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Assessment of transboundary aquifer resources in Asia: Status and progress towards sustainable groundwater management

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ABSTRACT

Study region: Asia.
Study focus: Internationally shared aquifers (Transboundary aquifers; TBAs) are recognised as an important water resource in Asia. Despite their importance, studies on the assessment of TBA resources have received less attention in comparison to transboundary rivers. A lack of expertise, experience, and institutional support has restricted the cooperative and sustainable management of the shared aquifer resources. This study attempts to provide a comprehensive overview of the status of transboundary groundwater resources in Asia, including the TBA inventories, socio-economic implications, and future perspectives. Specifically, the study focuses on the progress of the assessment of TBAs in Asia as a result of the Internationally Shared Aquifer Resources Management Initiative (ISRAM).
New hydrological insights for the region: In Asia, TBAs have played a major role in providing freshwater resources and sustaining socio-economic development. Since 2000, many regional cooperative initiatives have achieved considerable progress in developing TBA inventories of Asia, but the level of understanding of the shared aquifer systems remains limited, particularly for the developing countries. Legal and institutional frameworks for regional TBA cooperation are vital, and many countries in Asia have come to recognise the need to cooperate with their neighbours in dealing with TBA governance. Sustainable and equitable management of TBA in Asia requires an increasing effort from different sectors and countries in order to reach mutual acceptance of effective cooperation.

1. Introduction

Groundwater resources play an important role in sustaining water needs of Asia. Groundwater is widely adopted for crop irrigation, food production, industry, and domestic use in urban and rural communities, accounting for about 25% of total water usage in Asia (FAO, 2016). The groundwater withdrawal amount in Asia accounts for the majority (72%) of global usage value, caused by intensive agricultural activities and explosive population growth over the region including Bangladesh, China, India, Iran, and Pakistan (FAO, 2016; Gleeson et al., 2012; Shah, 2005). Groundwater also provides a valuable base flow, supplying water to rivers, lakes, and wetlands, thus serving as an essential resource for maintaining various ecosystems that depend on it (Bernadez et al., 1993;

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Danielopol et al., 2003; Kløve et al., 2014; Wösten et al., 2008). Apart from its environmental function, groundwater has significant socio-economic implications. For instance, it was estimated that groundwater irrigation in Asia contributes US$10 to US$30 billion per year to its economy (Shah et al., 2003; WWAP, 2015).

Transboundary aquifers (TBAs), like transboundary rivers, serve as vital sources of water upon which large numbers of people rely. Throughout Asia, complex relationships occur between upstream recharge areas and downstream regions across international borders, and the effective management of TBAs is of particular importance for the region. Despite their significance, TBAs have received less attention from policy makers, scientists, and local communities due to their hidden, diverse nature and the difficulty in conducting hydrological investigations across international borders. Consequently, there are substantial gaps in the water policies or agreements to manage these TBAs at international level. Given the significant contribution of TBAs to global water resources, their sustainable and equitable management should be undertaken based on international acceptance for effective cooperation among all relevant stakeholders.

In 2000, the UNESCO International Hydrological Programme (IHP) and the International Association of Hydrogeologists (IAH), in collaboration with the Food and Agriculture Organization (FAO) and the United Nations Economic Commission for Europe (UNECE), implemented an interagency collaboration programme (ISARM: Internationally Shared Aquifer Resource Management) aimed at improving the understanding of scientific, socio-economic, legal, institutional, and environmental issues related to the management of TBAs (Puri and Aureli, 2005). Since then, substantial multiagency efforts together with several regional initiatives have been made to develop TBA inventories, assess global TBA systems, and suggest legal and institutional frameworks in order to manage internationally shared groundwater resources in a sustainable manner (Puri et al., 2001; Puri and Aureli, 2005; UNECE, 2000, 2001; UNESCO 2004, 2010a). In Asia, regional collaboration initiatives have been implemented and considerable progress has been achieved in terms of the regional TBA inventories, understanding the status of groundwater resources, and engagement of the relevant (inter)national communities for TBA management (UNESCO, 2006, 2010b; TWAP, 2014; Zaisheng et al., 2008, 2013).

The objectives of this paper are: 1) to provide a comprehensive overview of the status and inventories of TBA resources in Asia; and 2) to summarise the progress of TBA management in Asia, focusing on hydrogeological and institutional achievements and future perspectives.

2. Status of TBAs in asia

2.1. Groundwater in Asia

Asia is the largest continent in the world in terms of both area (43.5 million km^2) and population (3.5 billion). It borders the Pacific Ocean in the east, Arctic Ocean in the north, the Indian Ocean in the south, and the Mediterranean Sea in the west, respectively. Asia is notable for dense and large settlements, including some of the most populous countries in the world, such as China, India, Indonesia, Pakistan, Bangladesh, and Japan (UN DESA, 2015). Asia is also characterised by extremely diverse climate zones and geographic features. Climates range from Arctic in Siberia to tropical in Southeast Asia and Southern India. The monsoon circulation dominates across Southeast Asia, South Asia, and the southeastern part of East Asia while Central Asia, Western Asia, and the inland regions of East Asia are in the arid zone. Precipitation also varies depending on the location and climate zone. Annual rainfall near the equator zones is more than 2000 mm/year whereas many parts of Southwest and Central Asia have precipitation rates of less than 150 mm/year (Zaisheng et al., 2013). There are several vast deserts in the inland regions of Asia, such as the Gobi Desert in Mongolia and the Arabian Desert in the Middle East. With respect to geographical features, the Himalayas, located between Nepal and China, is the tallest mountain range in the world. Some of the world's largest rivers are located in Asia, including the Ganges and the Brahmaputra (India), Yangtze (China), Yenisey, Lena, Ob, Amur (Russian Federation), and Mekong (South-East Asia).

Fig. 1 illustrates the hydrogeological mapping results from the China Geological Survey (CGS) on a 1:8 million scale (CGS, 2012). The occurrence of groundwater resources varies across Asia. Sedimentary aquifers, mainly composed of floodplain alluvial deposits, are developed along large rivers such as the Ganges, Yangtze, and Mekong. These aquifers are generally thick with good storage space, providing favourable conditions for groundwater development. Groundwater productivity (yield) from the sedimentary aquifers in West Asia, on the other hand, is generally low and these aquifers have very limited groundwater recharge sources. In the mountainous regions of Central and Northern Asia, groundwater generally occurs in complexes of joint hard rocks. Although there is little rainfall and strong evaporation in the inland arid areas of Central Asia, the thawing of glaciers and snow in the high mountains is favourable to groundwater recharge (UNESCO, 2010b). The carbonate rocks are widely distributed in Southeast Asia. In southern China and in some parts of the Indochina peninsula, there is stratified limestone from the late Paleozoic and Mesozoic eras in which karst systems are considerably developed. A lot of Quaternary volcanic rock is extensively distributed on the circum-Pacific islands.

Groundwater serves as an important source of freshwater supply in Asia. According to a statistical analysis on global water usage by FAO (FAO, 2016), total groundwater abstraction in Asia accounts for approximately 72% (6.1×10^{11} m^3/year) of global usage (8.5×10^{11} m^3/year). The results also show that eight out of ten countries with the largest groundwater extraction are located in Asia; India, China, Nepal, Bangladesh, and Pakistan, alone account for nearly half of world's total groundwater use, mostly associated with a huge population and intensive agricultural activities. Many countries in Western and Central Asia mainly rely on groundwater for water supply. In Bangladesh and Mongolia, about 80% of total water withdrawal comes from groundwater. Several countries in Western Asia with no permanent rivers (Saudi Arabia, United Arab Emirates, Oman, Kuwait, Bahrain, and Qatar) rely on groundwater for almost 100% of their renewable water source.

Groundwater extraction has increased greatly in Asia, particularly since the 1970s. Global estimates on the sustainability of groundwater usage strongly indicate that current groundwater consumption for some regions in Asia such as the upper Ganges River

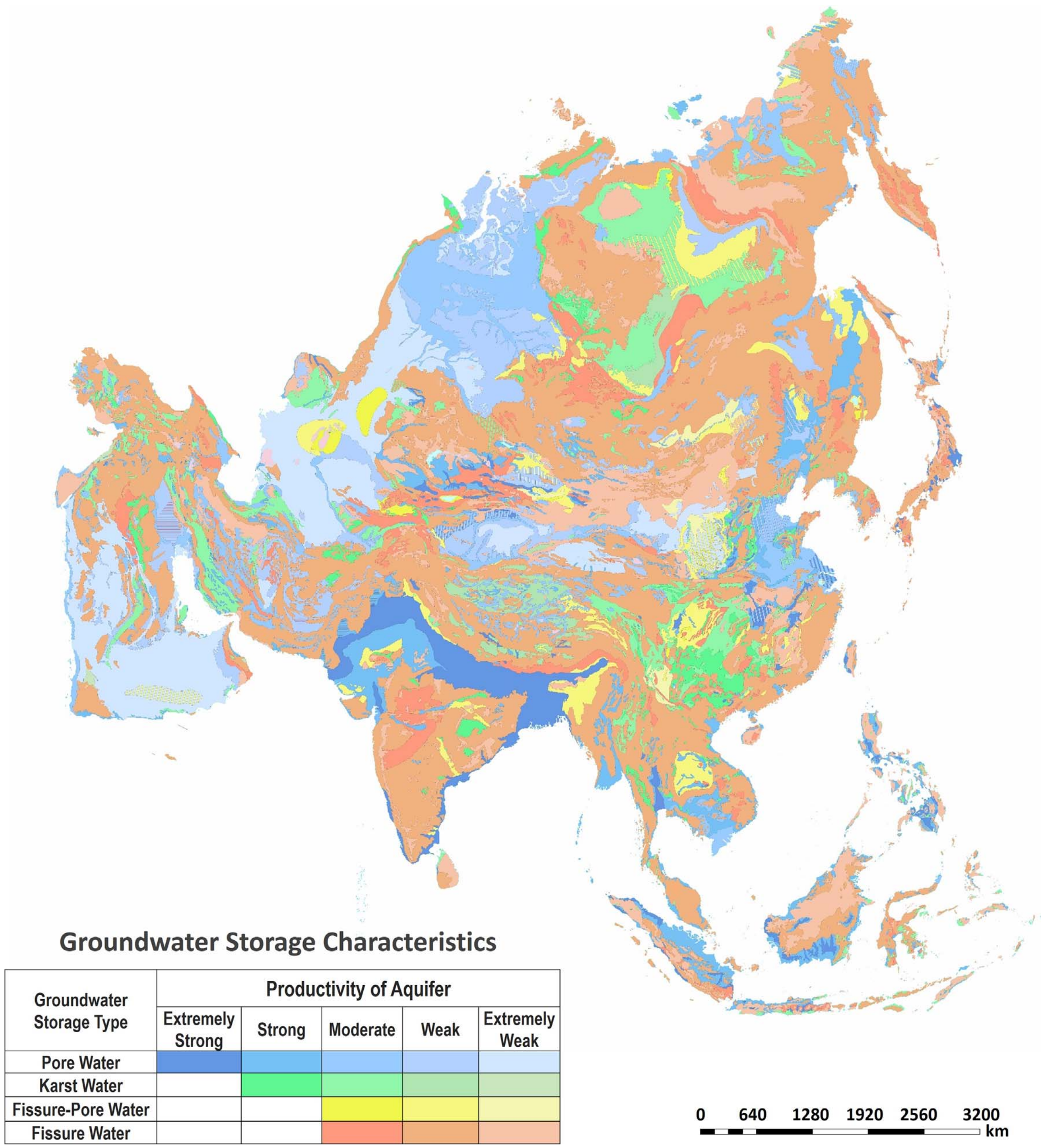

Fig. 1. Hydrogeology Map of Asia (Scale: 1: 8 000 000, modified from CGS (2012)).

Basin or North China Plain is likely to face serious aquifer depletion and water shortage problems (Gleeson et al., 2012). For instance, the groundwater extraction rate in China has increased from $57 \times 10^9\, m^3$/year in the 1970s to $111 \times 10^9\, m^3$/year in the 2000s, causing many serious environmental issues such as groundwater depletion or land subsidence (UNESCO, 2006). In Northern India, satellite-based estimates of groundwater storage-change suggest that groundwater is being depleted over the area at a rate of approximately $17.7 \pm 4.5\, km^3$/yr, which is double the capacity of India's largest surface-water reservoir (Rodell et al., 2009). Consequently, without proper measures being taken to ensure sustainable groundwater usage, over 100 million residents of the region may suffer a serious reduction in agricultural output and a shortage of potable water, leading to extensive socio-economic stress. In Thailand, the increasingly heavy pumping of groundwater in Bangkok between 1955 and 1982 caused a decline of 45–50 m in groundwater levels. The lowering of water levels by these depths resulted in abandonment of old wells, increased pumping costs, and land subsidence problems (Gupta and Babel, 2005; Phien-wej et al., 2006). Vietnam has also suffered from serious groundwater depletion caused by the unsustainable consumption of groundwater for irrigation and other anthropogenic use (Erban et al., 2014).

In terms of groundwater quality, a high arsenic content is easily observed in many regions of Asia. In Bangladesh and the neighbouring Indian States of Western Bengal, a high level of arsenic in the groundwater used for drinking has become a massive

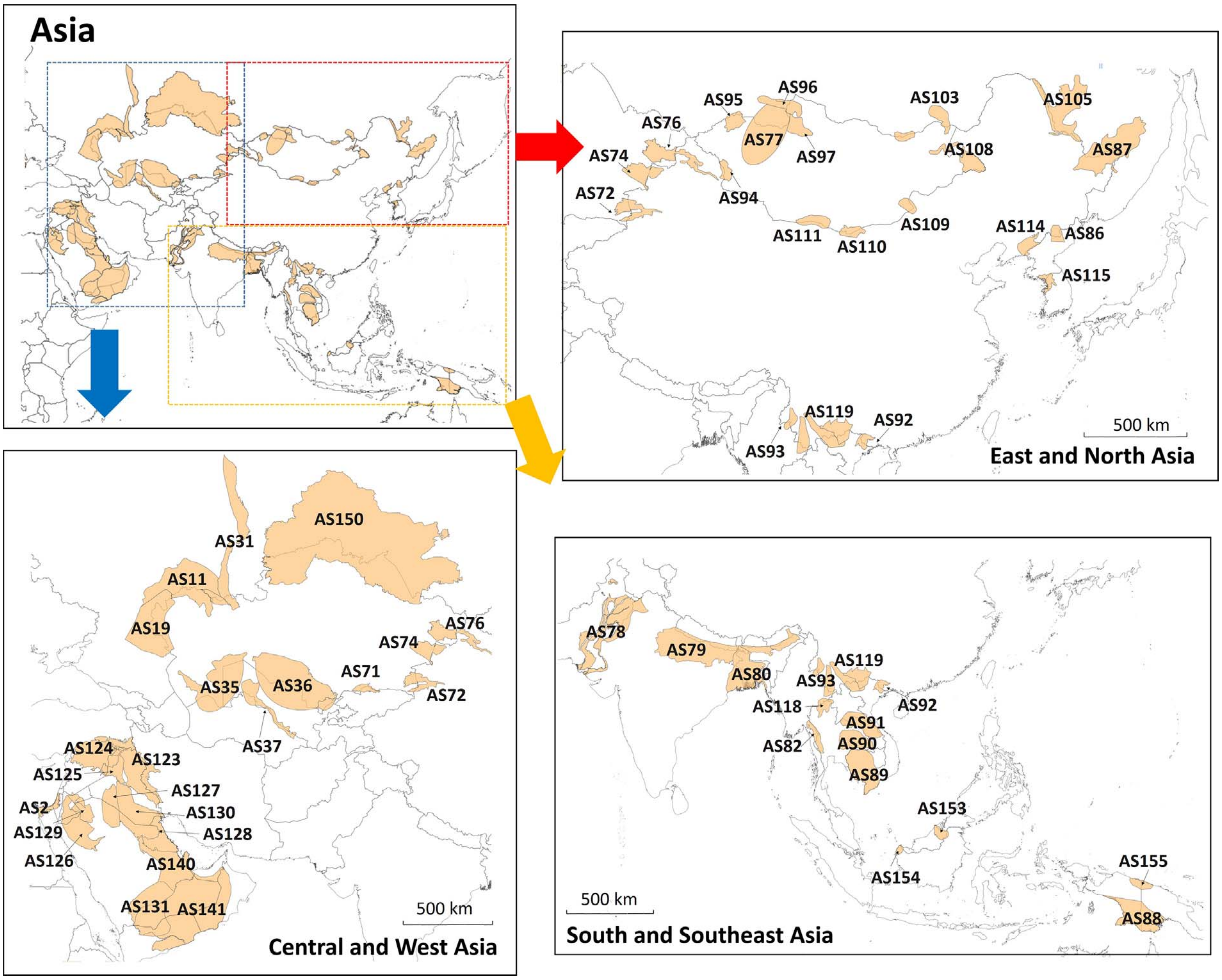

Fig. 2. Map of major Transboundary Aquifers (TBAs) (Area > 10,000 km^2) in Asia and the international codes (label) of the TBAs (modified from IGRAC (2015)).

public health issue (Brikowski et al., 2014 Nickson et al., 1998). Previous research suggests that about 35 million people in these areas are at risk of being exposed to arsenic poisoning through drinking groundwater (Chowdhury et al., 1999; Hasan et al., 2009; Harvey, 2008; Radloff et al., 2011; Shukla et al., 2010). In China, groundwater with a high arsenic level was found in Inner Mongolia and other areas (Rodríguez-Lado et al., 2013). In Southeast Asia, groundwater contamination by arsenic was observed mostly in the alluvial aquifers along major rivers such as the Mekong Delta in the southern part of Vietnam and Cambodia (Erban et al., 2013; Fendorf et al., 2010). With an increase in economic activity, groundwater quality deterioration frequently occurs in Asia as a result of industrial, agricultural, and subsistence pollution (Singh et al., 1995; Hosono et al., 2011; Taniguchi et al., 2008).

2.2. Inventory of TBAs in Asia

An updated inventory of global TBAs identified 129 shared aquifers in Asia (IGRAC, 2015). The total area of TBAs in Asia measures approximately 9 million km^2, covering about 20% of the entire region. According to the global TBA inventory, a total of 38 countries in Asia are identified as having internationally shared aquifer basins. In terms of TBA numbers, most TBA basins in Central Asia are shared with neighbouring countries. Uzbekistan shares the most TBA basins (total number: 31), followed by China (21), Russia (21), Tajikistan (15), Kyrgyzstan (14), Kazakhstan (14), Mongolia (14), Azerbaijan (13), and Iran (10). Fig. 2 illustrates the location of major TBAs (area > 10,000 km^2) together with their international codes. In terms of single TBAs, the Iryhsh-Obsky Aquifer Basin (AS150) between Russia and Kazakhstan is the largest (1,368,000 km^2), followed by AS141 (Umm er Radhuma-Damman Aquifer (South) between the United Arab Emirates and Yemen), AS131 (Wajid Aquifer System between Saudi Arabia and Yemen), AS36 (Syr Darya Aquifer between Kazakhstan and Uzbekistan), and AS79 (South of the Outer Himalayas Aquifer between India and Nepal). The major aquifer lithology of the TBA is composed of porous layers or a combination of porous and fissured sedimentary rocks, which are associated with relatively high groundwater productivity of these geologic units.

Table 1 presents a list of the major TBAs in Asia requiring attention in terms of a reduction in available groundwater resources. In Table 1, TBAs are selected with an aquifer stress index (AQSI; defined as groundwater exploitation rate divided by aquifer recharge)

Table 1
Transbounday aquifers in Asia.

Label	Aquifer Name	Neighbouring Countries	Area (km^2)	Major aquifer type
AS4	Anti-Lebanon	Lebanon, Syria	3850	Sedimentary rock –limestone
AS11	Syrt	Russia, Kazahstan	229,174	Sediment-sand
AS47	Pretashkent Aquifer	Kazakhstan, Uzbekistan	21,472	Sediment-sand
AS72	Illi River	Kazakhstan, China	46,124	Sediment/Sedimentary rock- sandstone
AS74	Tacheng Basin/Alakol	Kazakhstan, China	47,763	Sediment- sand and gravel
AS76	Ertix River	Kazakhstan, China	66,282	Sediment- sand and gravel
AS77	Yenisei Upstream	Mongolia, Russia	190,456	Sedimentary rock
AS78	Indus River Plain Aquifer	Pakistan, India	311,632	Sediment-sand
AS79	South of outer Himalayas Aquifer	India, Nepal	373,250	Sediment-sand
AS80	East Ganges River Plain Aquifer	Bangladesh, India	215,568	Sediment-sand
AS82	Salween River Aquifer	Myanmar, Thailand	38,362	Sedimentary rock-sandstone
AS89	Cambodia- Mekong River Delta Aquifer	Cambodia, Vietnam	204,077	Sediment- sand, gravel, silt
AS90	Khorat Plateau Aquifer	Laos, Thailand	108,529	Sedimentary rock- sandstone/siltstone
AS91	Lower Mekong River2 Aquifer	Thailand, Lao PDR, Vietnam	122,216	Sedimentary rock- sandstone/siltstone
AS118	Lower Mekong River 1 Aquifer	Myanmar, Thailand, Lao PDR	36,769	Sedimentary rock – limestone
AS125	Neogene Aquifer System (North-West): Upper and Lower Fars	Syrian Arab Republic, Iraq	84,298	Sedimentary rock – sandstones, limestone, dolomites, marls and gypsum
AS126	Saq-Ram Aquifer System (West)	Jordan, Saudi Arabia	184,518	Sedimentary rock – sandstone
AS127	Wasia-Biyadh-Aruma Aquifer System (North): Sakaka-Rutba	Saudi Arabia, Iraq	103,778	Sedimentary rock – sandstone
AS128	Neogene Aquifer System (South-East): Dibdibba- Kuwait Group	Iraq, Kuwait, Saudi Arabia	179,370	Sediment- sand
AS129	Tawil Quaternary Aquifer System: Wadi Sirhan Basin	Jordan, Saudi Arabia	56,039	Sedimentary/Crystalline rock
AS130	Umm er Radhuma-Dammam Aquifer System (North): Widyan-Salman	Iraq, Kuwait, Saudi Arabia	297,943	Sedimentary rock- limestone and dolomites
AS131	Wajid Aquifer System	Saudi Arabia, Yemen	427,125	Sedimentary rock- Sandstone
AS140	Umm er Radhuma-Dammam Aquifer System (Centre): Gulf	Saudi Arabia, United Arab Emirates, Bahrain, Qatar	345,213	Sedimentary rock- limestone and dolomites
AS141	Umm er Radhuma-Damma-Aquifer System (South): Rub'al Khali	United Arab Emirates, Yemen	797,877	Sedimentary rock- sandstone and dolomites
AS143	Basalt Aquifer System (South): Azraq-Dhuleil Basin	Jordan, Syria	10,503	Crystaline/Sedimentary rock

greater than 50% (0.5) or aquifers where notable rates of groundwater level decrease were reported (IGRAC, 2015; TWAP, 2014; Wada and Heinrich, 2013). Some important TBAs in the region might not be included in the list, mainly due to the lack of available data. Despite this lack, it is apparent that groundwater is aggressively exploited in many parts of the TBAs, leading to increased aquifer vulnerability and unsustainable aquifer management conditions. Gleeson et al. (2012) and Wada and Heinrich (2013) reported that over the Indus River Plan (AS78 in Table 1), the groundwater extraction rate from the TBA exceeded its natural replenishment significantly, implying that current groundwater consumption cannot be maintained sustainably. Due to the rapid expansion of human activities, groundwater resources from the TBAs in Western Asia (AS125 – 131, 140, 143 etc.) are also vastly over-exploited. The AQSI for these aquifers has increased more than 250% over the last 50 years (Wada and Heinrich, 2013). For example, in the Saq-Ram Aquifer System (AS126) between Saudi Arabia and Jordan, the groundwater extraction rate has dramatically increased since 1980 in order to support wheat production and the domestic water supply, resulting in a reversal of the groundwater flow field between the two countries. Several TBAs in Central Asia (AS11, 77, 80, etc.) have also experienced similar problems. In Southeast Asia, the increasing abstraction of groundwater in the Mekong Delta (AS89) region has resulted in continuous depletion of groundwater resources and related environmental issues such as land subsidence; Ho Chi Minh City suffered the greatest land subsidence in the delta region (> 4 cm/yr) (Erban et al., 2014).

The groundwater quality of TBAs in Asia showed varying characteristics depending on climate, geological medium, and human activities. The regional TBA survey carried out by TWAP (Transboundary Water Assessment Programme) identified that among 25 TBAs in South, Southeast and East Asia, almost 50% of the region's TBAs are suitable for human consumption (TWAP, 2014). Some TBAs, on the other hand, showed serious groundwater quality problems. In the Indus River Plain Aquifer (AS78), it was estimated that about 80% of the aquifer area within the Pakistan territory is unsuitable for human consumption as a result of elevated amounts of natural salinity as well as high levels of fluoride and arsenic. Several TBAs in Western Asia (AS125, 128, 130, 141, etc.) also do not satisfy water drinking standards, mainly due to the natural salinity and continuous deterioration of groundwater quality by human activity. In the case of the Mekong Delta aquifer on the Vietnam side (AS89), intensive groundwater extraction for agricultural activities has led to seawater intrusion into the aquifer. Elevated nitrate concentration caused by excessive use of fertilisers is another rising issue for groundwater quality management of the TBAs (TWAP, 2014; UNESCO, 2010b).

3. Socio-economic implication of TBAs

Groundwater plays a significant role in socio-economic development and provides numerous benefits including drinking water supply, mitigation of natural disasters, increased food production job creation, and livelihood enhancement. These benefits are closely linked to the inherent characteristics of groundwater as a resource. For instance, the high buffering capacities of aquifers against climate variations help to stabilise the water supply for human consumption or agricultural activities during peak drought seasons. The almost ubiquitous availability of groundwater makes it easy to access and provides a valuable source of drinking water. In some regions, a significant proportion of the economy is attributed to tourism such as groundwater springs, which generate revenue for local business and create jobs (WWAP, 2016).

The social and economic benefits of groundwater are of particular importance to the agricultural activities of Asia. Agriculture is the key to general economic development, especially in many Asian developing countries. Global estimates suggest that irrigated agriculture accounts for approximately 79% of the total water withdrawals in Asia, which is higher than the global average of 70% (FAO, 2016; WWAP, 2016). Groundwater has served as an important source of irrigation for Asia, contributing towards food security and alleviating poverty in the region. About 38% of the total irrigated area in Asia is estimated to rely on groundwater resources for water supply (FAO, 2016). The considerable dependence of agricultural practices on groundwater is highly attributed to the increase in food productivity or lack of an available surface water resource, particularly in Central and Western Asia. For example, India, with the explosive growth in population (increasing by 190% between 1960 and 2015), the overall food production index of the nation was boosted by approximately 330% (DataSource: http://data.worldbank.org/). Groundwater is a critical component for achieving dramatic food production growth, serving about 60% of the irrigated areas (Shah, 2007). In Pakistan, groundwater is known to provide about 40% of the total water requirements for irrigation (Qureshi and Barrett-Lennard, 1998). Water use for irrigation activity is also inextricably linked to job creation. Employment rates in the agricultural sector are 39% in South-East Asia and 44.5% in South and South-West Asia, respectively (ILO, 2014; WWAP 2016). In India, it has been estimated that more than half of the total workforce remains in the agricultural sector (Chand and Parappurathu, 2012). Some evidence suggests that a casual link between local GDP and groundwater abstraction exists in the major cities of Asia. Consequently, groundwater aids urban growth and its rapid economic development (IGES, 2007).

The role of TBAs in Asia cannot be separated from the social and socio-economic development aspects. Despite a lack of proper estimation, the simple combination of national population density data and areal extent of TBAs suggests that more than 500 million people in Asia reside in TBA regions (Data Source: www.un-igrac.org). Several agricultural systems of global importance are also located in shared aquifer basins such as the East Ganges River Plain Aquifer (AS80), Cambodia-Mekong River Delta Aquifer (AS89), etc. In these basins, groundwater has contributed significantly to growth in irrigated areas and agriculture productivity. For most of the TBAs in West Asia region (AS125-131, 140-141, 143), groundwater is vastly exploited for domestic and agricultural use. In China, groundwater from the Illi River Basin Aquifer (AS72) has sustained the socio-economic development of the Xinjiang Province in China and regions with large populations in Kazakhstan (Zaisheng et al., 2008).

However, the intensive use of shared groundwater resources has led to simultaneous aquifer depletion and pollution. In India's East Ganges River Plain Basin, the increased water demand associated with intensive cultivation such as rice-wheat rotation has resulted in salinity, water logging, and groundwater depletion problems (Pingali and Shah, 2001). The over-exploitation of groundwater in the TBAs between Lebanon and Syria (AS4) has caused gradual decreases in the discharge of freshwater springs which have served as the main source of drinking water supply to the nearby city (Damascus). For TBAs between Jordan and Saudi Arabia (AS129), a serious overdraft of fresh groundwater from the large commercial farms in the Saudi part has reportedly led to an increase in groundwater salinity, and now poses a long-term negative impact on the groundwater quality in both the upstream (Saudi) and the downstream (Jordanian) of the TBA (IGRAC, 2017).

4. Legal and institutional frameworks for TBA management in Asia

Given the significant role of TBAs in linking hydrological, social, and economic sectors between neighbouring countries, the issues relating to shared aquifer management should be dealt with by institutional and legal frameworks, based on the mutual agreement of relevant stakeholders. Although the importance of TBAs components of global water resource systems has been recognised recently, the issues have been scarcely addressed in international water policy, legislation, and institutional instruments (Puri and Aureli, 2005). Many countries do not have legal and institutional instruments to regulate the use of groundwater resources and only limited bilateral agreements exist for TBA resources management. Consequently, there are few legal instruments to address the specific characteristics of TBAs and their sustainable management at global and international level. Similarly, most countries in Asia have also shown a substantial lack of water policies for dealing with internationally shared groundwater resources.

Since the early 2000s, numerous international efforts have been made to raise awareness in policy and decision makers regarding the significance of TBAs and the need for a legal/institutional framework to promote the sustainable use of shared aquifer resources. In Asia, several regional initiatives have been launched for compiling a regional hydrogeological inventory and analysing legal/institutional frameworks for TBA management cooperation (CGS, 2012; He, 2017; IGRAC, 2015; TWAP, 2014; UNESCO, 2006, 2010b; Zaisheng et al., 2008, 2013). The recent regional survey about legal/institutional instruments for TBA cooperation in Asia has been addressed in selected literature (ESCWA, 2009; TWAP, 2014). The results of this regional survey indicated that many TBAs bordering China or Mongolia are the subject of signed bilateral agreements, although the scope of the issues covered varies in each case. China, in particular, has endeavoured to cooperate internationally in shared water resource management by establishing TBA institutes as well as creating mutual agreements with its neighbours. Most of these signed bilateral agreements, however, do not explicitly cover groundwater (He, 2017) and need to be ratified. In West Asia, no formal agreements exist for most of the TBAs. With increased awareness towards water security and sustainability issues, countries are beginning to recognise the importance of their TBAs and the need to cooperate with their neighbours. Recently, for example, mutual negotiation has been initiated between Jordan and Saudi Arabia for sustainable use of the Saq-Ram Aquifer System (AS126) straddling across the two countries (ESCWA, 2009), which is a significant milestone. In the Mekong Region, the Mekong River Commission provides a platform for TBA cooperation, although less attention has been paid to transboundary groundwater resources (Bach et al., 2014). At national level, there are institutions specialising in groundwater resources management including transboundary groundwater issues, but the extent of the mandate and its capacity is uncertain. For example, in Pakistan, a national institute exists with a mandate and the capacity for TBA management, but the regulations on groundwater abstraction and quality management are quite limited (IGRAC, 2017).

The stress on fresh water from climate change and anthropogenic activities is expected to increase the risk of freshwater security. These challenges on water shortage and quality deterioration will likely exacerbate tensions between countries. Transboundary groundwater resources, like transboundary rivers and lakes, can have significant impacts on international relationships, regional stability, and economic development (He, 2017). Therefore, international cooperation for TBA identification, assessment, and governance mechanisms is important to ensure the sustainability and security of future global water resources. Given the significant contribution of groundwater resources to the water supply and socio-economic development of Asia, it is necessary to foster cooperation for TBA management within the context of international groundwater governance and institutional support beyond national borders.

5. Case Studies: status and management of TBAs in the Greater Mekong Subregion (GMS)

5.1. Groundwater in GMS

The Greater Mekong Subregion (GMS) is an international zone of the Mekong River Basin in Southeast Asia. The Mekong River is the longest river in Southeast Asia, the seventh longest in Asia, and the twelfth longest in the world. Bounded by the natural river basin, the environment, culture, and livelihood of the GMS countries (Cambodia, Lao PDR, Myanmar, Thailand, and Vietnam) are closely linked to each other. Groundwater resources in the GMS have been regarded as increasingly important, providing water for drinking, irrigation, and industry as well as supporting natural river water flows and relevant ecosystems (Eastham et al., 2008; Landon, 2011).

The climate of GMS shows strong spatial and temporal variations. In general, both temperature and precipitation tend to increase from north to south. The entire basin is under the influence of the southwest monsoon with distinct wet and dry seasons. The rainfall is not uniformly distributed; about 80% of the total precipitation is concentrated during the wet season. Heavy rains mainly occur in the mid period of the wet season, occasionally leading to severe flooding (MRC, 2005, 2010). Water scarcity during the dry season can be acute in parts of the basin (Eastham et al., 2008). Most of the flow in the Mekong River system is derived from the surface runoff of precipitation, followed by groundwater base flow and snowmelt.

An overview of the hydrogeological setting of the GMS has been presented in several previous studies (Charuratna and Phu, 1992; CGS, 2012; Johnson, 1986; Landon, 2011; Workman, 1970). The upper part of the river basin in China is characterised by the fissured rocks or karst aquifer whereas the delta region (Mekong Delta) is extensively covered by unconsolidated alluvial sediments, extending from the coast to the northwest in Cambodia, including the Tonle Sap Lake (Fig. 3). In the delta region, the thickness of the alluvial sediment is large and these units are characterised as the primary aquifer. Along the central part of the basin, consolidated rock units (basalt, limestone, fissured sandstone, etc.) serve as localised aquifers with high potential groundwater yield (Landon, 2011; UNESCO, 2010b).

In the lower basin of the Mekong River, groundwater provides water for approximately 60 million people (MRC, 2010). Frequent water shortage problems in this area are normally managed by increasing the supply from groundwater resources, particularly during the dry season. For this reason, TBAs in the GMS receives increased attention from national stakeholders and international communities.

5.2. TBAs distribution in GMS

Several important TBAs straddle along the GMS area, including the Cambodia-Mekong River Delta Aquifer (AS89), Khorat Plateau Aquifer (AS90), and Lower Mekong River 2 Aquifer (AS91), etc. Fig. 4 illustrates the locations of TBAs in the GMS (IGRAC, 2015). Details of major TBAs in the regions are described in the following section.

5.2.1. Cambodia-Mekong River delta aquifer (AS89)

The aquifer is shared by Cambodia and Vietnam, extending from Dan Bian Mountain in Cambodia to Mekong River. The whole area is approximately 200,000 km^2 and about 63% of the TBAs lie within the Cambodian territory. Tonle Sap, the largest lake in the Indochina Peninsular, is hydraulically connected to the Mekong River and serves as a natural regulating reservoir (Burnett et al., 2017; Kummu et al., 2014; Masumoto et al., 2008).

The annual precipitation is between 1400 and 2200 mm/year, with a subtropical climate pattern. Situated in the delta region, the TBA shows the typical characteristics of an alluvial aquifer. The aquifer consists of Quaternary sediment with a varying depth (up to 800 m). The lithology of the aquifer in the delta region is divided into eight alluvial units (multi-layered) separated by interbedded clay units (Fig. 5). Each alluvial unit is deposited during different geological times: from Miocene to Holocene. Although groundwater is abstracted from all aquifers, the Upper-Middle Pleistocene and Middle Pliocene Aquifers are considered to be the two primary groundwater production aquifers (Vuong et al., 2016).

The groundwater resources in this TBA have a considerable impact on human livelihoods and socio-economic development. In

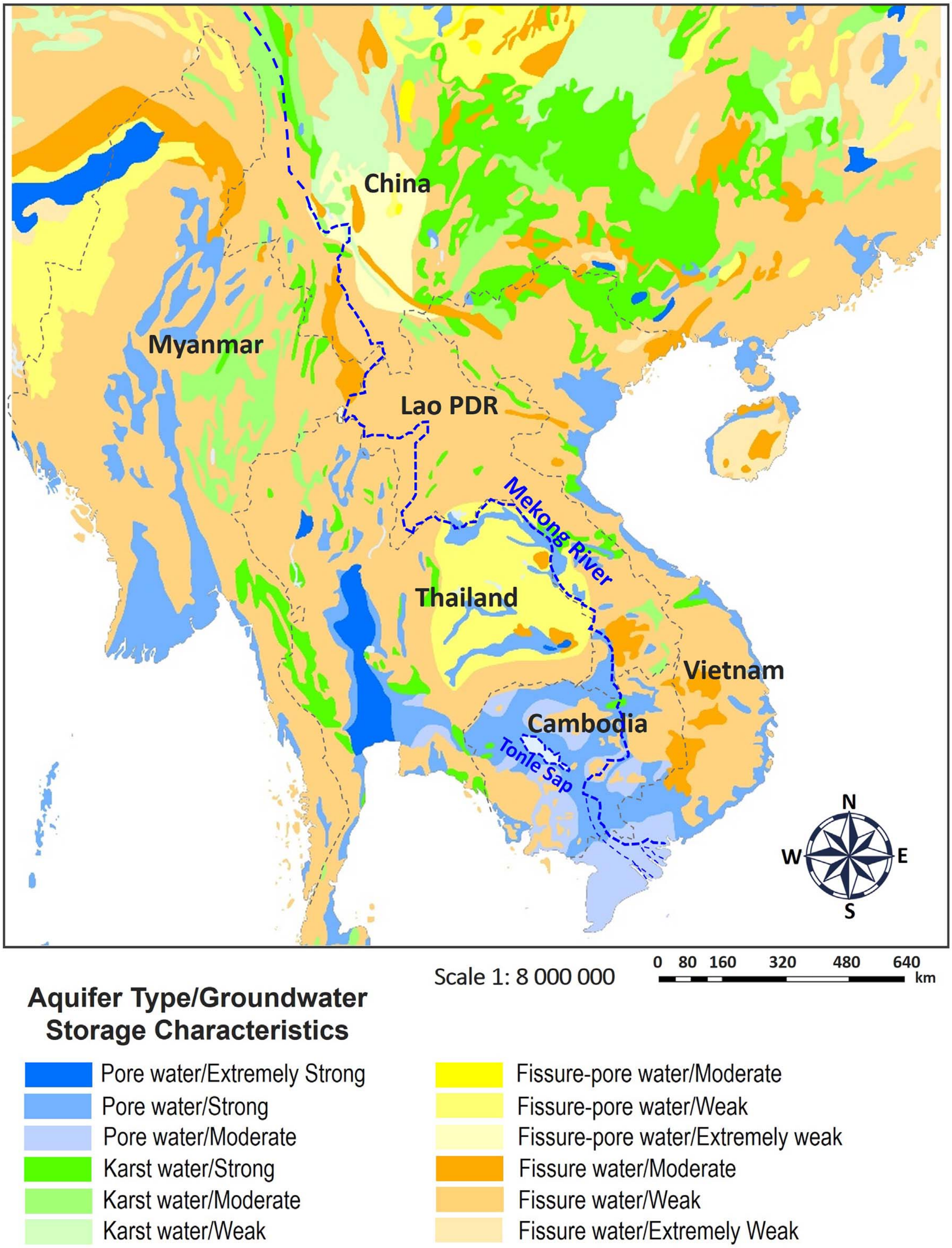

Fig. 3. Hydrogeology Map of Greater Mekong Subregion (modified from CGS (2012)).

major cities, such as Phnom Penh and some other cities in Vietnam, groundwater is utilised for urban water supply. In Vietnam, rice production from the delta regions makes a substantial contribution to the national GDP, including half of Vietnam's rice production and more than 80% of rice exports (UNESCO, 2010b). In Cambodia, the agriculture sector accounts for half of the GDP and employs 80–85% of the labour force. For these reasons, the aquifers are heavily exploited for irrigation and water supply. The annual

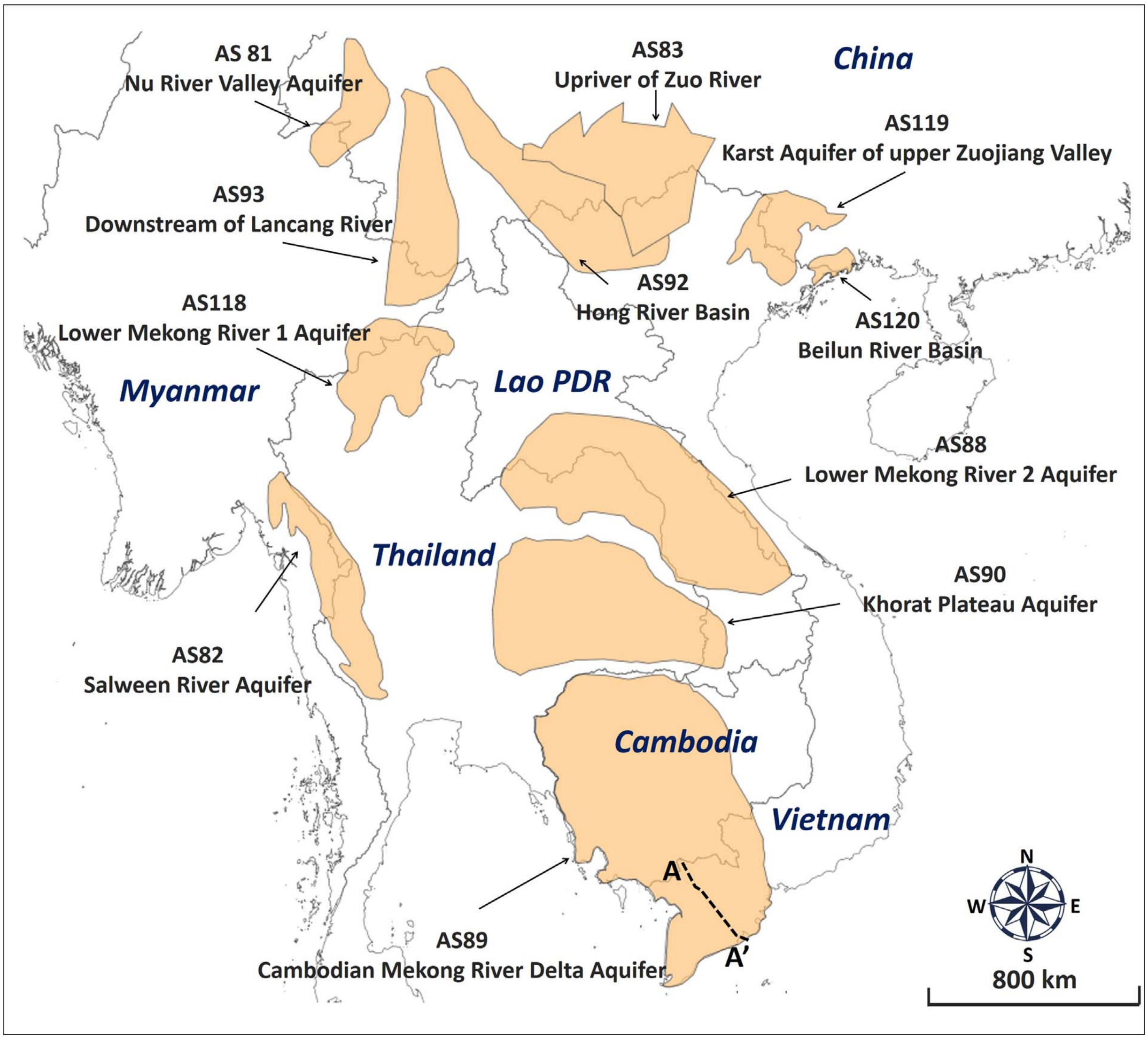

Fig. 4. Transboundray aquifers in Greater Mekong Subregion and adjacent region (modified from IGRAC (2015)).

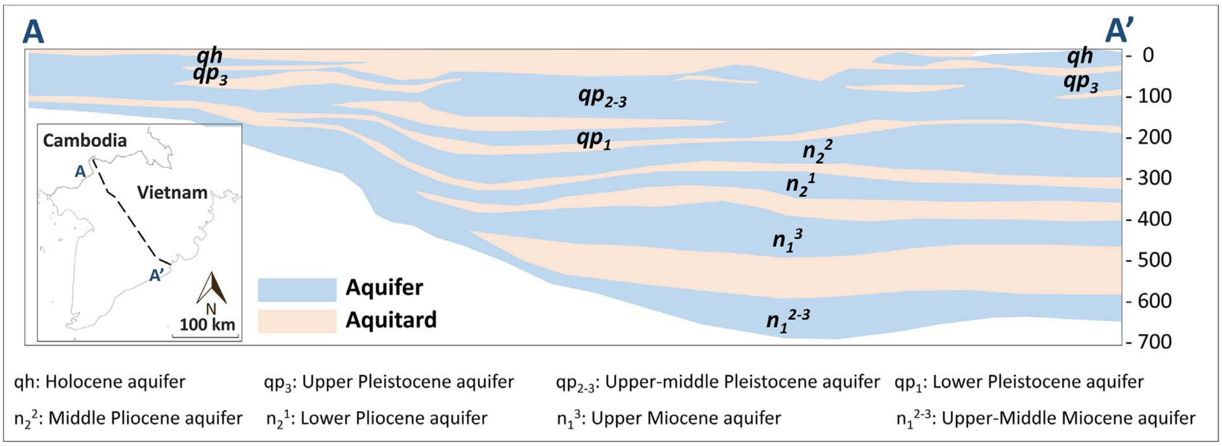

Fig. 5. Hydrogeological profile of the Mekong Delta (modified from Vuong et al. (2016)).

groundwater extraction rate throughout the TBA is estimated to be about 800–900 million m^3/year (Vuong et al., 2016, IGRAC, 2017).

Due to the rapidly increasing population and fast economic development, the demand for water resources has also rapidly increased, leading to the over-exploitation of groundwater. The resulting groundwater reduction and quality deterioration are the main problems threatening future water security (Erban and Gorelick, 2016). Groundwater levels have significantly declined, particularly in the delta area. Monitored groundwater levels indicate a significant drop in water level (over 20 m since the 1990s) in many parts of the delta. The observed decreasing levels of groundwater range from 10 to 80 cm/yr (Vuong et al., 2016). Increased groundwater salinity has also significantly affected freshwater supply capacity. According to the study by Vuong et al. (2016), the distribution of saline groundwater in the aquifers covers 62–84% of total area, posing an immediate threat to the water supply. Due to the low geographical topography, sea level rises and increased groundwater consumption, the aquifers in the delta are increasingly vulnerable to seawater intrusion. Besides seawater intrusion, salty groundwater in the delta is likely to be influenced by multiple causes, including old seawater trapped during the deposition of sediments, dissolution of aquifer materials and re-circulation of irrigation water (Khoi et al., 2002; Larsen et al., 2017; Renaud et al., 2015). Another quality issue for TBAs is the occurrence of arsenic contaminated groundwater and water pollution by increased anthropogenic activities. In Cambodia, around 20% of aquifers are not suitable for human consumption: mainly associated with elevated levels of arsenic (IGRAC, 2017). Some anthropogenic groundwater pollution by households and agricultural practices has been identified, causing the deterioration of shallow aquifers (Chamroeun and Sokuntheara, 2016).

One of the major issues in terms of TBA management in this area is the limited institutional framework for the co-investigation of TBAs and inconsistent hydrological database between the two countries. In Vietnam, at least eight alluvium aquifers were distinguished on the basis of depositional sequences (Vuong et al., 2016) whereas the lithology in Cambodia involves a simpler division – young alluvium and old sediment deposits (Chamroeun and Sokuntheara, 2016). The inconsistent database and different levels of understanding of the TBA system have restricted the strategic planning of cooperative groundwater resources management. Furthermore, different groundwater management policies between Cambodia and Vietnam increase the difficulty in reaching a bilateral agreement for sustainable TBA development. The cooperative management of this TBA system is of particular importance because the Mekong Delta and its surrounding area are considered as a region with high economic dependence on water resources, low levels of socio-economic development, and high exposure to climate-related risks (floods and droughts). For Vietnam, the security of water resources in this area cannot be achieved without a proper understanding of the regional groundwater flow regimes, especially with regard to the up-gradient recharge zones within the Cambodian territory. Developing an improved hydrogeological database for TBAs is also a priority task for Cambodia since much of the country suffers from a lack of available hydrogeological information.

5.2.2. Khorat Plateau aquifer (AS90)

This TBA is located across the border between Thailand and Lao PDR. The whole area is about 109,000 km^2, and Thailand covers most of it (91,000 km^2) while Lao PDR accounts for a small section in the northeastern area. The mean annual precipitation is about 1000 mm/year. The brackish/saline groundwater is locally observed, due to the existence of salt rock underneath (Williamson et al., 1989). The strata of the area is mainly composed of limestone, siltstone, shale, sandstone, and Holocene loose sediments. Fissured rock aquifers such as basalt can be found in the eastern part, mostly within the territory of Lao PDR. Groundwater in this aquifer is mainly used for the agricultural sector associated with rice paddy or sugarcane cultivation. Decreasing groundwater levels and deterioration of groundwater quality (salinity), particularly from Thailand, are major concerns threatening a sustainable water supply for irrigation and domestic water demand.

5.2.3. Lower Mekong River 2 aquifer (AS91)

This TBA covers Thailand, Lao PDR, and Vietnam. The area of the TBA is about 122,000 km^2, and Lao PDR covers about 73% of the total area with Thailand and Vietnam accounting for 21% and 6%, respectively. The aquifer is mainly composed of fissured sedimentary rocks overlain by alluvial sediments, although its structure is generally complex and the groundwater supply shows varying characteristics depending on the region. In similarity to AS90, the buried salt rock locally influences groundwater salinity. Although the natural rainfall is considered to be the main aquifer recharge mechanism of the region, the hydraulic connection between groundwater and the Mekong River is also regarded as a significant process for recharging or draining the aquifer, depending on the season. One of the most economically important areas of Lao PDR lies within this TBA, including Vientiane (the capital) and the irrigation land in the lowland plain. Groundwater serves for domestic, agricultural, and industrial purposes. Expansion of groundwater exploitation for irrigation, domestic use, and rapid urbanisation is an emerging issue, particularly for areas with limited surface water access. The implications for TBAs has been poorly studied and not considered in groundwater management.

5.3. Regional cooperation and framework for shared aquifer management

The essential components for the sustainable development of TBA resources lie in the adequate understanding of TBA systems and strengthened cooperation. In the GMS, the Mekong River Commission (MRC) has provided a regional platform to jointly manage the shared water resources. The mission of MRC is to promote and coordinate the sustainable management of water resources for the countries' mutual benefit (MRC, 2005). Although the MRC includes groundwater in its mandate, the activities so far have mainly focused on surface water or integrated water resource management (IWRM). Consequently, in the GMS, bilateral agreements only exist under the IWRM framework and activities focusing on cooperation and shared groundwater resources management have not been sufficiently implemented. However, with increased groundwater usage, the significance of TBA resource management has now been recognised by national stakeholders, regional organisations, scientists, intergovernmental agencies, and local communities, and their efforts are leading to improved understanding of the regional TBA system, enhanced institutional capacity for sustainable groundwater management, a strengthened network through participatory workshops, and increased awareness for cooperative TBA management in the GMS (Landon, 2011; Lee et al., 2017).

6. Conclusions

Water is increasingly becoming one of the most critical environmental concerns. TBAs, like transboundary rivers, have provided vital water resources for people's livelihoods and socio-economic development. The international community has paid increasing attention to the proper management of TBAs because prioritising the use of shared groundwater resources by one government may affect the opportunities of its neighbours, and accordingly, raise tensions between the bordering countries. In order to manage internationally shared groundwater resources in a sustainable manner, continuous efforts have been made to develop global TBA inventories, assess the TBA resources, and establish a legal and institutional framework.

In Asia, TBAs have played a major role in providing vital freshwater resources as well as sustaining the economic development of the region. Currently, Asia consumes more than 70% of global groundwater; in particular, groundwater has supported the dramatic growth of the agricultural sector in the region. Many TBAs in Asia have been vastly exploited, which has led to the reduction and quality deterioration of groundwater resources. With an increase in population density and economic development, stress on shared aquifer resources is expected to increase further in the future. These challenges to groundwater will likely exacerbate regional conflicts by countries competing over the limited water resources.

The sustainable management of shared aquifer resources requires reliable TBA inventories and improved knowledge on the shared groundwater systems. These technical aspects are critical for managing shared groundwater resources in a reasonable and equitable manner. In Asia, many regional cooperative activities have been undertaken to develop TBA inventories and gain a better understanding of shared aquifer systems (CGS, 2012; UNESCO, 2010b; TWAP, 2014; Zaisheng et al., 2013). Considerable progress has been achieved, but the level of understanding of the shared aquifer systems in Asia remains limited. There is still a lack of reliable TBA data, particularly for the developing countries, suggesting that continuous efforts are necessary to improve knowledge of the TBAs and facilitate information sharing and access to TBA data.

International cooperation in the identification, assessment, and governance mechanisms for TBAs is important in order to ensure the sustainability and security of future global water resources. Institutional frameworks and legal agreements are vital for achieving regional stability with regard to shared water resources management. In Asia, several regional initiatives have been launched to promote the establishment of legal/institutional frameworks for TBA cooperation. With these efforts, many countries in Asia have come to recognise the importance of their TBAs and the need to cooperate with their neighbours in dealing with TBA governance. Several countries, such as China, have endeavoured to cooperate internationally towards shared water resource management by establishing TBA institutes as well as creating mutual agreements with neighbouring countries, which is a significant milestone. However, despite such progress, it is still hard to find formal, ratified agreements exclusively dealing with TBA management. Some developing countries do not have the capacity to carry out groundwater investigation and proper groundwater management practices. Consequently, the sustainable and equitable management of TBA resources in Asia requires an increasing effort from intergovernmental agencies, policy makers, scientists, and local communities in order to reach mutual acceptance of effective cooperation. From the academic and technical perspectives, more attention should be paid to establish a link between hydrogeological knowledge on groundwater management practices based on the improved understanding of TBA basins and their impact on water cycles.

Conflict of interest

None.

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