

An overview of groundwater chemistry studies in Malaysia

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Abstract In this paper, numerous studies on groundwater in Malaysia were reviewed with the aim of evaluating past trends and the current status for discerning the sustainability of the water resources in the country. It was found that most of the previous groundwater studies (44 %) focused on the islands and mostly concentrated on qualitative assessment with more emphasis being placed on seawater intrusion studies. This was then followed by inland-based studies, with Selangor state leading the studies which reflected the current water challenges facing the state. From a methodological perspective, geophysics, graphical methods, and statistical analysis are the dominant techniques (38, 25, and 25 %) respectively. The geophysical methods especially the 2D resistivity method cut across many

subjects such as seawater intrusion studies, quantitative assessment, and hydraulic parameters estimation. The statistical techniques used include multivariate statistical analysis techniques and ANOVA among others, most of which are quality related studies using major ions, in situ parameters, and heavy metals. Conversely, numerical techniques like MODFLOW were somewhat less admired which is likely due to their complexity in nature and high data demand. This work will facilitate researchers in identifying the specific areas which need improvement and focus, while, at the same time, provide policymakers and managers with an executive summary and knowledge of the current situation in groundwater studies and where more work needs to be done for sustainable development.

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Introduction

Groundwater accounts for almost 99 % of the available liquid freshwater resources on earth, living only 1 % to surface found in rivers and lakes among few (Cavazza and Pagliara 2000). Out of the global groundwater resources, it has been estimated that about 900 km³ is pumped out annually for human activities (Jones 2011) ranging from agriculture to urban development and even recreational activities (Vrba and van der Gun 2004). This reliance on groundwater varies from place to place. Countries like Swaziland, Saudi Arabia, Iceland, Mongolia, the Russian Federation, and Libya among others already depend on groundwater resources for up to 75 % of their freshwater supply (Vrba and van der Gun 2004). It has been estimated that almost one third of the world population relies on groundwater for their day-to-day activities (Hiscock 2011). Moreover, groundwater feeds the rivers and lakes with

freshwater through baseflow, particularly during the dry season (Morris et al. 2003; Howard and Merrifield 2010). Hence, caution is required, as this pressure can make the matter worst through contamination and/or damage to the hydrogeological system if care is not taken (Jones 2011). The world has already started seeing the effects of these problems as the decline in the groundwater table, land subsidence, and depletion in groundwater reserves have been widely observed. Similarly, the quality of the groundwater deteriorates as the deprivations of ecosystems in addition to seawater intrusion are currently affecting many coastal areas in the world (Jousma and Roelofsen 2004).

Malaysia is one of the developing countries in southeast Asia with a population of about 27.73 million distributed over an area of about 329,750 km² (Ong, et al., 2011). The country is divided by South China Sea into two regions (West Malaysia and East Malaysia). Geographically, the country is located between the longitudes 100° and 120° east and latitudes formed by the equator and 7°. The West Malaysia (popularly known as peninsular Malaysia) is bordered by Thailand from the north, Indonesia, and Singapore from the southwest and south respectively while East Malaysia (constituting Sabah and Sarawak states) is bordered by Philippine Islands and Indonesia from the north and the south, respectively. The country's climate is of tropical type, receiving over 2800 mm of rainfall annually. The humidity and temperature ranges between 80–90 % and 21 to 32 °C, respectively (Manaf et al., 2009).

Groundwater in Malaysia accounts for less than 10 % of the country's freshwater supply (Abd-Razak and Abd-Karim 2009). There has been an increase in freshwater demand due to huge economic growth and infrastructural development in the country within the last three decades. Groundwater usage varies from one part of the country to another. In states like Kelantan, Pahang, and Terengganu, all situated in the western and northern part of the country, as well as Sabah and Sarawak states from the eastern part, strongly rely on groundwater as the major source of their freshwater (Nampak et al. 2014). Kelantan state in particular was reported to have sourced more than 70 % of its freshwater from groundwater (Manap et al. 2013). The situation is even more severe in the small islands, such as Kapas and Manukan among others where groundwater is the only source of freshwater. This is attributable to their topographical and geological nature which makes the existence of surface water in such areas virtually impossible (Falkland and Custodio 1991; Aris et al. 2007, 2009; Baharuddin et al. 2013a, b; Kura et al. 2013). The country's groundwater demand has been estimated to rise by 63 % from 2000 to 2050 (Manap et al. 2013). This is coming at a time when very little is known regarding the groundwater chemistry (Aris et al. 2009) due to insufficient data on groundwater particularly in small tropical islands (Aris et al. 2007). Therefore, there is need for more groundwater studies in order to help hydrogeologists and environmental managers to come

up with a reliable solution to the impending water crisis. Review is one of the key ways that can enhance researchers understanding and provide them with clear picture and sense of directions of the past and future works (Praveena et al. 2010a).

It is worth mentioning that very few reviews exist in respect of Malaysian groundwater studies which are mostly restricted to coastal and/or island areas. For example, the two reviews by Praveena et al. (2010a, b) both focused on coastal and small islands. In their findings, they reported that most of the studies were academic research-related and centered on seawater intrusion. An attempt was also made by Karim et al. (2014) to give a general overview of groundwater chemistry in Malaysia using multivariate statistical analysis. Based on the current challenges regarding economic and population growth resulting in high water demand, there is need for a wider review that will cover the entire country which can provide a clear picture of the current status of groundwater studies. Such review will most importantly serve as a guide for future research to ensure the sustainability of groundwater resources. For that reason, this paper attempts to review Malaysian groundwater studies. Recommendations are made based on the following criteria: (1) whether the research took place in inland, coastal or island, (2) evaluation of the problems affecting each area, and (3) analysis of the methodologies used in these studies based on simplicity, availability and reliability.

Groundwater occurrence

Groundwater in Malaysia accounts for over 90 % of the country's water resources. The groundwater storage in aquifers is estimated to be around 5000 billion cubic meters with annual recharge rate of 64–120 billion cubic meters (Heng 2004; Manap et al. 2013). This resource is spatially distributed all over the country and can be found in four types of aquifers, namely: alluvial, limestone, crystalline igneous rocks, volcanic and sedimentary rocks (Fig. 1) (Zawawi 2002; Heng 2004; Karim et al. 2014).

Alluvial aquifers are the most productive aquifers in the country with hydraulic conductivity of 30–50 m³/h. These aquifers are mostly situated along the coastal areas and are made up of Quaternary deposits comprising sand and gravel with silt and clay in some areas as the compositions vary from place to place (Heng 2004). For example, the eastern coastal areas of Peninsular Malaysia (Pahang, Terengganu, and Kelantan states) are characterized by thick alluvial deposits of more than 20 m, most of which are made up of sand and gravel making the aquifers along these areas very productive, whereas the alluvial aquifers that are located in the west coast are largely associated with clay sediments. Thus, the hydraulic conductivity of these types of aquifers was generally less

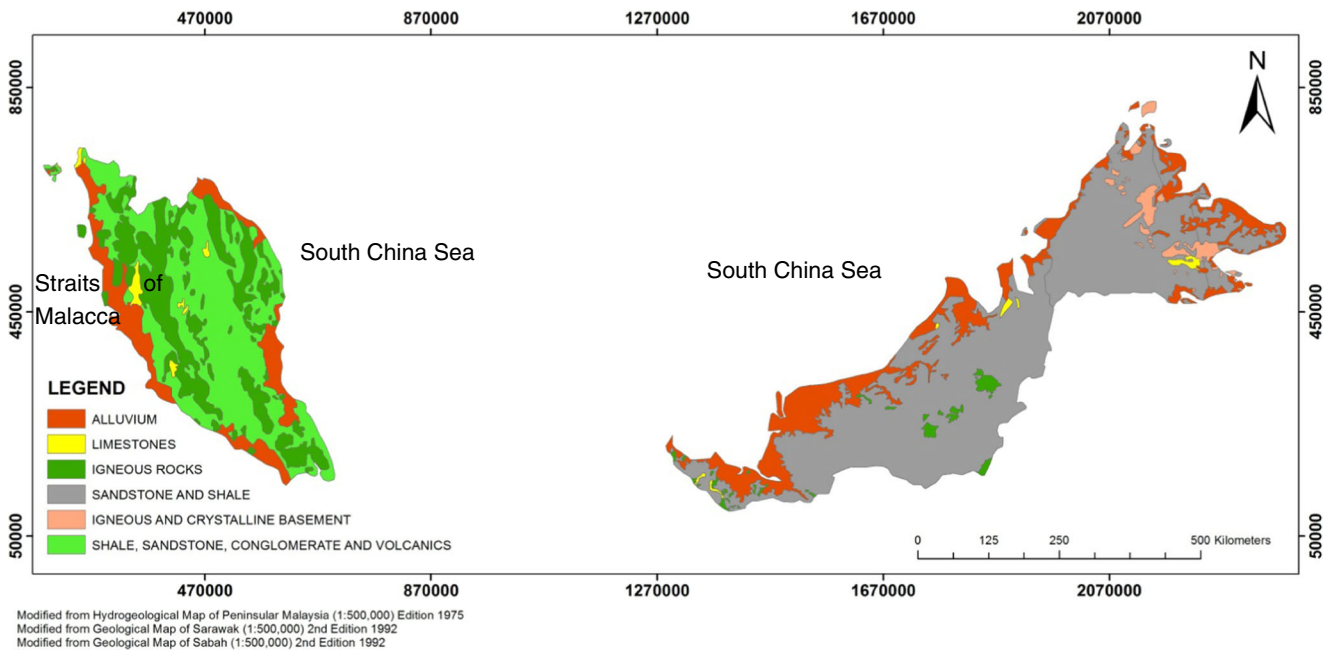


Fig. 1 Simplified hydrogeological map of Malaysian map (left: Peninsular Malaysia, right: Sabah and Sarawak). Modified from (Chong and Tan 1986; Omang and Tahir 1994; Heng 2004)

productive (15–25 m³/h) compared to the east coastal aquifers (Chong and Tan 1986; Omang and Tahir 1994; Heng 2004).

Among the hard rock aquifers, the most productive are the limestone aquifers which are found in Selangor, Perlis, Pahang, Perak, Kelantan, and Kedah states. Some of these aquifers are characterized by high hydraulic conductivity reaching up to 30 m³/h. This is followed by sedimentary and volcanic rocks aquifers with average hydraulic conductivity of 5–15 m³/h. These types of aquifers are characterized by fractured sandstone, conglomerate, quartzite, and volcanic rocks covering most parts of Sabah and Sarawak and few states in Peninsular Malaysia like Johor and Kedah (Heng 2004).

The least productive aquifers (5 m³/h) are the fractured crystalline igneous rocks aquifers. These types of aquifers can be found in Selangor, Negeri Sembilan, Melaka, Kedah, and Johor states as well as in Sabah and Sarawak (Fig. 1) (Chong and Tan 1986; Omang and Tahir 1994; Heng 2004).

Category

The study areas were classified into three categories: inland-based, coastal-based and island-based. The result shows that, about 44 % of the groundwater related studies were island-based which mostly concentrated on evaluation of seawater intrusion. The inland-based accounts for about 40 % of the entire studies reviewed, living the remaining 16 % to coastal areas. The inland-based studies cut across subjects ranging from exploration and determination of potential groundwater zones to tracer studies on contaminants. Selangor state was

found to have the highest number of groundwater studies in this review (19) (Baharuddin et al. 2013a, b; Crowther 1989; Juanah et al. 2013; Manap et al. 2013; Hamzah et al. 2006; Shamsuddin et al. 2014) which is more likely attributable to the challenges facing the state concerning water scarcity (Manap et al. 2014). This was followed by Sabah state with 13 groundwater studies mostly within the Manukan Island (Aris et al. 2007, 2009; Praveena et al. 2011a, c, 2012). Terengganu and Kedah states were third and fourth with six and four groundwater studies, respectively. Groundwater studies were also conducted in Negeri Sembilan, Kelantan, Perak, Melaka, and Pahang states (Fig. 2 and Table 1). This is likely a reflection of the significance of groundwater resources in these areas due to insufficient surface water.

Methodology

From the methodological context, various techniques have been employed by different researchers to assess series of problems in their study areas. These techniques comprise both qualitative and quantitative approaches ranging from hydrochemistry/geochemistry, geophysics, numerical models or simulation models, and statistical analysis.

Hydrochemistry

Groundwater hydrochemistry provides researchers with all the information needed to understand the physical processes and chemical reactions through which the groundwater undergoes, starting from rainfall, runoff, and infiltration to the roots which

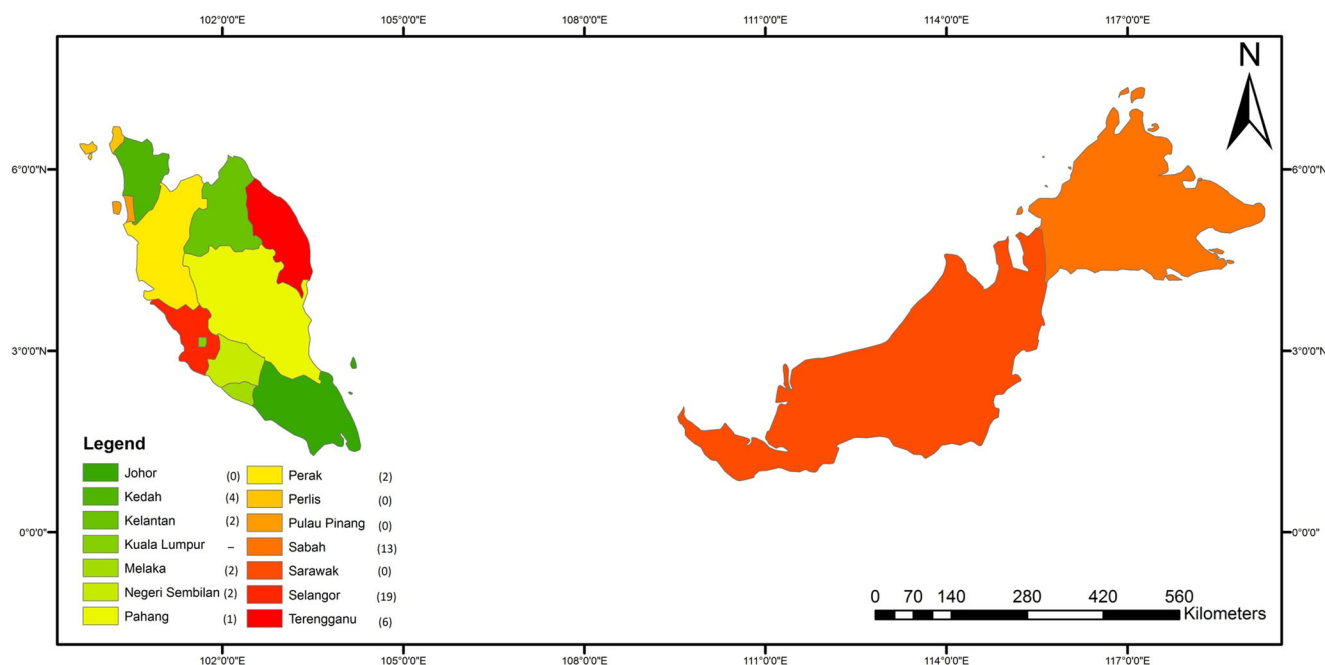


Fig. 2 Malaysian map showing spatial distribution of number of groundwater studies across the state

it passes through to reach the vadose zone and finally recharge the aquifer (Bartolino and Cole 2002; Nelson 2002). The weak acid form by the mixture of rain and CO_2 accelerates the weathering of the minerals available in the rocks and soils, thereby changing the chemical composition of the groundwater to reflect the types of geological materials in the area (Bartolino and Cole 2002). Hence, a proper understanding of a given groundwater system and the factors responsible for its chemistry is virtually impossible without a systematic study of the representative groundwater samples of the area involved. As such, in situ and laboratory analysis of some physical and chemical parameters can be utilized to make sense of the groundwater properties of the area in question (Aris et al. 2007; Kura et al. 2013).

Major ions and in situ parameters

Generally, water quality parameters are classified into two groups: physical and chemical parameters. The physical parameters include pH, conductivity (EC), temperature ($^{\circ}\text{C}$), redox potential (Eh), total dissolved solid (TDS), salinity, turbidity (NTU), dissolved oxygen (DO), and water level; all of which are measured in situ because they change within a short time (Aris et al. 2009; Isa et al. 2012). Most of these parameters are interrelated (see Table 2). For example, pH, temperature, and Eh are responsible for the chemical state of groundwater by controlling chemical reactions in the water. Temperature influences virtually all physio-chemical and biological reactions taking place in water. For example, the increase in temperature will enhance chemical and microbial processes in the groundwater (Delpla et al. 2009). Similarly

TDS, EC, and salinity reflect the mineral salts in the water and are influenced by major ions in groundwater (Sundaray 2010). Hence, for the chemical aspect of groundwater chemistry, seven parameters are known to be responsible for 95 % of all water solutes known as major ions. These include: calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), bicarbonate (HCO_3), chloride (Cl), and sulfate (SO_4) (Bartolino and Cole 2002). Therefore, the basic quality of groundwater is primarily centered on these ions (Ahmad et al. 2003; Sundaram et al. 2007). This is likely the reason why more than (40 %) of the groundwater studies in Malaysia involved these parameters (Abdullah et al. 1997; Ahmad et al. 2003; Aris et al. 2007; Rahim et al. 2010; Isa and Aris 2012; Kura et al. 2013; Idris et al. 2014).

Graphical methods

A very crucial task in groundwater research is the collection, arrangement, and presentation of complex hydrochemical data so as to understand the system for better management strategy. In view of that, there is a need for a simple, logical, and scientific approach with the intention that the research outcome can easily be understood through visual inspection. Hence, numerous graphical techniques have been created (Freeze and Cherry 1979). Researchers in hydrochemistry have considered various graphical methods, particularly the trilinear diagrams, as standard techniques in groundwater chemistry assessment (Ahmad et al. 2003). These plots are suitable for tracer work by demonstrating a vast number of inquiries on a single diagram to describe specific trends or pollution. The evolution and connections governing the

Table 1 Summary of groundwater studies in Malaysia

No.	Source	Category	Methodology	Objectives	Results
1	(Crowther and Pitty 1982)	Selangor State (north of Kuala Lumpur), Kinta valley in Ipoh, Perak State and Alor Star in Kedah state (all in west coast of peninsular Malaysia). (Inland)	<i>Techniques:</i> Standard deviation (s.d) <i>Data:</i> (temperature)	To define the exact thermal physiognomies of natural groundwater prior to their emergence in surface flows.	Deeper groundwater was found to have more steady temperature while the shallow aquifer were characterized by fluctuating temperature. The wide range of temperature variability in the shallow aquifer (>2 °C s.d) is likely caused by interaction between the aquifer and atmospheric temperatures.
2	(Crowther 1989)	Selangor State (north of Kuala Lumpur), Kinta valley in Ipoh, Perak State and Alor Star in Kedah state (all in west coast of peninsular Malaysia) (inland)	<i>Techniques:</i> Hydrochemical analysis such as ionic ratios <i>Data:</i> (major ions)	To study the spatial and temporal differences in calcium and magnesium concentrations	The initial distributions for magnesium and calcium indicated that the dissolution is mostly restricted to the area very close to the upper zone. Whereas calcium and magnesium yearly uptake by tropical limestone forests is comparable to the groundwater net solute output in magnitude. The composition of bedrock is the main factor controlling magnesium, and the Mg/Ca + Mg ratios in the groundwater
3	(Abdullah et al. 1997)	Sipadan Island in southeast coast of Sabah State. (123, 000 m ²) (Island)	<i>Techniques:</i> Hydrochemical analysis such as titration <i>Data:</i> (major ions and in situ parameters)	To determine the effects of tides on groundwater quality.	At the center of the island, the results show that tides affect conductivity, dissolved oxygen, salinity and pH by 61, 53, 58, and 1.7 % respectively. While at 120 m away from coast, dissolved oxygen, salinity, conductivity and pH changed by 33, 42, 40, and 9 % respectively
4	(Nassir et al. 2000)	East of Yan, Kedah State, northwest Malaysia (9500 km ²) (Coastal)	<i>Techniques:</i> Geoelectrical imaging <i>Data:</i> (resistivity images)	the efficiency of the geoelectrical imaging method for the mapping of salt-water intrusion is examined To examine the efficiency of geoelectrical imaging technique in mapping seawater intrusion	The technique was able to enhance the quality of data. The results show freshwater with resistivity of 6 Ωm and above, floating on top of saline water with low resistivity between 2.8 and 3.5 Ωm. The result from resistivity profile 3 evidently revealed the sharp dropping curved edge between the saline water and freshwater zones. The low-resistivity zone agrees with seawater intrusion coming from the Straits of Malacca. While the high-resistivity zone reflects freshwater (recharge) descending from the Gunung Jerai mountain.
5	(Ahmed and Sulaiman 2001)	Seri Petaling in the state of Selangor, Malaysia (0.21 km ²) (inland)	<i>Techniques:</i> 2D electrical resistivity, geochemistry and ANOVA <i>Data:</i> (resistivity images, in situ parameters, major ions and trace elements)	To determine the effects of landfill on the groundwater	The result revealed higher concentrations of K, Na, and Cl in the downstream bore hole by 99.2, 99.1, and 99.4 %, respectively compared to the upstream bore hole indicating leached from a landfill area. However, SO ₄ and NO ₃ were found to be higher in stream than in the groundwater
6	(Yap and Kahoru 2001)	Pulau Perhentian (off the coast of Terengganu State) (Island)	<i>Techniques:</i> Physico-chemical and Bacteriological analysis <i>Data:</i> (in situ parameters and fecal coliform)	To evaluate the quality of the island's groundwater.	The island's groundwater was contaminated as the E. coli counts was beyond the acceptable limit especially at stations 7 and 9 (100–300 MPN per 100 ml) likely due to poor sewage system
7	(Rahman and Kuan 2004)	Kampung Tekek Tioman Island on the east coast of Peninsular Malaysia (Pahang state) (131 km ²) (Island)	<i>Techniques:</i> Visual MODFLOW (A 3D modeling software) <i>Data:</i> (hydraulic conductivity, aquifer thickness, recharge rate, vertical anisotropic hydraulic conductivity and specific head)	To determine the carrying capacity of the aquifer and evaluate nitrate pollution migration in the area	The result shows that the aquifer has the carrying capacity of 4000 m ³ /day. Moreover, the nitrate concentration was within the acceptable limit

Table 1 (continued)

No.	Source	Category	Methodology	Objectives	Results
8	(Samsudin et al. 2006)	Ampar Tenang, Bukit Kemuning (Selangor) and Taiping (Perak) (Inland)	<i>Techniques:</i> 2-D resistivity imaging <i>Data:</i> (resistivity images)	To determine the effects of landfill on the soils and the groundwater	The leachate plume was found to have contaminated the subsurface surroundings of the landfill sites at the depths of (10–20 m) especially at the Taiping landfill area
9	(Hamzah et al. 2006)	Banting area Kuala Langat, Selangor State (885 km ²) (Coastal)	<i>Techniques:</i> 2-D resistivity measurement <i>Data:</i> (resistivity images)	To delineate the marine clay layer and aquifer from the alluvial deposits of Beraus and Gula Formations	The results show the top layer with values of resistivity ranging from 0.1 to 10 Ωm, indicating a clay layer of 10 up to 45 m thick. While the subsequent layer starts from 45 to 70 m depth with resistivity values between 10 and 30 Ωm
10	(Aris et al. 2007)	Manukan Island, Sabah State, east Malaysia (206,000 m ²) (Island)	<i>Techniques:</i> Correlation, principle component analysis (PCA), linear regression, hydrochemical analysis and piper diagram <i>Data:</i> (major ions)	To determine the processes influencing the island's hydrochemistry	Over pumping of freshwater at the lower eastern area and integration of seawater with freshwater as well as the carbonate saturation condition are the major factors controlling the island's hydrochemistry
11	(Hamzah et al. 2007)	Kuala Selangor-Batang Berjuntai to part of the Tanjung Karang areas in the Selangor State (300 km ²) (coastal)	<i>Techniques:</i> Vertical electrical sounding (VES) and hydrochemical methods <i>Data:</i> (borehole records, pumping test data, VES data and major ions, heavy metals and in situ parameters)	To examine and delineate the groundwater types	The result suggests that both brackish and freshwater exist in the area. But the brackish dominant in the coastal part
12	(Samsudin et al. 2008)	The coastal area of north Kelantan State (15,099 km ²) (coastal)	<i>Techniques:</i> Schoeller diagrams, Geophysical <i>Data:</i> (VES and reflection seismic) and (major ions)	To assess the nature and spatial distribution of the saline water within the aquifers	For the first aquifer, mixture of fresh and saltwater is mostly at the coastal area, but it went further inland up to 6 km away from shore indicating likely trapped saline water from the ancient seawater
13	(Aris et al. 2009)	Manukan Island, Sabah State, east Malaysia (206,000 m ²) (Island)	<i>Techniques:</i> Ionic changes and saturation indices (PHREEQC) Piper diagram, linear regression <i>Data:</i> (major ions)	To characterize the origins of salinity and mechanisms of their mobility into the groundwater	The groundwater type is mostly dominated by Na-Cl water type suggesting seawater intrusion, and the ion exchange which resulted from fresh-seawater interaction, leading to exchange between Na with Ca and Mg at the lower eastern area
14	(Mohamed et al. 2009)	Langat basin Selangor State (2350 km ²) (Inland)	<i>Techniques:</i> 2D resistivity measurement, MODFLOW and SWOT analysis <i>Data:</i> (in situ parameters, major ions and heavy metals)	To analyze the groundwater potential and determine sources of groundwater and soil pollution	The Ampar Tenang landfill site was poorly located at a sensitive area. Thus, contaminants from the landfill such as heavy metals have migrated down to the groundwater of the area
15	(Lin et al. 2009)	Pulau Tiga, Sabah State, east Malaysia (7.25 km ²) (Island)	<i>Techniques:</i> Piper Diagram, ANOVA, Hydrochemistry analysis <i>Data:</i> (major ions)	To establish baseline data for future references	The water is mostly dominated by freshwater, Ca-HCO ₃ and then little interaction with seawater Ca-Cl waters type. Mineral dissolution was found to be the major process influencing the groundwater chemistry in the area. Seasonal changes (rainfall) influenced the groundwater chemistry, causing low ions concentrations due to dilution effects
16	(Lin et al. 2010)	Pulau Tiga, Sabah State, east Malaysia (7.25 km ²) (Island)	<i>Techniques:</i> One-way ANOVA test <i>Data:</i> In situ parameters, Cl, NO ₃ , total coliform and fecal coliform	To determine the effect of leakages from septic tanks	The results suggested that, Cl concentrations at the low lying part of the island were likely due to seawater intrusion, while all the sampling sites were affected by total coliform and fecal coliform. These might have originated from a toilet/septic tanks. Hence, the distances between the wells and the toilets/septic tanks were short

Table 1 (continued)

No.	Source	Category	Methodology	Objectives	Results
17	(Aris et al. 2010)	Manukan Island, Sabah State, east Malaysia (206,000 m ²) (island)	<i>Techniques:</i> PHREEQC modeling, Hydrochemistry <i>Data:</i> (major ions)	To examine the dynamics of groundwater flow and to evaluate the effects of groundwater extraction on geochemical processes in a small island aquifer	The seawater migrated up to 100 m inland wards, thereby creating more complex geochemical processes in the Island's aquifer. The results further shows calcification of the aquifer despite the seawater being supersaturated with carbonate minerals
18	(Rahim et al. 2010)	Ampar Tenang Selangor State (510 m ²) (Inland)	<i>Techniques:</i> Sodium adsorption ratio (SAR), Piper diagram, 2D resistivity technique <i>Data:</i> (resistivity images and major ions)	To determine the effects of the Ampar Tenang landfill on the groundwater	There is high concentration of chloride, nitrate, nitrite, ammoniacal-N, sodium, iron, and lead beyond the acceptable limits, suggesting that the contamination plume has traveled far away from the landfill site
19	(Praveena and Aris 2010)	Manukan Island, Sabah State, east Malaysia (206,000 m ²) (island)	<i>Techniques:</i> SEAWAT-2000 modeling <i>Data:</i> (aquifer hydraulic parameters and Cl)	To determine the best management practice for sustainability of the island's groundwater	The findings indicate that, decrease in pumping rate and an increase in recharge rate have the capacity to flush out the seawater intrusion and reinstate the groundwater level of the over pumped aquifer
20	(Baharuddin et al. 2011)	Carey Island in the western coastal area of the State of Selangor in Peninsular Malaysia (162 km ²) (coastal)	<i>Techniques:</i> Time-lapse resistivity (TLERT) survey and geochemistry <i>Data:</i> (resistivity images and major ions)	To evaluate the effects of salinity on groundwater aquifer	TLERT demonstrates resistivity alterations are more extensive at the image bottom, particularly during high tides, in both seasons. Increases in tide-controlled salinity changes dominantly below the boundary of freshwater zone. High contents of Na-Cl in all the monitoring wells with low resistivity suggesting brackish and saline water intrusion
21	(Dor et al. 2011)	The northwest corner of the state of Perak in Peninsular Malaysia (235.6 km ²) (Inland)	<i>Techniques:</i> 2D resistivity measurements, Water balance techniques, Stable isotopic analyses <i>Data:</i> (resistivity images, water inflow-outflow, and isotopes)	To detect the hidden aquifer and to determine the water gain/loss in the irrigation system. To identify the hydraulic interaction between surface and groundwater	The thickness of the aquifer ranges between (5–10 m). The groundwater was found to be affected by evaporation, precipitation. In addition, strong connection exists between the surface and groundwater chemistry in the area, suggesting an interaction between the two water systems
22	(Praveena et al. 2011a)	Manukan Island, Sabah State, east Malaysia (206,000 m ²) (Island)	<i>Techniques:</i> Numerical model SEAWAT-2000. <i>Data:</i> Aquifer hydraulic parameters such as porosity, hydraulic conductivity among others	To determine the current status of seawater intrusion	Over pumping led to seawater intrusion at the low lying area of the Island. The result of the model suggested that the current status of seawater intrusion in the island is about 14.6 % of seawater mixing ratio to freshwater beneath well (W6), while the mean Cl concentration during sampling period was 1899 mg/L (much higher than WHO standards)
23	(Praveena et al. 2011b)	Manukan Island, Sabah State, east Malaysia (206,000 m ²) (island)	<i>Techniques:</i> Numerical simulation method using SEAWAT-2000 <i>Data:</i> (aquifer hydraulic parameters)	To evaluate the existing and probable magnitude of seawater intrusion in the island based on different scenarios.	The impact of El-Nino event represented by a decrease in recharge rates and groundwater pumping was found to have boosted the magnitude of the existing seawater intrusion. On the other hand, a reduction in the pumping rate combined with an artificial recharge would lead to movement of seawater-freshwater towards the coast within 2 years
24	(Praveena et al. 2011c)	Manukan Island, Sabah State, east Malaysia (206,000 m ²) (island)	<i>Techniques:</i> Cluster analysis (CA) and multiple linear regressions (MLR) <i>Data:</i> (in situ parameters, hydraulic head and Cl)	To determine the factors controlling groundwater salinity using chemometric methods	The results show a mixture of seawater and freshwater. Salinity was also found to be the dominant factor controlling the island's groundwater chemistry
25	(Taha et al. 2011)	Ampar Tenang and Bukit Tagar (Selangor State) (8104 km ²) (inland)	<i>Techniques:</i> Hydrochemistry analysis	To determine the effects of landfill sites on the groundwater.	The BHI of Ampar Tenang landfill area was highly polluted (chemical oxygen demand (COD) values 3931–

Table 1 (continued)

No.	Source	Category	Methodology	Objectives	Results
26	(Sapari et al. 2011)	West Coast of Peninsular Malaysia (Melaka, Negeri Sembilan, Selangor and Kedah States) (Coastal)	<i>Data:</i> (major ions, trace elements and heavy metals) <i>Techniques:</i> Pumping test and piper diagram <i>Data:</i> (major ions for hydrochemistry)	To assess the aquifers yield and determine the quality of groundwater in fractured meta-sedimentary rocks	11,357 mg/l). While the Bukit Tagar did not show significant sign of pollution thanks to its adoption of zero discharge target, suggesting that a good engineering plan can reduce the leachate pollution from landfill site to groundwater The aquifers were found to have high yield (minimum flow rate of 100 m ³ /day while maximum was 890 m ³ /day) and the water was generally fresh and good for domestic, agricultural and industrial uses
27	(Aris et al. 2012a, b)	Manukan Island, Sabah State, east Malaysia (206,000 m ²) (Island)	<i>Techniques:</i> Factor analysis (FA), cluster analysis (CA) and a hydrochemical model (PHREEQC) <i>Data:</i> (major ions)	To ascertain and assess the key factors influencing the groundwater chemistry.	Redox reaction, cation exchange and aquifer salinization were found to be the major processes associated with the seawater intrusion at the lower south eastern part of the island
28	(Isa and Aris 2012)	Kapas Island, Terrangganu State, north eastern Malaysia. (2 km ²) (island)	<i>Techniques:</i> Piper diagram, correlation coefficient and Ionic ratios <i>Data:</i> (major ions and in situ parameters).	To determine the hydrochemical processes of the island's groundwater and to provide a baseline data for aquifer management.	The results show that, the fresh groundwater is subjected to numerous processes such as ion exchange and dissolution of aquifer bedrock at the lower western part of the island.
29	(Isa et al. 2012)	Kapas Island, Terrengganu State, northern peninsula Malaysia (2 km ²) (island)	<i>Techniques:</i> Ionic ratio, PHREEQC software for saturation index, (SI) and Piper diagram, correlation analysis. <i>Data:</i> (In situ parameters and major ions)	To examine the hydrogeological and hydrochemical aspects of the island's groundwater	Salinization effects, ion exchange and mineralization were the mechanisms controlling the groundwater chemistry. The island groundwater also shows a shift from Ca-HCO ₃ to Na-HCO ₃ , resulted from cation exchange at the western coast of the island
30	(Lin et al. 2012)	Manukan Island, Sabah State, east Malaysia (206,000 m ²) (Island)	<i>Techniques:</i> (ANOVA), (FA), (HCA) <i>Data:</i> (major ions and minor ions such as: Al, Ba, Be, Fe, Li, Mn, Pb, Se, Sr)	To define the temporal variability and processes controlling the island's hydrochemistry	Carbonate and silicate weathering were affecting the hydrochemistry of the area. The mixture of seawater with freshwater in the area led to shift of the island groundwater from Ca-HCO ₃ to Na-HCO ₃ . The hydrochemistry of the area was generally controlled by seawater intrusion rather than temporal effects
31	(Islami et al. 2012)	North Kelantan State (98 km ²) (Inland)	<i>Techniques:</i> 2D resistivity measurement, hydrochemical and soil particle size analysis <i>Data:</i> (resistivity images, soil samples and major ions)	To examine the groundwater chemistry and determine the effect of fertilizer application on groundwater	Fertilizer application in the southern part has led to high concentration of nitrate (>20 mg/l), which also corresponds with low resistivity value (18 Ω m). While in the northern part (non-fertilized area), the resistivity values were high (>35 Ω m) and the nitrate concentration was very negligible (near zero)
32	(Praveena et al. 2012)	Manukan Island, Sabah State, east Malaysia (206,000 m ²) (Island)	<i>Techniques:</i> Numerical modeling (SEAWAT-2000) and water balance approaches <i>Data:</i> (aquifer hydraulic parameters)	To determine a sustainable groundwater management plan in Manukan Island	Three scenarios were run; (A) current condition which shows over pumping and inconsistency in recharge causes more seawater intrusion with high chloride concentration (1889.9 mg/L). (B) Reducing the rate of pumping by 25 % demonstrates a raise in groundwater but still there is high concentration of chloride (1812.7 mg/L). (C) The pumping rate was reduced by 25 % and artificial recharge was increased by 40 %. This was found to be the best management strategy as it offer the lowest chloride concentration (1552.2 mg/L), highest hydraulic heads, and positive groundwater storage (254.3 m ³ /day)

Table 1 (continued)

No.	Source	Category	Methodology	Objectives	Results
33	(Ashraf et al. 2013)	Ampar Tenang in Selangor State in the west Malaysia (510 m ²) (Inland)	<i>Techniques:</i> Physiochemical and biochemical analysis <i>Data:</i> (Physiochemical parameters, organic contaminants, and toxic heavy metals)	To determine the possible concentrations of the major pollutants coming infiltrating into groundwater and surface water from the landfill	The high concentrations of heavy metals such as; Co, Mn, Cu, Cd and Pb particularly along the downhill side signifies that the pollution plume has moved far beyond the landfill area and contaminates the groundwater of the area
34	(Baharuddin et al. 2013a)	Coastal area of Caray Island, Selangor (162 km ²) (Coastal)	<i>Techniques:</i> 2D electrical resistivity and hydrochemical <i>Data:</i> (resistivity images and major ions)	To examine seawater intrusion in the area and determine suitability of the groundwater for oil palm cultivation	Freshwater with low TDS and high head was found to be dominant in the northwest part where the mangrove forest is available. While the southeast part was characterized with high erosion which resulted from deforestation and causing increased in seawater intrusion
35	(Baharuddin et al. 2013b)	Carey Island, Selangor State (162 km ²) (Coastal)	<i>Techniques:</i> Geochemistry- electrical resistivity technique TDS-ER <i>Data:</i> (resistivity images and TDS)	To evaluate the effects of seawater intrusion and irrigation water on groundwater	The areas with thinner aquifer and lesser trees were more vulnerable to seawater intrusion than areas with thicker forest. This suggests that the forest is enhancing recharge. The thicker forest area also shows higher groundwater potential than areas with thinner mangrove forest
36	(Juamah et al. 2013)	North of Gemas, Negri Sembilan State, located between Kampung Londa and Kampung Ulu Ladang (5,419,661 m ²) (inland)	<i>Techniques:</i> 2D Electrical resistivity measurement, induced polarization, and borehole geophysical techniques <i>Data:</i> (resistivity images, pumping test data and rock and soil data)	To determine the relationship between the aquifer and geology of the area and to enhanced the understanding of the groundwater potential in the study area	The result identifies two aquifer formations in the area: first originate from sandstone and tuffaceous sandstone. The second was found to be within a fractured tuff where the vertical flow of groundwater passes through. The total net volume of the aquifer was 9,798 × 10 ⁷ m ³ . Furthermore, the findings suggest that the aquifer spread over an area of about 3,250,555 m ² with a mean depth of 43.71 m
37	(Adiat et al. 2013)	Kedah State, Peninsula Malaysia (9500 km ²) (Inland)	<i>Techniques:</i> Multi-Criteria Decision Analysis (MCDA) and Analytical Hierarchy Process (AHP) and 2D resistivity imaging for hydraulic parameter estimation using Dar-Zarrouk parameters <i>Data:</i> (transverse unit resistance (TR) and the longitudinal unit conductance (S))	To create a groundwater potential map of Kedah state	The result classifies the area into four potential groups: very low (covering the upper north to northwest), low (covers the larger part of the area down to south), medium (mostly at the eastern part) and high (located at the center of the medium zone). The reliability of the prediction was found to be 80 %, indicating the dependability of the proposed method
38	(Kura et al. 2013)	Kapas Island, Terengganu State, northern peninsula Malaysia (2 km ²) (Island)	<i>Techniques:</i> PCA, HCA, Piper diagram <i>Data:</i> (major ions)	To determine the factors influencing the groundwater chemistry of the island	Anthropogenic pollution such as leachate from sewage at the central western coast, and seawater intrusion at the lower western coast (where most tourism activities take place) were the factors controlling the groundwater chemistry
39	(Manap et al. 2013)	Upper Langkat basin, (Selangor State) (492 km ²) (Inland)	<i>Techniques:</i> Geographical information system (GIS) and Remote-sensing (RS) <i>Data:</i> (geomorphology, slope, elevation, lithology, lineament, land use, drainage density, soil, and rainfall, LANDSAT 7 ETM + imagery)	To produce a groundwater potential zone map using a knowledge driven expert-based GIS and RS	The groundwater potential zone map categorized the area into four classes: low (northeastern and southeastern), moderate (spread over the largest part), high (central part) and very high (upper Langkat Basin) based on storage capacity and yield of each zone covering: 17, 66, 15, and 0.45 % of the total area respectively. The validity of the model shows about 76 % accuracy
40	(Manap et al. 2014)	Langkat basin (Selangor State) (2100 km ²) (inland)	<i>Techniques:</i> Probabilistic-based frequency ratio (FR), RS and GIS	To examine the use of the probabilistic-based frequency ratio (FR) model in mapping groundwater potential zone	Groundwater potential zones were classified into four categories: low (the hilly area from north east to south east), moderate (spread over the basin), high (mostly at the downstream area) and very high (center of the basin)

Table 1 (continued)

No.	Source	Category	Methodology	Objectives	Results
41	(Shamsuddin et al. 2014)	Southwest state of Selangor within the Langat Basin, Peninsula Malaysia, (10 km ²) (inland)	<i>Data:</i> (geology, slope, soil, curvature, land use, river, elevation, and lineament) <i>Techniques:</i> Bank infiltration (BI), pumping test, 2D resistivity survey, soil sieve analyses, <i>Data:</i> (resistivity images, isotope and major ions)	BI technique has proven to be a reliable method for freshwater supply in the area	covering 15, 20, 60, and 5 % of the area respectively with validation of 85 % accuracy. The result suggested that areas with high-frequency ratio correspond with slopes 0 to 1° and lithology dominated by clay, silt, sand, and gravel and fall within the class of high groundwater potential zones The result shows high reduction of turbidity from 5–98 %. Furthermore, reduction in HCO ₃ , Cl ⁻ , SO ₄ , NO ₃ , Ca ²⁺ concentrations were observed in the extracted water compared to the Langat River water. Moreover, the amounts of <i>E. coli</i> , total coliform and Giardia significantly decreased by 99.9 %. But, the extracted water indicates high concentrations of Fe ²⁺ and Mn ²⁺
42	(Shirazi et al. 2013a, b)	Melaka State (1650 km ²) (inland)	<i>Techniques:</i> DRASTIC model with GIS and remote sensing <i>Data:</i> (groundwater level, recharge, lithology, soil type, topography, hydraulic conductivity and landuse data)	To create a vulnerability map of Melaka State	The result divide the state into three vulnerability zones: high (23.45 %) mostly scattered all over the area but especially in the Melaka, Alor Gajah and Jasin city areas, moderate (61.53 %) also scattered all over, and then low vulnerable area (11.02 %) located at the northern part of the state. The agricultural, urban and industrial activities have boosted the high vulnerability area by 11 % in the risk map compared to the vulnerability map.
43	(May and Mazlan 2014)	Langat Basin, Selangor State (243.65 km ²) (Inland)	<i>Techniques:</i> Numerical model (MODFLOW) <i>Data:</i> (horizontal hydraulic conductivity, aquifer thickness, recharge rate, vertical anisotropic hydraulic conductivity, specific head and river conductance)	To evaluate surface water/groundwater interaction along the Langat River	The first scenario indicates that, the effluent condition of the stream was controlled by the groundwater from the northeast to the west. The pumping of groundwater was also found to have a great influence on the stream. The flow system was altered in the second scenario after the pumping activity was added to the simulation. The original function of the groundwater was lost but it received leakages from the stream near the pumping sites. The wet land was found to have increased the recharge of groundwater
44	(Idris et al. 2014)	Pulau Tioman, Pahang State, (136 km ²) (Island)	<i>Techniques:</i> Correlation matrix and Piper diagram <i>Data:</i> (physicochemical parameters)	To determine the quality of the island's groundwater	The groundwater type of the area is generally freshwater. Both major ions and physical parameters are within the acceptable limit
45	(Nampak et al. 2014)	Langat basin area (Selangor State) (2100 km ²) (Inland)	<i>Techniques:</i> Evidential belief function (EBF) model and GIS <i>Data:</i> (topography map, number of wells, hydraulic conductivity, soil map, normalized difference vegetation index (NDVI), geological map, landuse map, Lineament map, rainfall data and groundwater depth)	To determine potential application of (EBF) model for groundwater potential mapping	The middle stream and the downstream of the basin (westward) were found to have more groundwater potential compared to the upstream at the eastern part. The success-rate for EBF method was found to be 83 %
46	(Mogaji et al. 2014)	Batang padang in the Southern part of Perak State (2884 km ²) (Inland)	<i>Techniques:</i> GIS-based Optimized DRASTIC model and Analytic Hierarchy Process (AHP)	To determine the groundwater vulnerability of the area.	The model delineates the area into five vulnerability zones: no vulnerable, very low, low, moderate and high vulnerable covering 5, 18, 22, 34 and 23 % of the area respectively

Table 1 (continued)

No.	Source	Category	Methodology	Objectives	Results
47	(Kura et al. 2014)	Kapas Island, Terengganu State, northern peninsula Malaysia (2 km ²) (Island)	<i>Data:</i> (depth to water level, rainfall data, hydraulic conductivity, soil data, geological data and topography) <i>Techniques:</i> 2D resistivity measurement, geochemistry (Chadha's diagram, Stiff plots, bivariate scatter plots and ionic ratios and geostatistics (GIS) <i>Data:</i> (resistivity images and major ions)	To optimized the seawater intrusion assessment techniques	The proposed method was able to precisely pinpoint the lower western coast as the area undergoing seawater intrusion. Over pumping was believed to be the influencing factor
48	(Kura et al. 2015)	Kapas Island, Terengganu State, northern peninsula Malaysia (2 km ²) (Island)	<i>Techniques:</i> DRASTIC and GALDIT models <i>Data:</i> (depth to water level, rainfall data, hydraulic conductivity, soil data, geological data and topography)	To determine the island vulnerability to surface pollution and seawater intrusion	DRASTIC model identify five vulnerability classes: no risk, low, moderate, high, and very high, covering 4, 26, 59, 4, and 7 % of the island, respectively. Similarly, for seawater intrusion, the modified GALDIT model classifies the island into four vulnerability classes: very low, low, moderate, and high covering 39, 33, 18, and 9 % of the island, respectively. Both models identify the alluvium deposits at the lower western coast as the most vulnerable area. While the non-vulnerable area fall on the hilly parts of the island

compositions such as (Ca–HCO₃ to Na–Cl) generally signify the developments that are taking place along the flow paths or interaction between different water types (Sundaram et al. 2007). Of all the graphical methods (Durov diagram, Schoeller diagrams, and Piper among others), the piper diagram is the most conventional technique frequently used by many (Ahmad et al. 2003; Kura et al. 2013).

In Malaysia, graphical methods account for more than 25 % of the groundwater studies (Table 1). Researchers like Sapari et al. (2011), Isa and Aris (2012), Kura et al. (2013), and Idris et al. (2014) employed these techniques in various aspects of groundwater chemistry either to determine water types or other pieces of hydrochemical studies. Other techniques such as ionic ratios also utilized major ions in their analysis, whereby two or more ions are combined together or plotted against one another (e.g., Na/Cl) to determine the factors influencing the groundwater chemistry of an area (Isa et al. 2012). However, one of the limitations of graphical methods (Piper and Schoeller and Collins diagrams) is that they only consider major ions in assessing water chemistry; as such, some researchers do not regard these methods as appropriate for environmental studies (Praveena et al. 2011c). Moreover, these graphical methods lack the capacity to establish precisely the borders of individual water quality class, the number of classes, or which of the groundwater samples should be allocated to each class (Daughney et al. 2012). Thirdly, hydrochemistry based on ionic ratios or major ions relies on sampling which is intrusive in nature and this sampling can only give an average value of a local situation not the entire area. Therefore, there is need to take more samples from many points which is a very expensive and exhausting process (Niwas and Lima 2003). Additionally, ionic ratio in particular relies on specific values, for example (0.05–0.1) for SO₄/Cl ratio to indicate seawater intrusion (Lee and Song 2007; Aris et al. 2012a, b), and (>0.1) to represent leached from septic tanks (Rina et al. 2012). This makes ionic ratio a very complex technique and increases its uncertainty. For example, contaminants overlap can take place in an aquifer whereby more than one pollution process occurs simultaneously, such as seawater intrusion and leaching from septic tanks (Forcada and Evangelista 2008). Should such a scenario transpire, the ionic ratio results may lead to the wrong conclusion since it will only indicate the highest ionic ratio value (Kura et al. 2014).

Heavy metals

Another aspect of groundwater chemistry tackled by only a few researchers in Malaysia is the issue of heavy metals (Ashraf et al. 2013; Isa et al. 2014). Heavy metal is a term assigned to a class of metals and metalloids that are characterized by a high atomic density five times greater than water or more than 4000 kg m³ (Hashim et al. 2011). Environmentally

Table 2 An outline of water quality parameters and their significance (Modified from (Weight 2008; Lerner and Harris 2009))

Parameter	Sources	Significance
Calcium (Ca) and Magnesium (Mg)	<ul style="list-style-type: none"> • Soils and rocks • Seawater also contains high Mg 	<p>Accountable for</p> <ol style="list-style-type: none"> 1. Most of the hardness and 2. Scale-forming properties of water.
Sodium (Na) and Potassium (K)	<ul style="list-style-type: none"> • Soils and rocks • Industrial brines • Seawater and sewage 	<p>Indicates</p> <ol style="list-style-type: none"> 1. Salty taste when combined with Cl 2. High Na may damage plants when the concentration is >270 mg/l 3. Harmful to humans, especially those with controlled diets
Bicarbonate (HCO ₃)	<ul style="list-style-type: none"> • Soils and rocks • Corals dissolution • Oxidation of organic carbon • Atmospheric contact 	<p>Influence</p> <ol style="list-style-type: none"> 1. Alkalinity 2. Discharges CO₂ into the atmosphere in some reactions 3. Acidification of water due to buffering 4. A correlation of HCO₃ and Ca could mean freshwater or recharge
Sulfate (SO ₄)	<ul style="list-style-type: none"> • Gypsum from rocks and soils containing especially clays • Iron sulfides • Industrial waste • Seawater • Mining area • Sewage 	<p>Indicates</p> <ol style="list-style-type: none"> 1. Weathering or water-rock interaction 2. SO₄ and Ca in water forms a hard scale in steam boilers 3. In large quantities, makes water taste bitter 4. Influences redox reactions in water
Nitrate (NO ₃)	<ul style="list-style-type: none"> • Anthropogenic activities 	<p>Indicates</p> <ol style="list-style-type: none"> 1. Anthropogenic pollution such as fertilizer or sewage 2. Causes an increase in growth of algae and other organisms 3. Causes depletion of oxygen due to microorganism's activities 4. Very harmful to babies (blue babies) and can even be fatal
Chloride (Cl)	<ul style="list-style-type: none"> • Soils and rocks • Sewage • Industries waste and • Seawater (sea salt) • Atmospheric precipitation, eg. Rainwater. 	<ol style="list-style-type: none"> 1. When combined with Ca and Mg, it may boost the corrosive activities of water 2. Causes a salty taste in the water 3. Cl and Na can be an indication of seawater intrusion
Hydrogen ion activities (pH)	<ul style="list-style-type: none"> • Influence by rainwater • Runoff carrying organic and inorganic materials • Free CO₂ lower pH • HCO₃, hydroxides and silicates raise pH 	<ol style="list-style-type: none"> 1. pH is a measure of the acidity or alkalinity of groundwater. A pH value above 7 indicates alkalinity while below 7 indicates acidity 2. Low pH increases the weathering activity of water 3. An inverse relationship between pH and Eh can be an indication of redox reaction
Total Dissolved Solids (TDS)	<ul style="list-style-type: none"> • Mineral constituents from soils and rocks • Major ions 	<ol style="list-style-type: none"> 1. High concentration of TDS indicates seawater intrusion 2. As for drinking, TDS concentration in water should not exceed 1000 mg/l. Above 1000 mg/l is not acceptable for most uses
Temperature (°C)	<ul style="list-style-type: none"> • Atmospheric condition • Chemical reactions 	<ol style="list-style-type: none"> 1. Increase in temperature affects almost all chemical reaction in the water 2. Influence microbial activities 3. Influence weathering
Water Level	<ul style="list-style-type: none"> • Tide • Recharge from rainfall and snow 	<p>Indicates</p> <ol style="list-style-type: none"> 1. Flow direction 2. Recharge and discharge, influence exploration on the water quantity
Redox potential (Eh)	<ul style="list-style-type: none"> • Oxidation status of water in the aquifer • Redox is pH dependent • Influences microbial activities where organisms use oxygen as their source of energy • Sewage leaching can also increase Eh reaction 	<ol style="list-style-type: none"> 1. Together with pH and temperature, Eh influenced most of the microbial activity and chemical reactions in groundwater
Dissolved Oxygen (DO)	<ul style="list-style-type: none"> • Atmosphere • Rainwater • Chemical reactions. 	<ol style="list-style-type: none"> 1. Influence on microbial activities in water 2. Influence redox reaction 3. Pollution indicator
Conductivity	<ul style="list-style-type: none"> • Dissolved minerals in water 	<ol style="list-style-type: none"> 1. This shows the capacity of water to conduct electric current and it varies with temperature 2. Strongly related to TDS content in water 3. Indicator for seawater intrusion
Turbidity	<ul style="list-style-type: none"> • Particles from soils and rock minerals • Organic and inorganic matter 	<ol style="list-style-type: none"> 1. Can prevent sunlight from penetrating the water 2. Increase in microbial activities 3. Altered water temperature 4. Sensitive to seasonal changes

Table 2 (continued)

Parameter	Sources	Significance
Salinity	• TDS (dissolve ions influence salinity)	• Together with TDS and EC, they reflect the salt materials or mineral ions present in water
Heavy metals (As, Cu, Zn, Cr, Pb, etc.)	• Natural sources such as geological formations • Industrial waste • Mine areas and waters • Landfills	• Left unattended, they can lead to significant faunal problems in groundwater • Health risk (organs failure in human)

speaking, heavy metals are usually known to be more enduring compared to organic pollutants. These metals can easily move from one part of the soil to another depending on the metal's specification and the soil's pH. Moreover, these metals can occur naturally or from anthropogenic pollution and once they find their way into groundwater, then any remediation measure becomes highly complicated (Hashim et al. 2011; Hussin et al. 2014). The last part of Table 2 presents a summary of some of the most important heavy metals together with their sources.

Statistical techniques

A variety of statistical techniques have been used by many researchers with regard to groundwater studies in Malaysia (Table 1). In fact, about 25 % of the works reviewed in this paper used one or more statistical methods such as multivariate, multiple linear regressions (MLR), or analysis of variance (ANOVA) to address groundwater problem in many parts of the country (Lin et al. 2010; Praveena et al. 2011c; Isa and Aris 2012). The most frequently used method for statistical analysis of groundwater chemistry is multivariate statistical analysis. Multivariate statistical analysis such as CA and PCA are favored in groundwater studies due to the fact that groundwater chemistry is a complex system influenced by a variety of factors including geology, climatic conditions (rain and temperature), interaction between seawater and freshwater as well as anthropogenic activities leading to a complex and large collection of data (Aris et al. 2007; Praveena et al. 2011c; Isa et al. 2012, 2014; Kura et al. 2013; Karim et al. 2014). Thus, comprehending the processes which are involved and evaluating the most important factors responsible for groundwater chemistry requires a strong tool with the ability to simplify and make sense out of the voluminous amount of data. Multivariate statistical techniques offer a dependable and alternative way to interpret the large and complex hydrochemistry data (Jalali 2010; Kura et al. 2013).

Principal component analysis

Among all the group members of multivariate statistical analysis, PCA method is the most prominently utilized (Bakshi 1998; Ranjan et al. 2013). In PCA, patterns in data are first identified and subsequently arranged in order of similarities

and disparities. Extracting patterns in a complex data is a highly demanding challenge. The primary task of PCA is summarizing set of data that is multivariate in nature (Smith 2002; Pitkänen et al. 2004). Usually, the first few PCs will account for the largest discrepancy among the variables in the data. Besides, PCA normalizes all of the variables in the data on individual bases to unit variance. Therefore, all variables have an equal chance of contributing while the correlation matrix is employed (Famham et al. 2003; Uddameri et al. 2014). It is for these reasons that researchers like Aris et al. (2007), Lin et al. (2012), Kura et al. (2013), and Isa et al. (2014) among others from Malaysia have joined other researchers from other parts of the world in using PCA to evaluate the hydrochemistry of their respective areas of study.

Cluster analysis

Many clustering techniques exist, but hierarchical cluster analysis (HCA) is the most widely used among all the clustering methods (Tlili-Zrelli et al. 2013). HCA allocates the variables in a dataset into clusters in accordance with their homogeneity to one another and disparity from other clusters. The classification is done in an objective way, exclusive of any previous knowledge concerning the data so as to determine the original patterns of the dataset (Wanda et al. 2011; Mohapatra et al. 2011; Daughney et al. 2012). Moreover, there is no limitation in running HCA with regard to number or types of variables (physical or chemical and so on) or condition (distributed or not). The results of HCA are produced using average parameter values for every water quality group which has originated from the initial input data. Thus, the HCA results can easily be understood especially from a hydrochemical perspective (Daughney et al. 2012). This method has attracted many researchers in Malaysia such as Lin et al. (2012); Isa et al. (2014); Karim et al. (2014) to assess different groundwater related issues.

Geophysical techniques

Geophysical techniques are non-intrusive methods with the ability to evaluate geological properties and subsurface structures both vertically and horizontally (Samouëlian et al. 2005). Geophysics can be employed to continuously measure and

distinguish the sub-surface's geological materials within a large area, and it is cost-effective and rapid at acquiring data (Kneisel et al. 2008). Electrical resistivity measurements are the most commonly used among all the geophysical methods for groundwater studies (Goldman and Neubauer 1994). This technique measures the electrical response of a variety of geological materials close to the earth's surface, first by injecting an artificial electric current into the earth through electrodes and subsequently by measuring the prospective difference with other electrodes. These differences are then utilized in the determination of the sub-surface's true resistivity by translating the resulting values into apparent resistivity (Loke 2011). These give researchers the ability to delineate and map out the hydrogeological and lithological structures that are present at the subsurface. On most occasions, geophysical analyses disclose detailed information compared to the traditional methods of hydrogeological analyses such as a pumping test (Linde et al. 2004). Another advantage of geophysical techniques is the fact that they are somewhat remote-sensing orientated; in other words, information is being acquired without having a complete contact with whole area from which the data is being taken. The current advancement in geophysics, especially in resistivity techniques, has led to a massive adaptation of these methods in many hydrogeological, environmental, and subsurface geological assignments, such as in groundwater studies (Soupios et al. 2007).

In Malaysia, geophysical techniques constitute more than 38 % of the groundwater studies (Table 1). These studies were conducted in different places governed by diverse objectives ranging from determination of aquifer thickness (Dor et al. 2011) to a fully quantitative assessment of groundwater resources (Juanah et al. 2013) and to qualitative assessment which is mostly dominated by seawater intrusion studies (Nassir et al. 2000; Hamzah et al. 2007; Samsudin et al. 2008; Baharuddin et al. 2011, 2013b). Other studies include determination of effects of leachate from landfill on groundwater (Ahmed and Sulaiman 2001) or just normal groundwater pollution from the surface (Islami et al. 2012) as well as determination of aquifer hydraulic parameters (Rahim et al. 2010). However, there is major setback regarding the use of resistivity technique to evaluate seawater intrusion if the aquifer in question contains clay. Thus, caution should be exercised because the results can also be misleading since clays and seawater are known to have very low resistivity (<1–5 Ω m) (Rao et al. 2011). Another limitation, with respect to 1D resistivity model, is the fact that this model tends to neglect the horizontal differences while taking a resistivity measurement of an area (Khalil and Santos 2011; Loke et al. 2013). It is generally complicated or even unrealistic to actually reflect the true world geological states based on 1D modeling theory, especially in a complex geological setting. Therefore, 2D and 3D techniques should be prioritized in

environmental researches (Samouëlian et al. 2005; Khalil and Santos 2011; Loke et al. 2013).

One noticeable issue regarding geophysical applications in Malaysia and even in other parts of the world like India and Spain (Koukadaki et al. 2007; Baharuddin et al. 2011; Rao et al. 2011; Rey et al. 2013) is that it is yet to be developed or utilized to its maximum potentials (Niwas and Lima 2003; Soupios et al. 2007; Tizro et al. 2012). Therefore, efforts should be made in finding a way to create an integrated approach that can accommodate both geophysics and other methods in addressing environmental problems. Moreover, researchers should try to find a way in which 2D resistivity can be used to determine a 2D hydraulic parameters such as porosity and hydraulic conductivity in order to feed the exhausting demand of reliable data for hydro-geological modeling such as MODFLOW among others. For future reference, a summary of some of the geophysical techniques along with their strengths and limitations are presented in Table 3.

Geographical information system techniques

Geographical information system (GIS) is a technique that has the ability to manipulate, store, retrieve, overlay, analyze, and incorporate spatial and non-spatial data within single or multiple systems (Manap et al. 2013). In recent years, GIS has continued to gain more ground in water-related research and has been proven to be a reliable technique (Dörfliger et al. 1999; Liu et al. 2011; Shirazi et al. 2013a, b; Narany et al. 2013). The use of GIS in groundwater-related studies can generally be classified into six major groups: (1) groundwater resources and exploration assessment, (2) suitable artificial recharge area detection, (3) flow and contaminants transport modeling, (4) vulnerability and risk assessment for current and potential pollution mapping and management strategy, (5) evaluation of spatial distributions of natural recharge, and (6) data analyses in the field of hydrogeology and monitoring processes (Jha et al. 2007).

In Malaysia, GIS is gaining popularity among researchers as it covers 17 % of the country's groundwater-related research especially in the area of exploration and potential groundwater resource assessment. For example, Adiat et al. (2013) used GIS as a tool to integrate different factors through GIS overlay technique to evaluate groundwater potential zones based on multi-criteria decision analysis (MCDA). Similarly, Manap et al. (2013, 2014) and Nampak et al. (2014) utilized GIS to delineate groundwater potential zones in the Langat Basin.

GIS was also employed to assess groundwater vulnerability to contamination based on DRASTIC model (Shirazi et al. 2013a, b; Mogaji et al. 2014). Even though small islands are more vulnerable to anthropogenic pollution and seawater intrusions due to their topographical and geological nature

Table 3 Hydrologic properties inferred from geophysical measurement methods (adopted from Robinson et al. (2008))

	Dependent physical property	Moisture content	Porosity	Pore fluid electrical conductivity	Hydraulic conductivity	Rock stratification	Lithologic factors (rock type, grain size or surface area)	Faults and fracture
<i>Airborne</i>								
	Microwave remote sensing	P						
	Airborne electromagnetic			P			S	
	Airborne time domain electromagnetic			P		S	S	
	Aeromagnetic	Magnetization					P	P
<i>Ground-based</i>								
	Time domain electromagnetic	ER		P		P	S	
	Magnetotelluric	ER		P		P	S	
	Audio magnetotelluric	ER		P		P	S	
	Electromagnetic induction	ER		P		S	S	
	Ground penetrating radar	Reflection: permittivity Magnetic permeability	S			P		S
	Electrical resistivity imaging content sensors	Attenuation: resistivity ER	P	P		S	S	S
	Induced polarization	ER/capacitance			S		P	
	Electromagnetic water content sensors	Reflection: permittivity Magnetic permeability	P	P				
	Seismic	Attenuation: resistivity Elastic moduli; density			S	P	P	
	Gravity	Density					P	P
	Microgravity	Density	P					
	Magnetic	Magnetization					P	P
	Magnetic resonance sounding	Proton density	P	P	S			

This table serves as a guide and is not definitive, since new methods are frequently being developed
ER represents electrical resistivity, *P*, indicates primary property inferred, *S* indicates the secondary properties that might be inferred

(Falkland and Custodio 1991; White et al. 2007; Chase 2012), yet only recently, an attempt is made to evaluate small island’s groundwater vulnerability to anthropogenic pollution and seawater intrusion using modified DRASTIC and GALDIT models respectively with the help of GIS (Kura et al. 2015). Other than this work, hardly can one find groundwater vulnerability studies in small islands despite the significant pressure on the groundwater resources both from surface pollution and seawater intrusions. Therefore, appropriate management strategy should include the use of vulnerability maps to assess the susceptibility of these areas to contamination from seawater intrusion and anthropogenic pollution. Noticeably, such contamination would be catastrophic to both the economic sector (tourism) and the ecosystem (Kumar 2006; Sherif et al. 2012).

Another attempt was made by Kura et al. (2014) to integrate geophysics and geochemistry techniques in a GIS environment to optimize the current methods used in delineating seawater intrusion. This integration was able to overcome the weakness of the geophysics in the presence of clay materials

(which increase the uncertainty of the results) (Rao et al. 2011) and that of geochemistry in the case of contaminants overlap (ionic ratio) (Forcada and Evangelista 2008). The use of GIS to overlay geostatistical maps of resistivity and ionic ratios enable the author to determine the exact area that was under the influence of seawater intrusion (Kura et al. 2014).

Numerical modeling

Currently, numerical modeling is considered one of the most significant sections of groundwater research with the main goal of predicting the effect of current and future groundwater and how an aquifer may respond to certain scenarios in addition to other hydrologic changes. Moreover, this modeling system has the ability to provide researchers with an in-depth knowledge and understanding of a particular hydrogeological system and its properties (Maliva and Missimer 2012). These models for example (MODFLOW) and 3-D hydrodynamic model (SELF3D) are generally governed by an equation which joins water mass balance

and Darcy's law (Carroll et al. 2008). Numerical modeling, in particular MODFLOW which was originally developed by the US Geological Survey (USGS), has been employed by researchers in many areas around the world to execute a variety of groundwater studies ranging from groundwater flow and solute transport (Calvache and Pulido-Bosch 1994; Langevin and Guo 2005; Xu et al. 2012) to seawater intrusions (Calvache and Pulido-Bosch 1994; Rejani et al. 2008; Bakker and Schaars 2013; Chen et al. 2015). This model is regarded as a cutting edge technological development in the hydrogeological field in which data is being used to recreate the current and future scenarios in an aquifer (Shammas and Thunvik 2009).

However, the situation is different in Malaysia as indicated in Table 1; only 7 studies utilize this modeling technique, mostly in the area of seawater intrusion (Praveena and Aris 2010; Praveena et al. 2011a, 2012) in Manukan Island and then for groundwater flow and contaminants transport (Rahman and Kuan 2004), plus another one that used MODFLOW to determine the effects of groundwater pumping on river flow and discharge (May and Mazlan 2014). This may perhaps be attributable to the model's complexity in nature and the fact that it is highly data demanding, where on most occasions data is not obtainable. In fact, even where data is available, the expected complaint of insufficient data will persist (Kumar 2006). In hydrological modeling, inadequate data may obstruct the prediction ability of the model and subsequently lead to uncertainty and unreliability in terms of the resulting output (Comair et al. 2014).

In general, most of the islands and coastal groundwater chemistry are being dominated by seawater intrusion. Conspicuously, all the seawater-affected areas were in alluvium deposits situated in the islands and along the coastal areas all over the country (Aris et al. 2007, 2012b; Sapari et al. 2011; Baharuddin et al. 2013b; Karim et al. 2014). These alluvium deposits are characterized by high porosity and transmissivity, as such they lacked the natural capacity to prevent or even delay seawater from infiltrating into the aquifer (Loke 2011; Kura et al. 2015).

Conclusions

Groundwater studies conducted in Malaysia were reviewed. The aim and methodologies used in each of the groundwater studies reviewed were identified, assembled, and presented in a tabular format. The advantages and limitations of each method were discussed as well as some of the way to overcome those limitations. The review found that most of the Malaysian groundwater studies centered on determining the factors influencing the groundwater chemistry of the area in question. Most of these studies were conducted in islands (44 %) in both peninsular and east Malaysia where

groundwater is the only available freshwater source. While the inland-based studies accounted for 40 % of the groundwater studies in the country, similarly, the coastal area studies accounted for 16 % of the groundwater studies. The review indicates that seawater intrusion is the dominant factor influencing the groundwater chemistry of these islands and has already infiltrated most of the coastal aquifers (except for example in Kelantan and Negeri Sembilan).

In the case of techniques used to undertake groundwater studies, the review reveals that statistical techniques comprising PCA, CA, DA, MLR, and ANOVA were the predominant techniques used to assess groundwater chemistry. Most of the statistical-related studies are qualitative based (to determine the factors controlling groundwater chemistry). Major ions and in situ parameters were mostly used to understand the hydrochemistry of an area. In the graphical methods, Piper diagram is the dominant approach used to identify the water types. Largely, the dominant water types were Na–Cl, Na–HCO₃, and Ca–HCO₃. GIS and geophysical techniques were also employed in many Malaysian groundwater studies. In contrast, numerical modeling was found to be less popular, perhaps due to its high data demand and the complexity of the model.

In conclusion, for any groundwater study to be more successful, particularly in relation to hydrochemistry, it would be good for researchers to integrate different techniques together using GIS or other means. This will help to overcome the limitations attached to each individual technique. Similarly, there is need to improve and push the geophysical techniques to their limits, especially in the area of extracting hydraulic parameters and in seawater-related studies.

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