Groundwater Quality: Myanmar

This is one of a series of information sheets prepared for each country in which WaterAid works. The sheets aim to identify inorganic constituents of significant risk to health that may occur in groundwater in the country in question. The purpose of the sheets is to provide guidance to WaterAid Country Office staff on targeting efforts on water-quality testing and to encourage further thinking in the organisation on water-quality issues.

Background

The Republic of the Union of Myanmar (Burma) lies between India, Bangladesh and the Bay of Bengal in the west, China in the north, Thailand and Laos in the east and the Andaman Sea in the south. It is divided into seven regions (plains) and seven states (uplands), with a total land area of 676,550 square kilometres. The capital city is Nay Pyi Taw, having changed from Yangon in 2006 (Figure 1).

Myanmar attained independence from Britain in 1948. Decades of ethnic and political unrest have hampered development since that time but recent wide-ranging political, economic, civil and legal reforms have resulted in a partial opening of the country.

Topography is characterised by highest altitude in the north bordering the Himalaya, with steep, rugged north-south-running mountain ranges along the east and west borders and with elongate central lowlands. The mountain ranges include the Patkai, Naga, and Chin Ranges and Rakhine Yoma in the west, and the Shan Mountains in the east (Figure 2). Altitude varies from the highest point at Hkakabo Razi (5881 m) in the extreme north to sea level in the south. The Rakhine Yoma reach up to 2000 m in the west; the Shan Plateau forms a large dissected upland with elevation averaging 900 m in Shan State (Figure 1, 2). The central lowlands are divided unequally by the north-south-trending Bago Yoma Range which passes northwards into a line of extinct volcanoes, the highest being Mount Popa (1518 m) (Zaw et al., 2017). Around 30% of the population live in the central lowlands (Drury, 2017).

The Irrawaddy River (2170 km long) flows from the northern mountains along the central lowlands until

Figure 1. Map of Myanmar showing states and regions (source: CartoGIS Services, College of Asia and the Pacific, The Australian National University under licence: CC BY-SA 4.0).

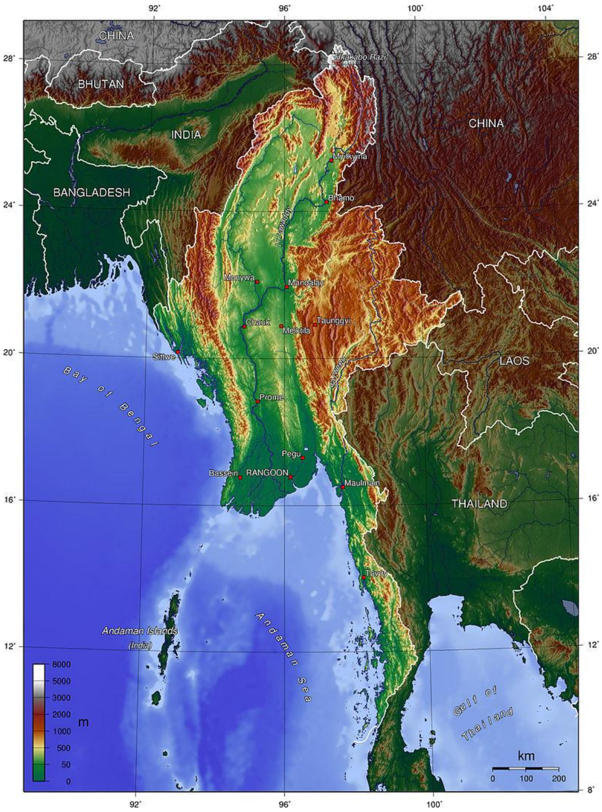

Figure 2. Topographic map of Myanmar (Burma) (source: https://commons.wikimedia.org/wiki/ under licence: CC BY-SS 3.0).

it branches at the delta (Figure 2). It has a number of tributaries, the largest being the Chindwin River which skirts the Patkai and Naga ranges. The Mekong River runs from the Tibetan Plateau, with part of its upper reach along Myanmar's eastern border with Laos. The Sittaung River flows north-south between the Shan Plateau and the Bago Yoma Range.

Climate ranges from dominantly temperate to sub-tropical in the north to tropical in the south. Northern highlands range through temperate above 2500 m to tundra above 3500 m. Myanmar is affected by both south-westerly and north-easterly monsoons, the dominant rainfall coming from the south-west. The southern delta has an annual rainfall of 2500 mm; the central lowlands, covering parts of Mandalay, Magway and lower Sagaing, known as the dry zone, have <900 mm and lie in the rain shadow of the Rakhine Yoma (Bacquart et al., 2015).

Almost half of Myanmar's land area is forested, with teak, pyinkado, rubber, acacia, bamboo and coconut being important in the lowlands and oak, pine and rhododendron in the northern highlands. Mangrove forest occupies coastal areas. Around 16% of landuse is arable. Rice, millet, maize, legumes, pulses, chillies and cotton are the dominant crops. Rice is rain fed in the delta area, but river irrigated in the dry zone.

Environmental pressures include deforestation and associated increased runoff and soil erosion, and water pollution from urban sources and mining-related activities.

Geology

Myanmar's geology reflects a long history of active tectonism related to Himalayan uplift and to subduction, rifting and continental collision involving the convergence of three plates. Tectonic fault zones cross the country, dominantly oriented north-south. As a result, the landmass is divided into three main structural units: the highlands of the Indo-Burman Range in the west, the lowlands of the Central Belt and the Shan Plateau in the east (Gardiner et al., 2016) (Figure 3).

The Indo-Burman Range consists of Cenozoic (65–5 million years) and older flysch deposits (rapidly deposited sands, silts, clays in marine continental margin settings, formed in relation to mountain building events) up to 15 km thick (Ridd and Racey, 2015), with a core of Jurassic ophiolites (mantle rocks and basalts associated with uplifted ocean crust), and underlying metamorphic basement.

The Central Belt hosts a number of Eocene to Miocene (55–5 million years) sedimentary sub-basins (Figure 3) , which accommodated volcanic rocks and cinder cones of the Popa volcanic arc range (basaltic to dacitic) of Miocene to Pleistocene age (10–2.5 million years) (Drury, 2017; Zaw et al., 2017). Underlying crustal basement is not exposed.

The Shan Plateau is composed of crystalline basement and metamorphosed sedimentary rocks of Precambrian to early Cambrian age (500 million years and older), overlain by a thick sequence of younger (Cambrian to Cenozoic) sedimentary rocks of marine and terrestrial origin (Zaw et al., 2017). The plateau's western edge is a prominent, fault-bounded escarpment known as the Shan Scarp.

To the west of the Shan Plateau, the Mogok Metamorphic Belt runs roughly north-south the entire length of the country. It hosts granitic and high-grade metamorphic rocks bearing gemstones which have been mined since the mid-1800s (Searle et al., 2017). The adjacent Carboniferous-Permian Mergui Slate Belt also lies to the west of the Shan Scarp.

Myanmar has a wealth of mineral and economic resources. The Cenozoic sedimentary rocks in the basins of the central lowlands and offshore have

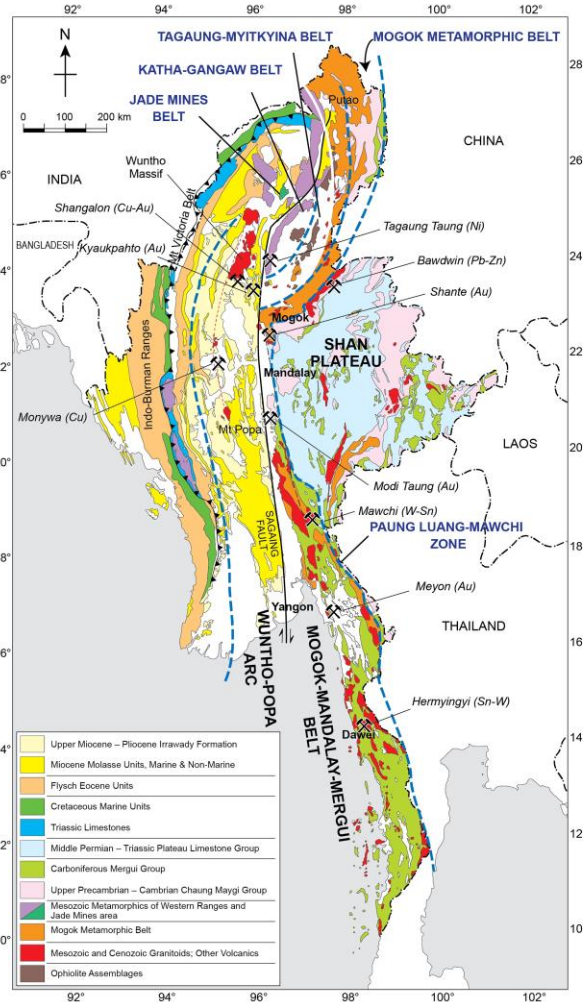

Figure 3. Simplified geological map of Myanmar showing major provinces and mineralised/mining areas. Reprinted from Gardiner et al. (2016) with permission from Elsevier.

excellent oil and gas potential. Mineral resources include tin and tungsten associated with granite and pegmatite in Kayah (Mawchi Mine) and Tanintharyi. Copper derives from the Monywa porphyry copper deposit along the Chindwin River, nickel deposits are associated with ophiolites in Chin State and in Katha District, Sagaing Region, and silver is associated with lead, zinc and antimony in sulphide minerals in the Namtu-Bawdwin mine of the Shan Plateau (Figure 3). Gold associated with metal sulphides occurs in the Central Belt and Kachin State including the Kyaukpahto gold mine in Sagaing Region (Gardiner et al., 2016). Gemstones (rubies, sapphires) are also extracted from the marbles of the Mogok valley and north of Mandalay (Bender, 1983; Guo et al., 2016; Searle et al., 2017; Zaw et al., 2017).

The highlands have thin, highly leached red-brown lateritic soils while the central lowlands include silty and clayey fertile alluvial soils and thin sandy or clay soils away from the alluvial plain.

Groundwater availability

Groundwater infrastructure is relatively undeveloped and groundwater abstraction is so far not regulated or registered. Although legislation exists for urban water use, there is currently no national requirement for groundwater monitoring or management and no national electronic database of groundwater abstractions exists (Drury, 2017). Nonetheless, improved drinking-water supply and sanitation and water for agricultural development are seen as national priorities by the Myanmar government (Drury, 2017).

An estimated 7–15% of the renewable groundwater resource in aquifers in the central lowlands is abstracted, the largest proportion from the dry zone (Viossanges et al., 2017). Dug wells and ponds are traditional sources of drinking water but tubewell drilling programmes started from the 1980s (Pavelic et al., 2015). About 45% of water supply nationally is derived from dug wells with another third from tubewells. Groundwater supplies about 50% of the national need for drinking water and domestic supply and about 22% of water needs for industry (Pavelic et al., 2015). It also provides for some irrigation in the central lowlands. In the mountainous areas, springs constitute an important water supply. Rainwater harvesting is also practised in rural areas.

Geological structure has a major impact on groundwater flow, with increased fracture flow along fault zones and structure defining thickness of sedimentary sub-basins. The main aquifers are Cenozoic to Recent sedimentary formations, with minor flows in fracture zones within igneous, metamorphic and indurated sedimentary rocks.

A Holocene alluvial aquifer along the course of the Irrawaddy River and its tributaries forms the most significant groundwater resource for the central lowlands. This aquifer consists of yellow to grey sand and gravel, silt and clay typically around 75 m thick with depth of abstraction typically 10–30 m. Thickness varies, however, and the unit is less than 15 m thick at Monywa for example (Drury, 2017). Groundwater occurs under confined, semi-confined or unconfined conditions. The aquifer overlies the Irrawaddy Formation (Miocene-Pleistocene) and Pegu Group (Eocene-Miocene) aquifers along the central lowlands (Pavelik et al., 2015).

The Irrawaddy Formation aquifer is a loosely cemented fluvial sand and gravel, clay and silt aquifer with ferruginous concretions occurring along the central lowlands and Rakhine coastal plain. Shallow deposits are commonly yellow to brown in colour, with blue/grey horizons at greater depth. The formation reaches up to 500 m thick. Tubewells are typically installed at 60–180 m depth in the central lowlands (Drury, 2017). Groundwater is usually confined and the aquifer is artesian in places. The formation has moderate to high groundwater yields.

The Pegu Group consists of fractured marine sandstone, siltstone and shale, with occurrences of gypsum and sodium efflorescences. The group also exists along the central lowlands and Rakhine coastal plain. The sediments have low groundwater yields and form a poor aquifer. Drury (2017) noted tubewell depths in the Pegu Group of 175–220 m in the central lowlands but 25–140 m in the Bago Yoma.

An Eocene aquifer of sandstone, silt, shale and mudstone occurs along the margins of the central lowlands. Groundwater yields are variable depending on permeability and increase in fractured sections associated with fault zones.

A low-yielding Eocene-Miocene Flysch aquifer occupies parts of the western highland areas (Khin et al., 2017). This comprises sandstone, siltstone, shale and mudstone.

The Permo-Triassic Plateau Limestone of the Shan Plateau is karstic and has numerous spring discharges which have long been used for domestic supply. Tubewells (ca. 75–130 m depth) also exploit this resource although groundwater yields are variable and determined by fractures (Viossanges et al., 2017).

Elsewhere in areas with igneous and metamorphic rocks, fewer dug wells and tubewells exist.

Groundwater Quality

Overview

Beyond the Irrawaddy valley, few systematic studies of groundwater quality have been carried out (Sakai et al., 2013; Viossanges et al., 2017). The main highlighted groundwater-quality problems are arsenic in the lower and middle Irrawaddy alluvial aquifer, salinity problems in groundwater from the Pegu Group sedimentary aquifer and saline intrusion in the delta and coastal areas, and problems with microbiological contamination (e.g. coliforms including *E. coli*) of dug wells, many of which are unprotected (Pavelik et al., 2015; Grzybowski et al., 2019). Few investigations have determined the influence of agricultural or mining activities on rural groundwater or industrial/urban activities on urban groundwater.

Nitrogen species

Nitrogen species include nitrate (NO_3), nitrite (NO_2) and ammonium (NH_4), all of which are naturally occurring but which can also derive from domestic or agricultural contamination. Among the most vulnerable groundwaters are shallow unconfined sandy aquifers and shallow groundwater in any aquifer accessed by unprotected dug wells. These are prone to contamination from surface pollutants (e.g. waste tips, animal waste, latrines). Nitrogenous fertilisers are also potential sources, although fertiliser use is likely to be low (IWRM, 2014). The karstic limestone aquifers are also vulnerable to surface-borne pollution due to rapid flows via fissures.

Groundwater from the Holocene alluvial and deltaic aquifer of Myanmar is known to have naturally high concentrations of ammonium due to the prevalence of anaerobic conditions. Concentrations of NH_4 up to 9 mg/L were reported by van Geen et al. (2014) in 55 groundwater samples from the Irrawaddy delta.

Salinity

Groundwater in the Irrawaddy alluvial aquifer is usually fresh with electrical conductance typically <1000 µS/cm and water of sodium-bicarbonate type (van Geen et al., 2014; Pavelik et al., 2015; Drury, 2017). Some dug wells there have slightly raised salinity, possibly due to evaporation and/or surface pollution. Grzybowski et al. (2019) reported electrical conductance values up to 3000 µS/cm in dug wells from Amarapura Township in the central Irrawaddy alluvial plain. Saline intrusion into the Holocene deposits is a concern in the southern delta area, especially in urban areas such as Yangon. The oldest known tubewell, drilled in 1889 to 53 m depth in Dalla Township, Yangon, was abandoned due to high salinity (Drury, 2017). Presumably this was impacted by saline intrusion.

The Irrawaddy Formation also has groundwater with usually low salinity, but may be brackish locally (Drury, 2017). Salinity varies with yield and prevalence of fractures.

Groundwater from the Pegu Group is typically brackish or saline with electrical conductance of the order of 2000–5000 µS/cm. Drury (2017) also noted some groundwater samples from this aquifer with high pH (>9) and with calcium-sulphate compositions. In the Bago Yoma area, saline waters of sodium-chloride type occur. Salinity likely reflects groundwater residence time and reaction with evaporite minerals in the sediments.

Salinity of groundwater in the Eocene aquifer is typically brackish, with waters of sodium-chloride and sodium-sulphate type (Drury, 2017); fresh groundwater is found in this aquifer in the upper Chindwin valley (Viossanges et al., 2017).

In indurated rocks, groundwater salinity is variable. Spring flows in mountainous areas are typically fresh with electrical conductance <500 µS/cm (Drury, 2017). However, salt springs have been found along major geological fault lines suggesting upflow of deep groundwater (Drury, 2017). Groundwater from copper-bearing volcanic formations near Monywa are found to be saline (1000–19,000 µS/cm) (Viossanges et al., 2017).

Fluoride

Bacquart et al. (2015) found uniformly low concentrations (≤0.4 mg/L) of fluoride in groundwater from the alluvial aquifer of the central lowlands, albeit with a small dataset (6 samples).

The same study found concentrations in groundwater from the Irrawaddy Formation of Myingyan Township, in the range (0.8–3.6 mg/L, median 1.45 mg, 12 samples). An exceedance of the WHO guideline value of 1.5 mg/L has also been reported for groundwater from the Irrawaddy Formation of Wetlet Township, Sagaing Region (Viossanges et al., 2017 and references therein). High concentrations there were from dug wells and shallow tubewells; 35% of 1114 samples exceeded the WHO guideline value, 1% exceeded 2.5 mg/L. Dental fluorosis was reported in residents of the Township (OEHD, 2018). Sakai et al. (2013) also reported a fluoride concentration of 1 mg/L in groundwater from a tubewell in the capital city, Nay Pyi Taw. Depth of the well was undefined, but the aquifer tapped is believed to be the Irrawaddy Formation.

Few other data appear to be available for fluoride in groundwater. High concentrations (>1.5 mg/L) might be expected in alkaline and brackish groundwaters, such as for example exist in the Pegu Group and Eocene aquifers. Nonetheless, these may be compromised in any case as sources for drinking water due to salinity. Areas of granite are also potential candidates for high fluoride concentrations. The strong links between fluoride in drinking water and fluorosis mean that fluoride should be tested for routinely in groundwater development programmes.

Iron and manganese

In the Holocene alluvial aquifer of the Irrawaddy Basin, anaerobic groundwater gives rise to high to very high concentrations of iron and manganese. Van Geen et al. (2014) reported concentrations of iron up to 21 mg/L and manganese up to 2.5 mg/L (55 samples) in groundwater from the Irrawaddy delta. In another small study, Bacquart et al. (2015) found concentrations of iron in the range 1.1–4.2 mg/L and manganese in the range 0.39–1.7 mg/L (12 samples) from shallow wells (15–25 m deep) in Tha Pyay Tha village, Myingyan Township, in the alluvial Irrawaddy floodplain of central Myanmar. By contrast, concentrations of iron were up to 1.2 mg/L but usually less than 0.1 mg/L and manganese up to 0.01 mg/L but usually <0.005 mg/L in the small number of groundwater samples from the Irrawaddy Formation to the east of the neighbouring Holocene alluvial aquifer.

Elsewhere, no information on distributions of iron and manganese has been found. Increased dissolved concentrations can be expected in anoxic conditions in deep and/or artesian groundwater from any of the aquifers. Presence of high concentrations of iron and manganese in groundwater ought to be visually evident as both precipitate as metal oxides from solution in aerated conditions e.g. around wellheads.

Arsenic

Probability mapping (modelling) using logistic regression on the basis of surface parameters (geology, soils) has been conducted for large parts of south Asia, including Myanmar, by Winkel et al. (2008). Within Myanmar, the study suggested that the Irrawaddy delta area had the highest probability of exceedance of the WHO (2017) guideline value for arsenic in drinking water of 10 µg/L (Figure 4). This is in line with observations from groundwater in other young (Holocene) alluvial and deltaic aquifers across South Asia. An elevated exceedance probability was also suggested for the Sittaung valley (Figure 4), also in Holocene alluvium.

A number of groundwater arsenic surveys have been carried out in Myanmar over the last two decades, particularly in the Irrawaddy alluvial and deltaic plain. These confirm the presence of arsenic exceedances above the WHO guideline value and proposed national standard of 50 µg/L. WRUD and Unicef (2002) reported data from Sagaing, Mandalay, Bago, Ayeyerwaddy and Yangon Regions and Chin, Kayah, Shan and Rakhine States (4969 samples) and found exceedances in Ayeyarwady, Bago, Rakhine and Shan. OEHD (2018) reported that 10% of 2085 analyses from tubewells and 0.9% of dug wells in Ayeyarwady Region had arsenic concentrations greater than 50 µg/L. They also reported 41% and 8% exceedances of 10 µg/L and 50 µg/L respectively in Bago Region. Tun (2003) also analysed 1912 groundwater samples from the shallow tubewells in the Irrawaddy delta and found 45% were greater than the WHO guideline value of 10 µg/L (21% greater than 50 µg/L); 55% had no detectable arsenic.

Table 1. Distributions of arsenic in groundwater from tubewells tested in the Irrawaddy alluvial aquifer. Data from WRUD (2005), reported by Pavelic et al. (2015), Drury (2017).

Region	Township	n	>10 µg/L		>50 µg/L	
			n	%	n	%
Sagaing	Chaung-U	500	34	6.8		
	Monywa	221				
	Shwebo	5,556	30	0.6	1	0.02
	Wetlet	563	91	16.2		
	Sagaing	1,809	264	14.6	9	0.5
	Myinmu	1,781	323	18.1	41	2.3
	Myaung	3,181	877	27.6	145	4.6
Mandalay	Kyauske	2,826	362	12.8	54	1.9
	Myingyan	614	60	9.8	17	2.8
	Mahlaing	500	102	20.4	6	1.2
	Amarapura	500	144	28.8	12	2.4
	Madayar	500	200	40	20	4
	Leway	2,782	809	29.1	63	2.3
	Sintgaing	4,650	765	16.5	82	1.8
	Myittha	6,061	933	15.4	37	0.6
	Tada-U	2,852	452	15.9	12	0.4
Magway	Yesagyo	522	96	18.4	7	1.3

Van Geen et al. (2014) found arsenic in the range <0.05–630 µg/L (median 22.9 µg/L, 55 samples) in groundwater from tubewells <60 m deep in the southern Irrawaddy delta. They found low concentrations in wells <10 m deep.

A survey of arsenic conducted by WRUD (2005) found relatively few groundwater samples with high arsenic concentrations but of those exceeding 10 µg/L, the greatest proportions were from Myaung, Amarapura and Madayar Townships (Table 1), all from the central Irrawaddy alluvial plain. Bacquart et al. (2015) also found arsenic concentrations in the range 10–134 µg/L (median 33 µg/L, 6 samples) in groundwater from wells 15–25 m deep in the central Irrawaddy alluvial floodplain.

Several studies have shown that the high concentrations of arsenic are commonly associated with high concentrations of iron, manganese and ammonium (van Geen et al., 2014). This supports the inference that the groundwater is anaerobic and akin to the conditions observed in the Holocene alluvial/deltaic aquifers of other parts of South Asia including Bangladesh and West Bengal, India.

Bacquart et al. (2015) found concentrations of arsenic in the range 1–22 μg/L (median 2 μg/L, 12 samples) in Myingyan City (Myingyan Township, central lowlands). These were in wells 30–60 m deep beyond the Irrawaddy floodplain, probably derived from the Irrawaddy Formation.

High arsenic is not reported in the areas of alluvium in the Mu and Chindwin river valleys (Drury, 2017; Viossanges et al., 2017). Here, groundwater is derived from either the Holocene or Irrawaddy Formation. The Holocene sediments in Chindwin are said to be yellow unconsolidated yellow-brown sand and gravel (Viossanges et al., 2017), suggesting an oxic groundwater condition less prone to arsenic contamination. Van Geen et al. (2014) also found low arsenic concentrations in groundwater from red-brown sand beneath the Holocene sediments in the delta, inferred to be from the Irrawaddy Formation.

Clearly, the observations of arsenic in groundwater in excess of the WHO guideline value are found in the Holocene Irrawaddy alluvial aquifer beyond the extent of that modelled to be of increased risk by Winkel et al. (2008). Of the Myanmar aquifers, those in the Holocene alluvium/delta accessed by tubewells appear to be the most vulnerable to arsenic contamination. This is a notable drawback for tubewell drilling programmes that seek to provide drinking water from a freshwater aquifer with abundant supplies at shallow depth. Reports vary on the vulnerability to contamination of shallow dug wells in this aquifer, but most appear to be low in arsenic. Groundwater from the underlying Irrawaddy Formation appears to be not or less contaminated.

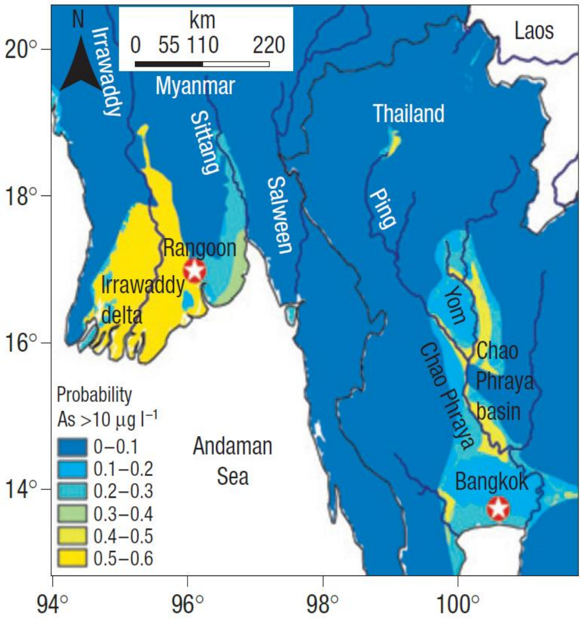

Figure 4. Map showing the probability of arsenic (modelled) in groundwater with concentrations >10 μg/L from the southern Irrawaddy Basin of Myanmar (reprinted by permission from Springer, from Winkel et al., 2008).

Few data for arsenic appear to be available for groundwater from other aquifer types. Igneous, metamorphic and fine-grained sedimentary rocks are also potentially vulnerable to arsenic contamination, especially in mining/mineralised areas where sulphide minerals are present and could oxidise to release arsenic into solution. Testing for arsenic more broadly across aquifers in Myanmar is advisable and should be routine for any new groundwater resource development.

Iodine

Healthcare efforts during the 1970s–1990s saw an eradication of iodine-deficiency disorders among populations in Myanmar, although maintenance of salt iodinisation programmes since has apparently not been rigorous (WHO, 2014). No data are available for iodine in groundwater and so evaluating the concentrations in different geological settings is not possible. Concentrations would be expected to be lowest in the freshwater aquifers and higher in the saline groundwater close to the coast and delta and within the Pegu Group. Compared to dietary influences, drinking-water iodine concentrations are unlikely to impact on iodine-deficiency outcomes.

Other trace elements

In the small study (6 samples) of the Irrawaddy alluvial aquifer of Tha Pyay Tha village (Myingyan Township) conducted by Bacquart et al. (2015), other trace elements tested for and worthy of note included the uniformly low concentrations of uranium (<1 μg/L) and selenium (<5 μg/L). These are in line with the inferred anaerobic conditions of the groundwater in this aquifer. Molybdenum was not tested for in the study but data from other analogous aquifers (e.g. the alluvial aquifer of Bangladesh) would suggest potential for elevated concentrations, possibly approaching or exceeding the WHO (2017) health-based value for drinking water of 70 μg/L.

The Bacquart et al. (2015) study found concentrations of uranium in the 12 groundwater samples from Myingyan City from the Irrawaddy Formation in the range 5–45 μg/L (median 13 μg/L). Some exceedances of uranium above the WHO guideline value of 30 μg/L therefore occur in the Irrawaddy Formation. Concentrations of selenium were also mostly <5 μg/L but ranged up to 14 μg/L. The highest value is elevated but not in excess of the WHO (2017) guideline value. Concentrations of chromium were <30 μg/L, lead ≤2 μg/L, boron <400 μg/L and barium <300 μg/L in all groundwater samples (18 in total) from the Bacquart et al. (2015) study.

No other data for these trace elements appear to be available for remaining aquifers across the country. Although there is no evidence for widespread occurrence of uranium or selenium in the groundwater, the limited results for the Irrawaddy Formation support the case for testing for them in water monitoring programmes.

The prevalence of mining and metal mineralised zones across many areas of Myanmar means that the probability of observing elevated concentrations of trace metals in groundwater is increased, at least locally. Of the trace metals in mineralised areas listed above, mobilisation of antimony, copper, lead, nickel and zinc is possible and merits further scrutiny. Porphyry copper deposits worldwide are also recognised sources of dissolved molybdenum. Molybdenum concentrations in groundwater around the Monywa porphyry copper deposit require particular attention.

Unregulated artisanal gold exploration occurs in sulphide mineralised areas and from alluvial placer deposits in the middle Irrawaddy basin. Mercury has been used in these operations and although most is recovered, contamination with mercury of river sediments and fish, though not water, has been reported (Osawa and Hatsukawa, 2015). Any mercury contamination of groundwater is likely to be a local phenomenon in line with the scale of artisanal activities, but reconnaissance analysis would be prudent.

Little information is available so far for the trace metals described above in groundwater across Myanmar. A large number of them can be readily measured together using ICP-MS instrumentation which would greatly increase the database of available information in vulnerable areas at marginal additional cost.

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