at the West coast of Peninsular Malaysia and occupies an area of about 1,288 km² (Figure 1). It has an equatorial monsoon climate and it receives an average precipitation of around 2,420 mm/year. The basin is underlined predominantly by Quaternary alluvial deposits forming shallow unconfined to semi-confined aquifers with hydraulic conductivities in the range of 10⁻⁵ to 10⁻³ m/s. Recharge occurs primarily through direct infiltration of rainfall and lateral inflow from the surrounding highlands, with groundwater flow directed generally westward towards the Straits of Malacca.



Fig. 1. Location of the Klang River Basin, Peninsular Malaysia.

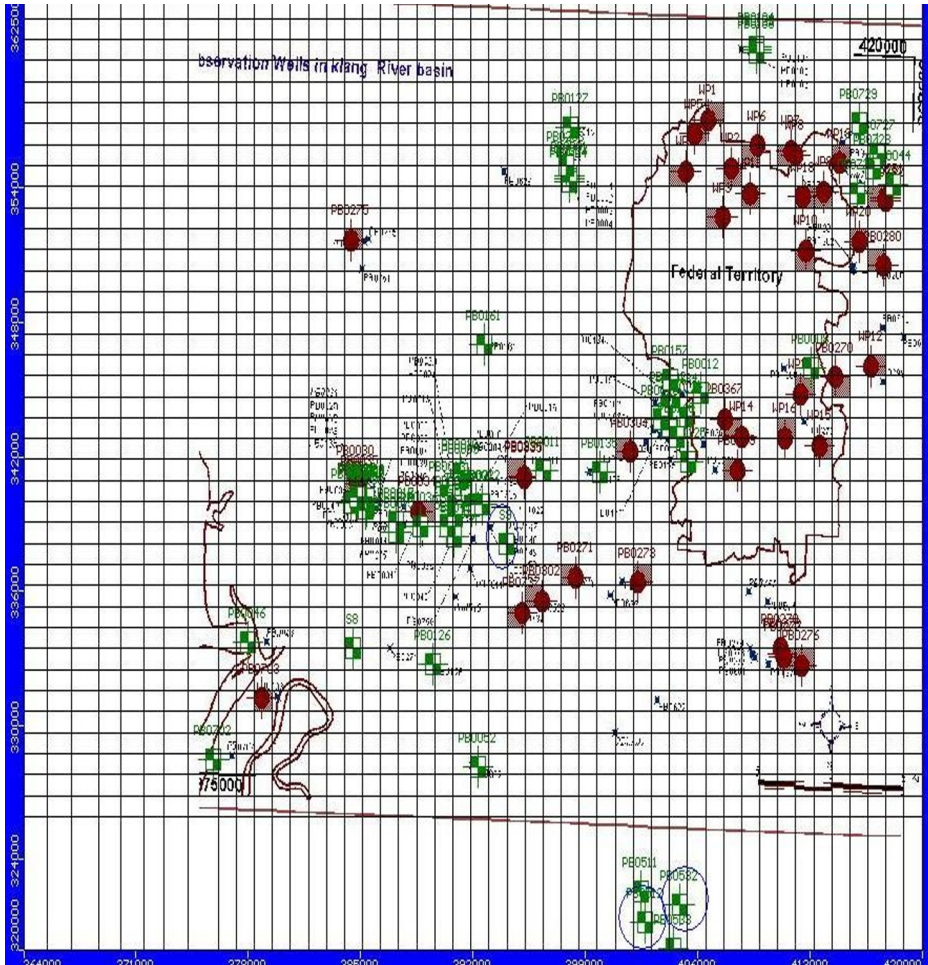


Fig. 2. Location of groundwater monitoring well S9 within the Klang River Basin.

3.2 Sample analysis and sampling of groundwater

The samples of groundwater were taken at the S9 monitoring well (Figure 2). Physical factors such as pH, temperature and electrical conductivity were determined on-site. Groundwater samples were collected on an approximately annual basis from 1998 to 2018, with additional sampling events in 2016 and 2017. Samples were collected in pre-cleaned HDPE bottles, preserved with HNO₃ (pH < 2) for trace metal analysis, and stored at 4 °C prior to laboratory processing. ICP-OES (detection limits: As 0.001 mg/L, Fe 0.005 mg/L, Hg 0.0001 mg/L) was used to analyse major ions and trace metals against USEPA Method 200.7 calibration standards.

3.3 Pumping Test Data

Hydraulic properties of aquifers were estimated using the pumping test data that had been obtained in JMG.

3.4 Groundwater Flow Modelling

A three-dimensional steady-state MODFLOW model was constructed using Visual MODFLOW Flex. The model domain covered the Klang River Basin with a grid resolution of 36 columns \times 33 rows (cell size approximately 500 m \times 500 m) and four hydro-stratigraphic layers representing the alluvial sequence. Constant-head boundaries were assigned along the coastal margin and major river channels; no-flow boundaries were applied at the watershed divide. Hydraulic conductivity values ($K = 1 \times 10^{-4}$ to 5×10^{-3} m/s) and specific storage ($S_s = 1 \times 10^{-4}$ m $^{-1}$) were derived from JMG pumping test records. Model calibration was performed by minimising the root means square error (RMSE) between simulated and observed hydraulic heads at monitoring well S9, achieving RMSE < 0.05 m. Simulations were targeted at quantifying drawdown at well S9 under existing abstraction conditions.

4 Results and Discussion

Groundwater Quality Assessment as shown in Table 1 for conductivity (Condu.) is in μ S/cm; As, Hg, Cd, Cr, Fe, Cl, NO₃, PO₄, SO₄ and T-Hardness are in mg/L; TDS is in mg/L; temperature in $^{\circ}$ C; pH is dimensionless. Table 1 provides an overview of the groundwater quality parameter and comparison with EPA standards.

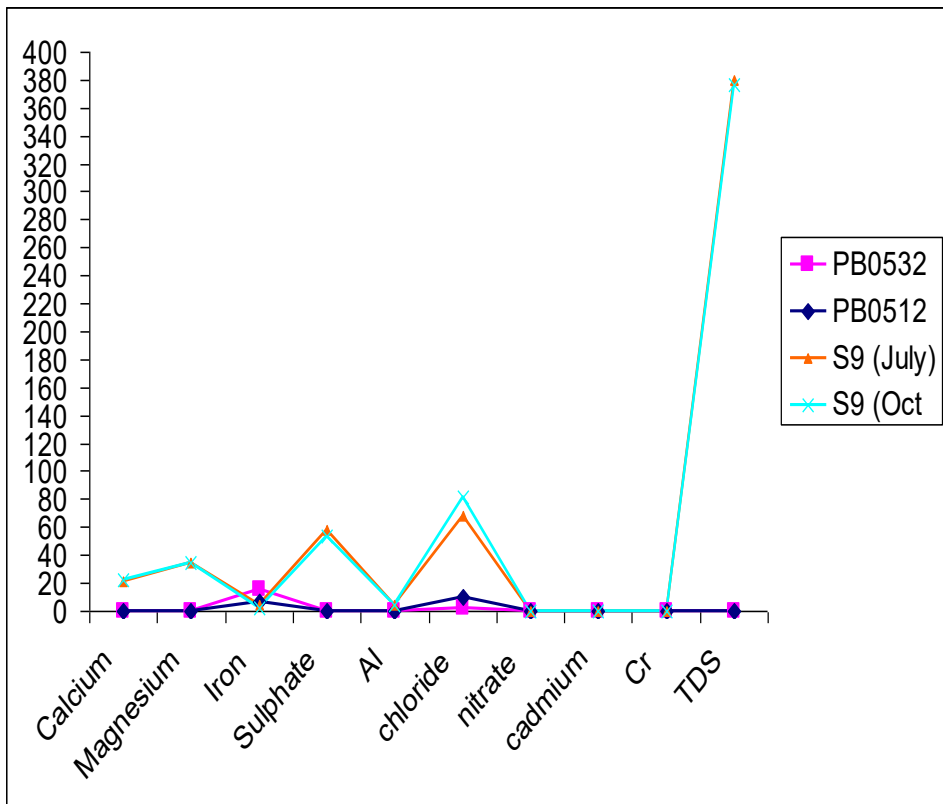


Fig. 3. Simulated drawdown distribution at well S9 obtained from the MODFLOW model.

The temporal trends of groundwater temperature, pH, EC, TDS, chloride, iron and trace metal concentrations were evaluated over the 1998–2018 monitoring period. Mann–Kendall trend tests were applied to each parameter series; no statistically significant monotonic trends (τ , $p > 0.05$) were detected for pH, EC, TDS or chloride, confirming overall hydro-chemical stability. Iron concentrations showed high temporal variability (CV = 112%) without a directional trend, consistent with episodic geogenic or borehole-corrosion influences. Temporal parameter profiles are shown in Figure 3. The number of dissolved solids was within freshwater levels as long as the study period lasted.

The concentrations of arsenic, the variations of cadmium, chromium and mercury against the EPA standards were studied. Iron concentrations consistently exceeded the EPA guideline of 0.3 mg/L (Table 1, Figure 3). Elevated iron in this alluvial aquifer can be attributed to reductive dissolution of iron oxyhydroxide minerals under anoxic conditions—a process common in organic-rich Quaternary sediments—and/or corrosion of mild-steel borehole casing material. The absence of co-elevated manganese or arsenic rules out sulphide-mineral dissolution as a primary source, pointing instead to diagenetic iron mobilisation or casing corrosion as the dominant mechanisms. The chloride level was found to be lower than the intrusion level of seawater (Figure 3) and was also a sign of little marine effects. The trends of sulphate concentration are provided in Figure 3.

4.2 Comparison with ELIT Wells

ELIT (PB0532 and PB0512) and monitoring well S9 locations can be seen in Figure 4. The summary of comparative groundwater quality results of the period 2017 are given in Table 2 and Table 3. They showed the major ions and TDS levels higher at well S9. The ELIT wells (PB0532 and PB0512) are shallow monitoring boreholes completed in the uppermost alluvial layer, whereas S9 penetrates deeper semi-confined zones. The higher TDS, Ca^{2+} , Mg^{2+} , sulphate and chloride concentrations at S9 compared with ELIT wells reflect the greater water–rock interaction time and longer flow path in the deeper aquifer unit, rather than seawater mixing, which is consistent with the sub-threshold chloride levels observed.

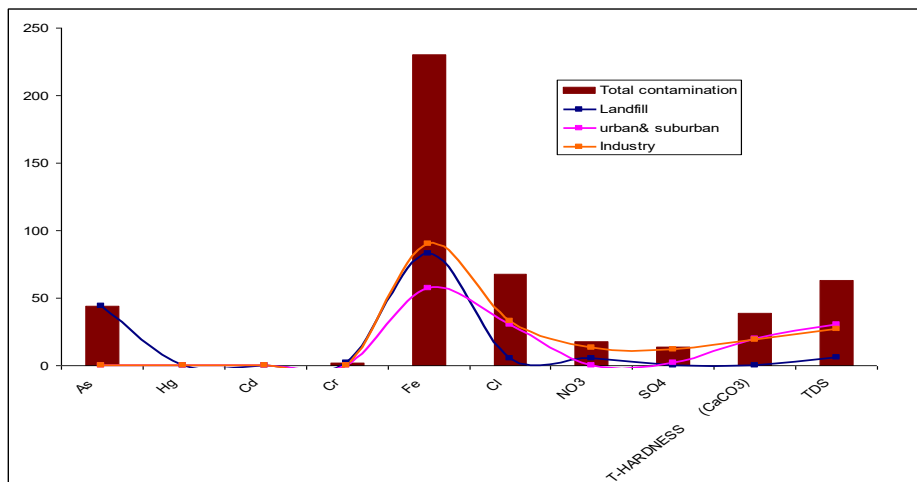


Fig. 4. Location of ELIT wells (PB0532, PB0512) and monitoring well S9.

Table 1. Long-term groundwater quality parameters for monitoring well S9 (1998–2017) compared with EPA standards

Year	1998	1999	2000	2001	2013	2014	2016 (31/5)	2016 (7/11)	2017 (11/7)	2017 oct	Standards
Temp	29.00	34.00	29.50	28.20	27.97	29.78	NA	NA	29.53	29.2	
pH	5.41	5.87	6.18	5.62	6.77	7.20	NA	NA	7.54	5.95	6.5-9.2
Condu.	511.0	193.6	541.0	243.9	0.001	490.0	NA	NA	625	639	
As	0.0115	0.006	0.005	0.001	0.0026	0.0016	NA	NA	NA	NA	0.01
Hg	<0.0001	<0.0001	0.0001	<0.0001	0.0013	<0.0001	0	0	NA	NA	0.001
Cd	<0.0002	0.0002	<0.0002	<0.0002	<0.0002	<0.0002	0.0001	0.0001	<0.0002	<0.0002	0.003
Cr	<0.0002	0.0002	0.004	0.0005	0.0007	0.0158	0.0082	0.0181	0.0376	0.0056	0.05
Fe	1.7	6.46	9.3	8.82	1.7	0.00193	40	7.58	4.43	2.35	0.3
Cl	84	99	82	87	84	74	2.7	100	68	82	250
NO ₃	<0.22	0.13	0.05	<0.05	<0.05	0.3	0.1	0.2	0.17	0.2	10
PO ₄	<0.10	<0.10	0.10	<0.10	<0.10	0.1	NA	NA			
SO ₄	63	66	82	68	18	69	560	70	58	54	250
T-Hardnes	66	72	68	65	71	74	215	80	194	185	500
TDS	350	288	275	280	300	273	600	270	380	377	1000

Table 2. Comparison of groundwater quality parameters for ELIT wells (PB0532, PB0512) and monitoring well S9 for 2017.

Well No.	Date	Ph	Cond.	Ca	Mg	Iron	Sulphate	Al	Chloride	Nitrate	Cd	Cr	TDS
PB0532	2017	6.1	54	4.5	2.1	16	<5	<1.0	2.0	<0.5	<0.01	<0.01	54.00
PB0512	2017	6.6	138	4.7	2.3	6.2	<5	<1.0	10.0	<0.5	<0.01	0.01	104.00
S9	Nov2017	7.54	625	21.5	34.3	4.43	58	4.57	68	0.17	<0.0002	0.0376	380
S9	Oct 2017	5.95	639	21.9	35	2.35	54	4.21	82	0.2	<0.0002	0.0056	377

Table 3. Landuse mapping with types of contaminations

Type of contaminants	Landfill	urban& suburban	Industry	Total contamination
As	44	0	0	44
Hg	0	0	0	0
Cd	0	0	0	0
Cr	2	0	0	2
Fe	83	57	90	230
Cl	5	30	33	68
NO ₃	5	0	13	18
SO ₄	0	2	12	14
T-HARDNESS (CaCO ₃)	0	20	19	39
TDS	6	30	27	63

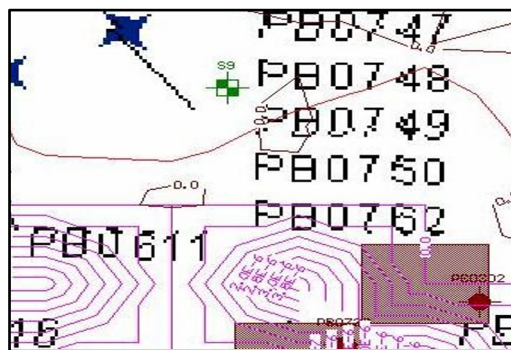


Fig. 5 Simulated Drawdown at Well S9

4.3 MODFLOW Simulation Results

The abstraction conditions at the current abstraction conditions are shown in Figure 5 at a simulated drawdown at well S9. The results given by the model show minimal drawdown (less than 0.01 m), which would mean that the risk of abstraction-driven seawater intrusion is low. A one-at-a-time sensitivity analysis was conducted by varying hydraulic conductivity ($\pm 50\%$), recharge rate ($\pm 30\%$) and pumping rate ($\pm 50\%$). Simulated

drawdown at S9 remained below 0.05 m across all scenarios, confirming the robustness of the low-intrusion-risk conclusion under plausible parameter uncertainty.

5 Conclusions

This report introduces a combined evaluation of the groundwater quality and the possibilities of seawater intrusion in the Klang River Basin, relying on the long-term hydrochemical records and the numerical groundwater flow simulation. The findings show that the groundwater of the monitoring well S9 is largely fresh with no significant changes in the electrical conductivity, total dissolved solids, and chloride levels within the monitoring period. The low simulated drawdown and the lack of high levels of chloride at the present abstraction conditions imply that the threat of seawater intrusion is low.

The majority of analysed trace metals, such as arsenic, mercury, cadmium and chromium, were all often below EPA guideline values. Nevertheless, the levels of iron were found to be beyond acceptable levels throughout the period of the study, which means that there was an effect of geogenic processes or borehole material. The simulations in the MODFLOW indicate that the drawdown depleted; however, further monitoring is necessary as the groundwater consumption in the basin increases due to the high rates of urbanisation and the overall growth in demand.

The principal scientific contribution of this study is the first integration of a 20-year multi-parameter hydro-chemical dataset with a calibrated three-dimensional MODFLOW simulation for the Klang River Basin—a rapidly urbanising tropical coastal catchment with no prior published numerical groundwater model. The combined framework shows that current abstraction poses a negligible risk of seawater intrusion, while persistently elevated iron concentrations warrant continued monitoring. This approach provides a transferable and replicable methodology for groundwater sustainability assessment in data-scarce coastal urban basins across Southeast Asia.

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References

- [1] Freeze, R.A., Cherry, J.A. Groundwater. Prentice Hall, Englewood Cliffs, New Jersey (1979).
- [2] Todd, D.K., Mays, L.W. Groundwater Hydrology, 3rd edn. John Wiley & Sons, New York (2005).
- [3] Kumar, C.P. Seawater intrusion in coastal aquifers: fundamental concepts, assessment techniques, and preventive measures. *Hydrology Journal* 39, 1–15 (2016).
- [4] Department of Environment Malaysia (DOE). Groundwater Monitoring Programme Report. Ministry of Environment and Water, Malaysia (2018).

- [5] Foster, S., Hirata, R., Gomes, D., D'Elia, M., Paris, M. Groundwater Quality Protection: Guidelines for Water Utilities, Municipal Authorities, and Environmental Agencies. World Bank, Washington, DC (2002).
- [6] Custodio, E. Overview of European coastal aquifers: hydrogeological characteristics and management challenges. *Hydrogeology Journal* 18, 269–280 (2010).
- [7] Mineral and Geoscience Department Malaysia (JMG). Hydrogeological Map of Peninsular Malaysia. JMG, Putrajaya, Malaysia (2017).
- [8] Ramani Bai, V. Impacts of seawater intrusion on coastal groundwater systems and associated erosion processes. *International Journal of Open Hydrology* 6, 52–57 (2012). <https://doi.org/10.2174/1874378101206010052>
- [9] Bear, J., Cheng, A.H.-D. *Modeling Groundwater Flow and Contaminant Transport*. Springer, Dordrecht (2010).
- [10] Werner, A.D., Bakker, M., Post, V.E.A., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., Simmons, C.T., Barry, D.A. Advances and challenges in seawater intrusion processes, investigation methods, and management strategies. *Advances in Water Resources* 51, 3–26 (2013).
- [11] Appelo, C.A.J., Postma, D. *Geochemistry, Groundwater and Pollution*, 2nd edn. CRC Press, Boca Raton (2005).
- [12] Vengosh, A., Rosenthal, E. Saline groundwater in Israel and its implications for hydrochemical interpretation. *Water Resources Research* 30, 3349–3360 (1994).
- [13] Custodio, E., Bruggeman, G.A. *Groundwater Problems in Coastal Areas*. UNESCO, Paris (1987).
- [14] Post, V.E.A., Groen, J. Dispersive mechanisms governing seawater intrusion in coastal aquifer systems. *Hydrogeology Journal* 20, 157–174 (2012).
- [15] Harbaugh, A.W. MODFLOW-2005: U.S. Geological Survey Modular Groundwater Model—Groundwater Flow Process. USGS Techniques and Methods 6-A16 (2005).
- [16] Perumal, M., Sekar, S., Carvalho, P.C.S. Global research trends in seawater intrusion studies (2000–2020): a bibliometric perspective. *Sustainability* 16, 1266 (2024).
- [17] Cao, X., Guo, Q., Liu, W. Multi-factor analysis of seawater intrusion patterns in coastal aquifers under sea-level rise conditions. *Water* 16, 3457 (2024).
- [18] Solórzano, J., Ramos-Sánchez, E., Aguilar-Aguilar, M., Ramírez-López, A., Sánchez-Zambrano, E., Baque, M., Carrión-Mero, P. Geophysical techniques applied to seawater intrusion studies: a systematic review. *WIT Transactions on Ecology and the Environment* 262, 631–643 (2024).
- [19] Kumar, P., Tiwari, P., Biswas, A., Acharya, T. Review of geophysical investigations for seawater intrusion in high-quality coastal aquifers of India. *Environmental Science and Pollution Research* 30, 9127–9163 (2023).

[20] Lyra, A., Loukas, A., Sidiropoulos, P., Mylopoulos, N. Climate-driven modeling of seawater intrusion in coastal aquifers. *Hydrology* 11, 49 (2024).

[21] Shalev, E. Conceptual understanding and management implications of seawater intrusion in coastal aquifers. *Water* 13, 2719 (2021).