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Groundwater resources and quality in Syria

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ABSTRACT

The resources of groundwater and its pollution in Syria are identified, and pathways of contaminants to groundwater are described. Then, suggestions for improvement of groundwater quality in Syria are evaluated. Syria is located in a region where water scarcity is dominant. About 87% of all water in Syria is mainly used for irrigation, with almost 60% of this water taken from groundwater resources. The rest is used for domestic and industrial purposes, which account for 9% and 4%, respectively. Due to over-pumping and the increase in the number of unsustainable wells observed in recent decades, groundwater is quantitatively deteriorating. In general, sources of groundwater contamination fall into two main categories: natural and anthropogenic sources. Important sources of natural groundwater pollution include climate effects. About 43% of groundwater has a high concentration of SO_4 and/or NaCl. This is specifically dominant in the eastern region of Syria due to the harsh environment where precipitation is relatively low, and evaporation is high. One of the major sources of anthropogenic groundwater contamination is civil war. Most of the damaged regions are located on permeable rocks, which increases the probability of groundwater contamination due to chemical weapons (CW) used. It is vital to manage and control groundwater resources well. With the increase in water contamination and with the absence of poor water management, access to drinking water will be more of a problem than it is now.

1. Introduction

Syria is renowned for its special location, which is the center of the world's three most dominant continents, Asia, Europe, and Africa, and has a population of over 22 million (Fig. 1). Syria is located in a region where water scarcity is dominant. Water in Syria has mainly used for irrigation, and nearly half of irrigation systems use groundwater as their water resource (Salman and Mualla 2004) (Fig. 2). According to FAO (2018) special report on Syria, the country can be divided into the five Agro-Ecological Zones (AEZs) based on the level of annual precipitation received, as shown in Fig. 3:

- Zone I cover some 2.7 million hectares and have an average annual rainfall of 400–650 mm.
- Zone II covers about 2.5 million hectares and has an average annual rainfall of 300–400 mm.
- Zone III covers about 1.3 million hectares and has an average annual rainfall of approximately 200–300 mm.
- Zone IV is agriculturally marginal, with a total area of around 1.8 million hectares and an average annual rainfall of 100–200 mm.
- Zone V is the Badia or steppe; it has approximately 8.3 million hectares and an average annual rainfall of less than 100 mm.

Agriculture accounts for 87% of the water withdrawn from Syria's aquifers, rivers, and lakes (FAO 2015; Aw-Hassan, 2014). Unfortunately, water availability from both surface and groundwater is decreasing and is expected to decrease further in the future. Due to the development of groundwater-based agriculture, water in semi-arid regions, where water stress is already present, and precipitation is low, is being over-consumed and pumped compared to the previous two decades. For instance, irrigated areas in some regions of Syria with precipitation less than 350 mm/year doubled in the duration of 19 years (MAAR 2006). Even though an increase in irrigated lands using surface water from rivers or lakes, such as in the Euphrates River basin projects, is observed, the overall percentage of lands using groundwater as their resource had risen by 10% in 2004, according to MAAR (2006). Subsequently, the water table has lowered by 23 m on average in the years of over-exploitation (Luijendijk and Bruggeman 2008). This has an impact on the annual average water per capita, with a reduction anticipated to reach 23% between the years 1970 and 2025 (FAO 2011). Furthermore,

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Fig. 1. Location map of the studied area.

water quality and quantity have been affected dramatically in Syria for two reasons; natural and anthropogenic consequences, although an example of the first is climate change which, to some extent, can also be considered anthropogenic.

Human practices nowadays cause the highest percentage of damage to water resources around Syria, where practices have been unsustainable in recent decades. The quantity of groundwater has decreased due to over-pumping and the increase in the number of illegal and non-sustainable wells. Additionally, the quality is affected since salt concentrations increase with the absence of water. Irrigation also has a major influence on the quality of groundwater (Wada et al., 2012). Another major anthropogenic cause of damage is civil war. Lawrence et al. (2015) discussed the effect of warfare on the ecosystem, explaining that chemicals used in weapons that are built to cause damage to human lives also have an adverse effect on the environment. Such weapons-related chemicals can contaminate surface water, soil, and, groundwater which, in turn, toxifies plants, animals feeding on them, food irrigated by polluted water, springs, and rivers by the transport of contaminated sediments, etc. The direct effect of ongoing warfare related to water, such as safe access to water for displaced people, has been well examined. However, the indirect long-term effects of warfare, such as the percolation of contaminants into the soil, especially in cases in which chemical weapons (CW) have been used, have not been highlighted in the literature. Important sources of natural groundwater pollution in Syria include geogenic factors. The major sources of anthropogenic groundwater contamination in Syria are climate change, agricultural activities, over-pumping and chemical weapons. This paper aims to review groundwater resources and focus on underlying natural and anthropogenic influences on water resources in Syria.

2. Geological and hydrogeological properties of the studied area

Numerous studies were completed about the geological and tectonic properties of Syria (e.g., Ponikarov, 1966; Al-Maleh, 1976; Mouty and Al-Maleh, 1992; Sawaf et al., 1993; Sharland et al., 2001; Brew et al., 2001). These studies concentrated on the particularly well-exposed Mesozoic carbonate section in the Palmyride fold and thrust belt, the Syrian Coastal Ranges, and the Kurd Dagh Mountains (Fig. 4). Sharland et al. (2001) provided the first sequence stratigraphic synthesis of Arabian Plate stratigraphy, and Brew et al. (2001) synthesized the tectonic evolution of the entire country. Syria occupies an area of 186,000 km^2 located in the northern part of the Arabian Peninsula platform. Syria is renowned for its sophisticated geologic and structural setting. About 75% of Syria's land is covered by sedimentary rocks, which mostly consist of Carboniferous rocks, fragmented materials, and evaporate rocks, and the geological age of these rocks is Triassic and Neogene. The remaining part is mainly covered with volcanic rocks such as basalt flows from the upper Jurassic and Lower Cretaceous. Additionally, ophiolite rocks with associated volcanic-sedimentary rocks can be found in the north and northwest regions of Syria (Ponikarov and Mikihilov, 1989).

Geologically the country can be divided into two major parts: a mountainous chain in the western part which starts from the southwest and extends all the way to Turkey adjacent to the Mediterranean Sea, and the plateau part in the eastern region. The western mountains function as a precipitation barrier which explains the relatively low

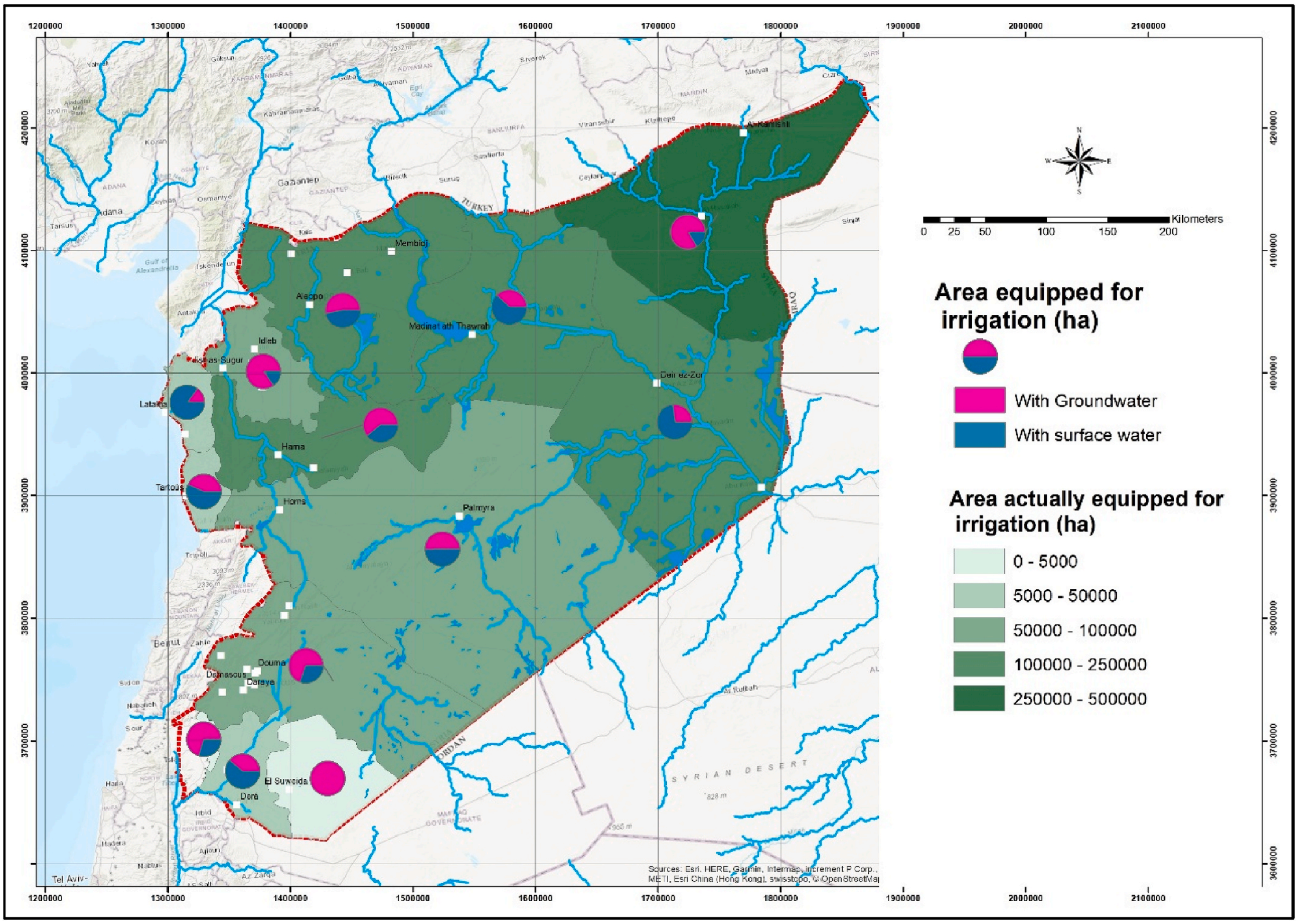

Fig. 2. Area equipped for irrigation (Mourad and Berndtsson, 2012).

precipitation rate on the plateau and the presence of deserts. This geologic evolution and tectonic properties of Syria have created conditions most suitable for preserving groundwater resources. Subsequently, groundwater is mainly found in abundance in the western part with a relatively greater supply and, subsequently, better groundwater quality.

Also, numerous studies were completed about the hydrogeological properties of Syria. Most of these studies focus on a local problem. Al-Charideh and Kattaa (2016) concentrated on hydrostratigraphic properties of units in Syria, Aw-Hassan (2014) studied the impact of food and agricultural policies on groundwater use in Syria, Voss et al. (2013) studied groundwater depletion and transboundary water management in the Tigris-Euphrates, Luijendijk and Bruggeman (2008) studied groundwater resources Jabal Al Hass region, Kattan (2006) focused on the characterization of surface water and groundwater in the Damascus Ghotta basin, JICA (2001) studied of water resources development in the western and central basins in Syrian, La-Moreaux (1989) studied hydrogeological assessment-Figeh Spring, Damascus, Wolfart (1964) worked on the hydrogeology of the Damascus Basin and Asmael et al. (2014) studied on hydrochemistry to delineate groundwater flow conditions in the Mogher Al Mer area.

Al-Charideh and Kattaa (2016) provided a summary of the hydrostratigraphic units (Fig. 5). Lower and Upper Cretaceous aquifers are generally the main hydrogeological succession in Syria. The existence of Paleogene, Neogene, and Jurassic aquifers is minor. Limestone and dolomite aquifers constitute more than 50% of other types. Selkhozpromexport (1979) and Khouri et al. (1984) described aquifer and aquitard systems in more detail. The Regional-Deep Cretaceous Aquifer contributes to more than 80% of aquifers in the stations shown in Fig. 3a, which is an indication that it is part of the massive Upper Mesozoic sedimentary sequence that constitutes the major aquifer units in Syria and the Middle East. As for carbonates, they constitute the most extensive aquifers in Syria and the most vital water resources (Al-Charideh and Kattaa, 2016).

Very few studies were done about groundwater modeling in Syria. Groundwater modeling has been widely used to investigate groundwater system dynamics and understand flow patterns (Anderson and Woessner, 1992; Chiang and Kinzelbach, 1998). Asmael et al. (2015) developed a groundwater model representing the groundwater flow system in the complex of the northeastern part of Mt. Hermon and improved the hydrogeological understanding of this system. The result of this study is indicated that the lateral discharge from the Jurassic karstic aquifer into Neogene conglomerates and the recharge by infiltrated meteoric precipitation are the most important mechanisms in recharging the upper aquifer horizon.

3. Methodological approach

The geopolitical characteristics of Syria turn it into a unique subject of study while natural resources are being investigated. Generally, we can divide the data sources available in the case of study into two main periods; before and post-era of war in Syria. While it can be found several studies and sources of information about the natural, geographical and socio-economical structure of Syria before 2011, these resources dramatically decrease in the post-war period. Consequently, there are significant knowledge gaps about the case of study in the post-2011 era. This un equivalent Geospatial data quality is the main

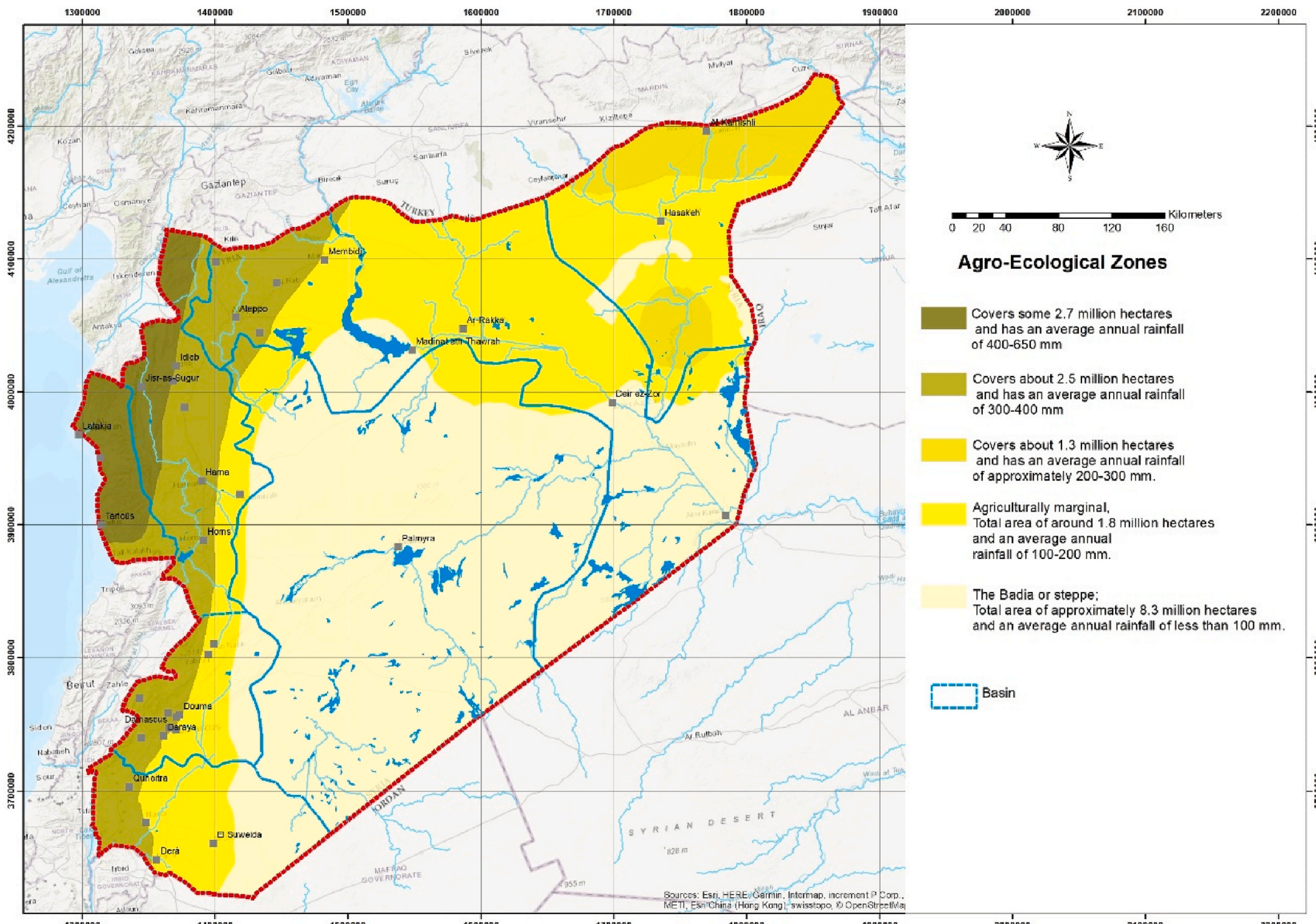

Fig. 3. Agro – ecological zones (FAO, 2018).

challenge of the study for understanding the issue.

This study classified the available sources of information as main and clues in a geospatial database. The main data sources are used to understand the geographical characteristics of Syria and used for creating, enhancing, and verification of further rare data sources after the 2011 period. Initially, the study gathered official and academic published data in the same geospatial dataset; geo-referencing, digitizing, and geo-processing of these sources information provide is the essential content of the main database. Later other sources of information with a lower level of accuracy or consistency are gathered in the clue database. Overlapping these two databases provide a third source of geographical information that is used for the evaluation subject of study. Fig. 6 briefly illustrates the main methodological approach of this study.

4. Water resources of Syria

4.1. Surface water

There are seven main basins in Syria (Fig. 7). Table 1 shows some characteristics of these basins. Most of the surface water in Syria is shared with other neighboring countries. Surface water is the general source in Syria. The Euphrates River alone accounts for about 85% of the water that is available to Syria (Lowi, 1995). It covers a total distance of 2800 km, and also a population of 5.930 million inhabitants lives there. The basin of Orontes, with a population of 3.830 million inhabitants and nearly 18.000 ha areas, owns a second-high capacity of precipitation. The next river in terms of internal size is the Oronates which originates from Lebanon, passing through Syria, and Turkey is also located in this basin. The most famous lake on that river is found in Homs district. Other major rivers include the Tigris, Khabur, Sajur, and Balikh. Areas that are irrigated with surface water have remarkably increased. For instance, 583,000 ha of irrigated lands used surface water in 2002 compared to 334,000 ha in 1985 (Somi et al., 2002).

European Commission published data about surface water resources of Syria in 2019, which gives remarkable information about the case of the study's surface water situation in 34 years. According to this data set, the recurrence percentage of surface water resources in Orontes, Euphrates, and Aleppo basins remain notably high while in East regions (Dajleh and Khabour Basins) is significantly low (Fig. 8). Water occurrence maps (Fig. 9) provide critical information on surface water availability in a different region in the same period. For example, Membidi, Homs, and Hasakeh regions are mostly recognized with permanent surface water, while in regions like Palmyra or Aleppo, surface water resources are temporary. Water occurrence change intensity is shown in Fig. 10. In 34 years' east regions have increased change intensity in surface water; this factor remains with no change in some northern regions and Aleppo and Homs. Another significant variable in the data set is the transition of surface water that elaborates in Figs. 11 and 12.

The data set also provides clear information about the transition of surface water in this period. The observation results indicate that in regions like Hasakeh and Membidi or Palmyra, some new seasonal and permanent surface water is available; this transition reveals for the Aleppo region in more detail in Fig. 12.

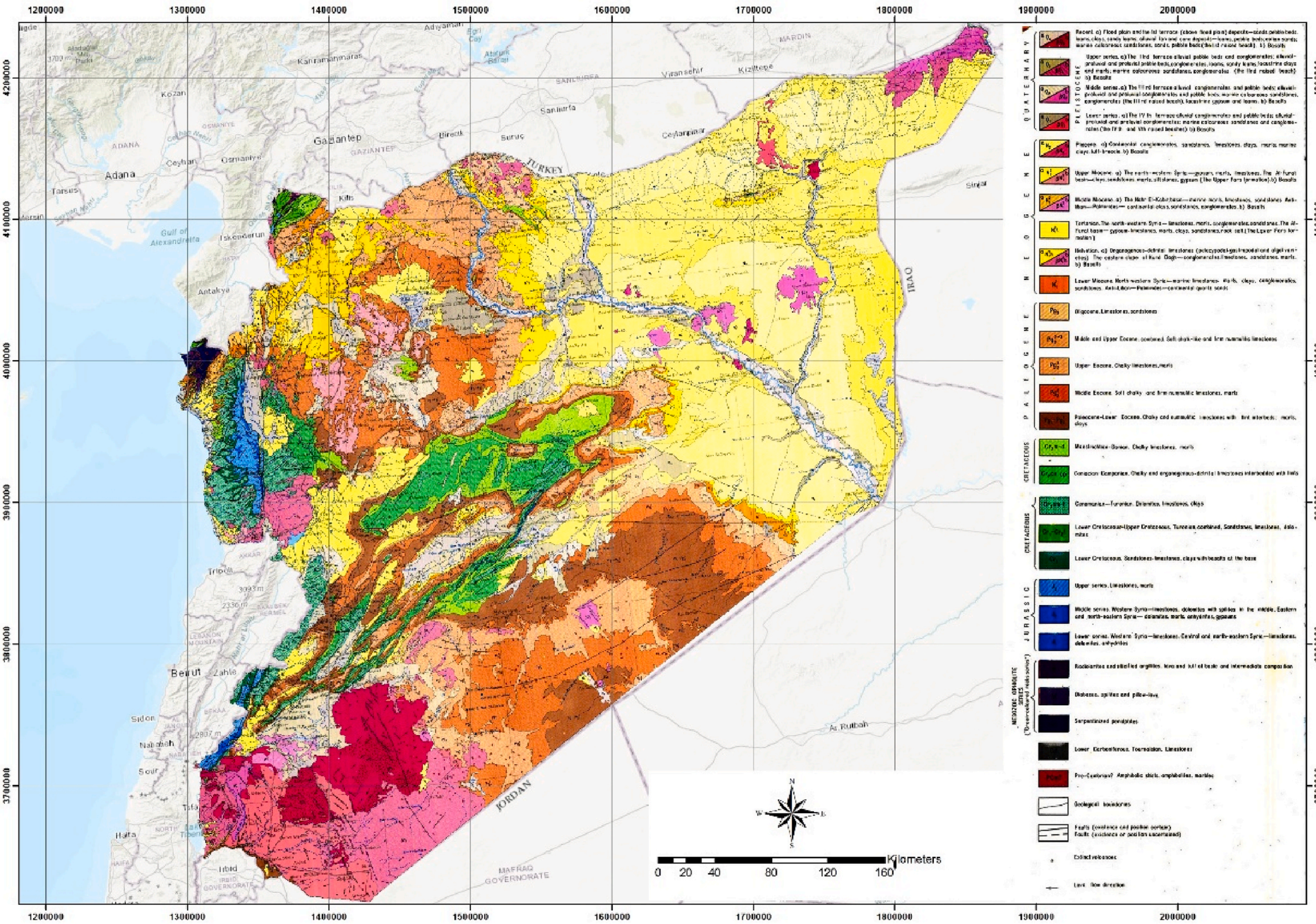

Fig. 4. Geological map of the studied area (from Ponikarov and Mikhailov, 1989).

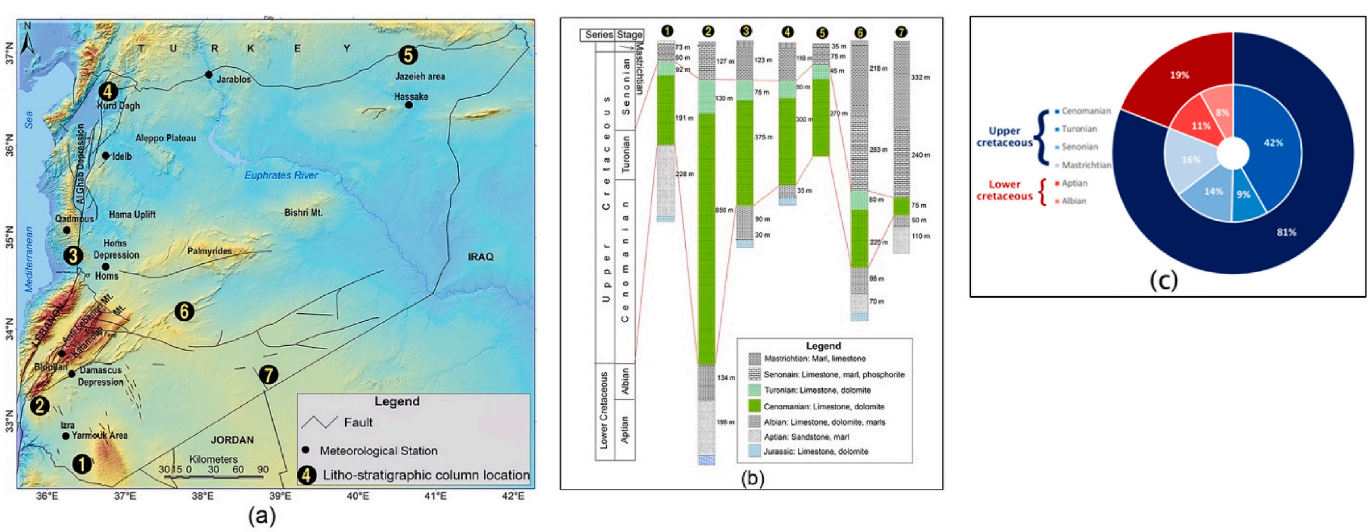

Fig. 5. a. modified map of Syria showing general geographical features b. Stratigraphic correlation column of the meteorological stations c. Upper and lower cretaceous ratio in the given stations (Al-Charideh and Kattaa, 2016).

4.2. Groundwater

In developing countries such as Syria, the lack of hydrological data affects groundwater resource assessment. Groundwater models provide the means to fill the gaps in the available data in order to improve the understanding of groundwater systems (Asmael et al., 2015). Data on water use and pumping are essential to developing a water budget or groundwater flow model. The accurate monitoring of agricultural water use is an important factor in reducing the uncertainty of water balance calculation. However, quantifying groundwater abstraction remains a difficult but necessary challenge. Agriculture sectors have been used about 60% of the water withdrawn from groundwater resources (FAO,

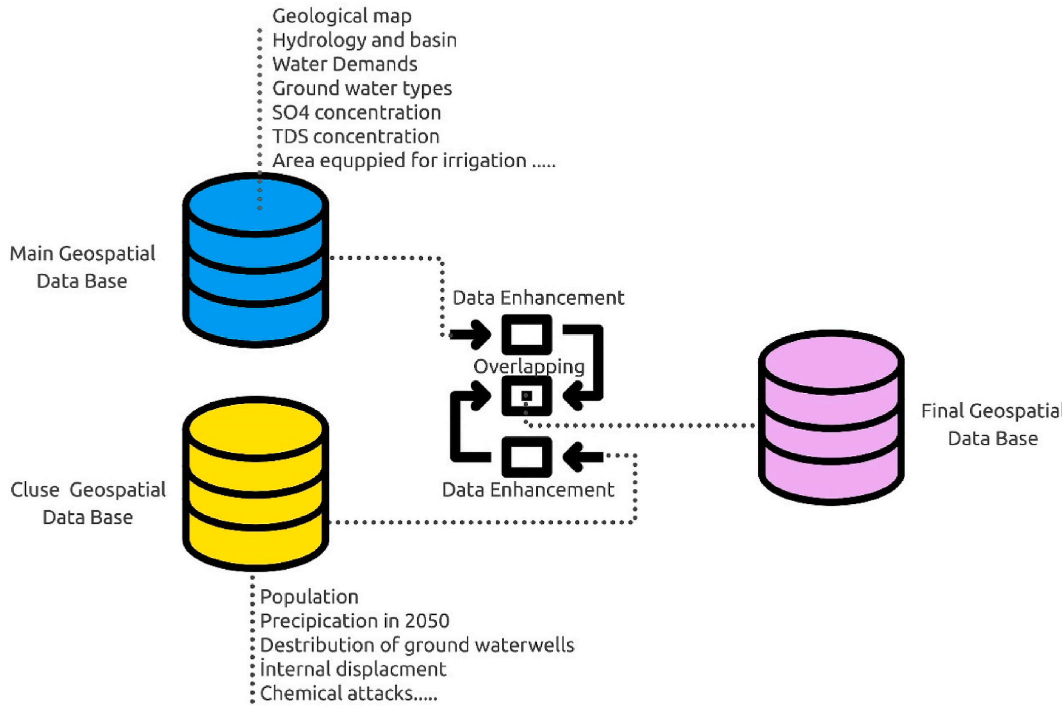

Fig. 6. The main methodological approach of this study.

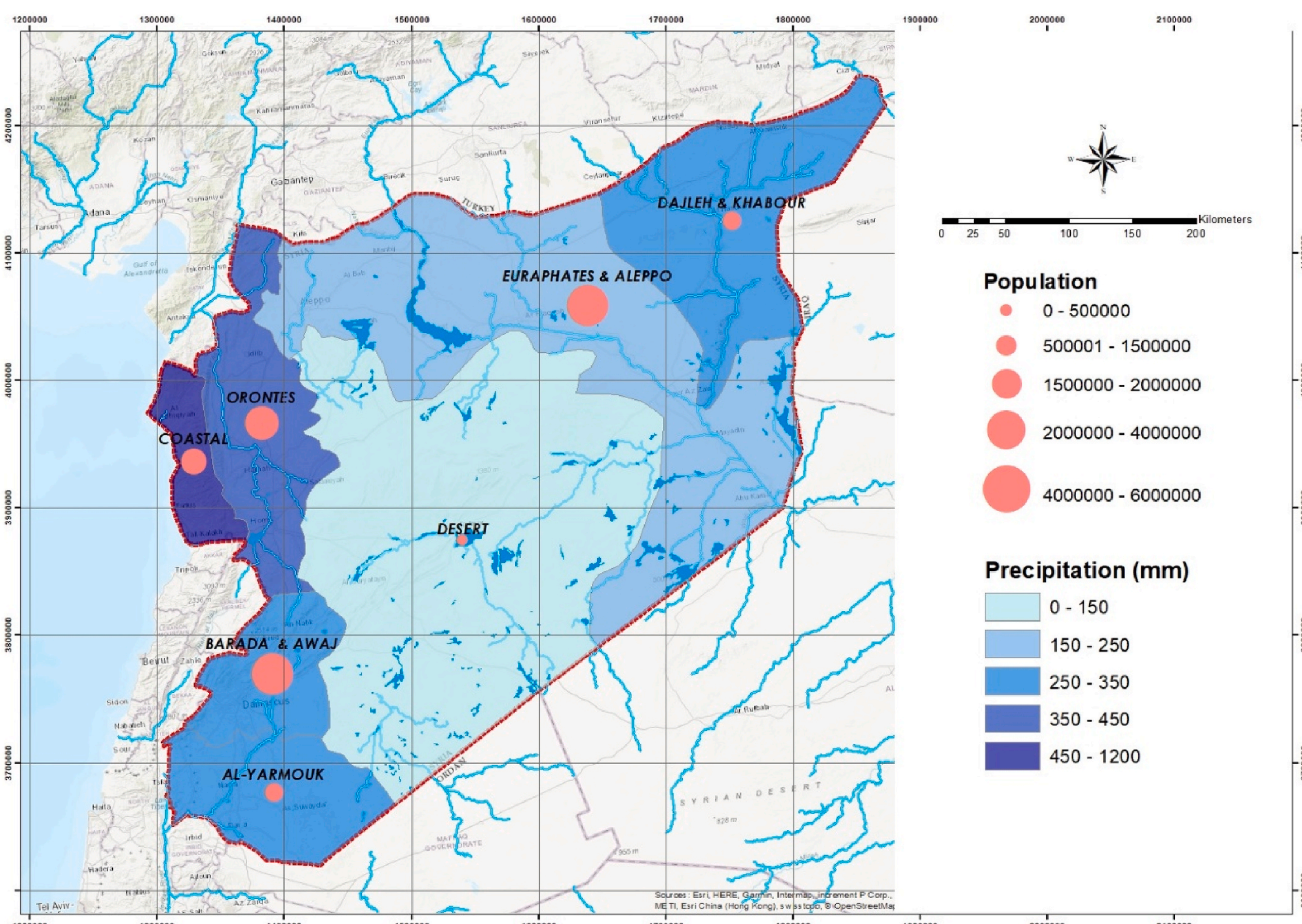

Fig. 7. The seven basins of Syria and Population/Precipitation rate (Mourad and Berndtsson, 2012).

Table 1
Syria's main basins and their characteristics (Mourad and Berndtsson, 2012).

Water Basin	Population (million)	Area (Ha × 10^3)	Precipitation (mm)
Barada & Awaj	5.700	8.630	275
Al-Yarmouk	1.404	5.764	318
Orontes	3.830	18.362	415
Dajlah & Khabour	1.340	21.129	279
Euphrates & Aleppo	5.930	51.238	217
Desert	0.369	70.786	141
Coastal	1.780	5.049	1147

2015; Aw-Hassan, 2014). Karstic carbonate rocks are the most interesting potential groundwater reservoirs in Syria and the major Middle East countries. They have high economic value in the regions where they are the main exploitable resource for domestic water supply for the large cities such as Damascus (Al-Charideh, 2011). The main recharge zone of North Syria is found on the Turkish side due to very well-developed karstic limestone and a higher rainfall rate. However, recharge is very low on the Syrian side due to the lower rainfall rate, the presence of impermeable Neogene deposits, and the low-density drainage network. In the Upper Jezireh Basin, several aquifer systems have been identified: Upper Cretaceous, Paleogene, Neogene, Pliocene, and Quaternary (GCHS, 2000; Kattan 2001; 2002; Abou Zakhem, 2017). The Paleogene and Quaternary formations constitute good aquifers with high capacity and hydraulic conductivity.

The thickness of the Jurassic aquifer is about 1000 m on average and can reach a thickness of 2000 m in some places within the basin. According to Kattan (2006), the hydraulic conductivity of this aquifer ranges from 2 to 99.3 m/d and, on average, is about 18 m/d; thus, the transmissivity could attain a value of around 3085 m^2/d. Cenomanian-Turonian strata illustrate the Cretaceous aquifer. The thickness of this aquifer ranges from 400 to 1000 m. The hydraulic conductivity of this aquifer system can increase to 80 m/d, and its transmissivity ranges from 12 to 7435 m^2/d (Kattan, 2006). This aquifer unit, together with the Jurassic one, forms the most important water-bearing system in the whole country and even in the Middle East (Kattan 2006; UN 1982; JICA 2001). These two units form large fresh groundwater reservoirs with large storage and withdrawal capacity as well as a considerable discharge of issuing springs (La-Moreaux et al., 1989). The Neogene deposits largely outcropped along the Euphrates River, where these deposits consist mainly of gypsum, sandstone, siltstone, silty clays, clays, and pebbles (Kattan, 2018). Also, some borehole tests of the Neogene aquifer system in this region indicate a high heterogeneity of gypsum formation. This formation's transmissivity values are reported at 1.6×10^{-4} to 8.1×10^{-2} m^2/s (UN-ESCWA and BGR, 2013). Abou Zakhem and Hafez (2015) studied about Damascus Oasis region. They focus on a Quaternary alluvial aquifer system consisting of pebble, gravel, sand, silt, and clay with 400–450 m thickness. The hydraulic conductivity of this aquifer sharply varies from 3.7 to 142 m/d, and thus the transmissivity (165–3700 m^2/d) (Selkhozpromexport 1986).

Groundwater use in Syria has increased considerably and is overexploited in an unsustainable manner. Almost 60% of all irrigated sites in Syria depend on groundwater (Salman and Mualla 2004). Areas irrigated by groundwater increased by 140% from 1985 to 2002 (Somi et al., 2002). According to Fig. 13, about 17% of all groundwater in Syria is of good quality with large supplies; meanwhile, 40% is good quality but non-renewable to semi-renewable supplies. Up to 43% of groundwater has a high concentration of SO_4 and/or NaCl. The groundwater resources of Damascus are NaCl and $MgSO_4$ type. Most groundwater resources in Ar-Raqqa and Deir-ez-Zor are $MgSO_4$ and $CaSO_4$ water-type. A high percentage of Na–Cl-type groundwater resources are observed in Aleppo City. Generally, As-Sweida, Latakia, and Tartous cities have good quality groundwater resources (Fig. 13).

4.3. Water usage in Syria

About 87% of all water is used for irrigation, with almost 60% taken from groundwater resources, which leads to immense and unsustainable exploitation of these resources (Wada et al., 2012). The rest is used for domestic and industrial purposes, which account for 9% and 3%, respectively (Salman and Mualla 2004). Therefore, the highest water consumption can be detected in areas where irrigation is common. About 44% of water is consumed in the Euphrates & Aleppo basin, followed by Dejlah & Khabour. Most of the groundwater wells were drilled in Al Hassake Region for irrigation (Fig. 14), followed by Aleppo and Al Raqqa, respectively, where these regions are responsible for almost 70% of groundwater pumping in total (Table 2). When dividing amounts of withdrawals by the area of each region, the Al Hassake region also accounts for the highest withdrawal per km^2 followed by Deir-ez-Zor, and Ar-Raqqa (Fig. 15).

5. Factors affecting groundwater quality

5.1. Natural factors

Syria has 182 km of direct coastline with the Mediterranean Sea, and this provides a relatively high level of precipitation in the coastal region. However, due to the presence of mountain chains along the coast, they work as a barrier and block most of the movement of rain clouds from reaching the central and western parts of Syria. This explains the huge difference in precipitation levels in the different basins (Fig. 16). With low precipitation levels, water quantity and quality decrease with the increase in salinity concentration. Additionally, due to climate change, the temperature in the Middle East is expected to rise 2.5 °C, which will impact precipitation levels of approximately 20%–25%, which will affect river flow rates. This is the case in the Euphrates River, which is considered the main surface water resource as previously mentioned, and will reduce by 29%–73% by the year 2050 (Trondalen, 2009). This is specifically dominant in the eastern region of Syria due to the harsh environment where precipitation is relatively low (100 mm) compared to 900 mm in the western part (Al-Charideh et al., 2016) and evaporation is higher, which facilitates the natural presence of these salts.

In many parts of the country, groundwater quality and quantity have been quite degraded. In Quayq Valley, for instance, high salinity and depression are present, which were expected by Wolfart (1966) to result from the evapotranspiration of groundwater. Considering the absence of halite in Qwayq Valley as discovered by Gruzgiprovodkhoz (1982) and due to the evapotranspiration of groundwater close to earth's surface, this can be an indication of the high concentrations of Cl^- found in the valley since groundwater depth there is shallow.

Luijendijk and Bruggeman (2008) made an assessment about the Jabal Al Hass region located near Aleppo and found that its groundwater contains Cl^- ranging from 0.5 to 3 dS/m. Water with Na–Cl contributes relatively more to excess salinity than other types of water, such as the more dominant Na–SO_4 type. A similar conclusion can be obtained from the location of the Jabal Al Hass region according to Fig. 5, which is located over groundwater with high NaCl. Fig. 17 shows the highest TDS to be in the Jabal Al Hass region as well. The surrounding region and Al Hassake have TDS ranging from 2500 to 3500 mg/l. Al Hassake and Aleppo contribute to more than 50% of the total number of wells in Syria (Fig. 9). Syria's desert and the eastern side have precipitation of less than 200 mm, which not only makes water scarce but also worsens its quality. Figs. 17 and 18 illustrate this quite obviously. SO_4 concentration ranges from 150 up to 2000 in desert areas and the Euphrates basins, while TDS is between 1500 and 2500 mg/l. Meanwhile, these concentrations gradually decrease moving west, where precipitation rates are higher.

Kattan (2018) studied groundwater quality in the Euphrates alluvial aquifer. He found that the groundwater salinity is primarily due to Na^+, Cl^- and SO_4^{2-} species. These ions can largely be liberated from the

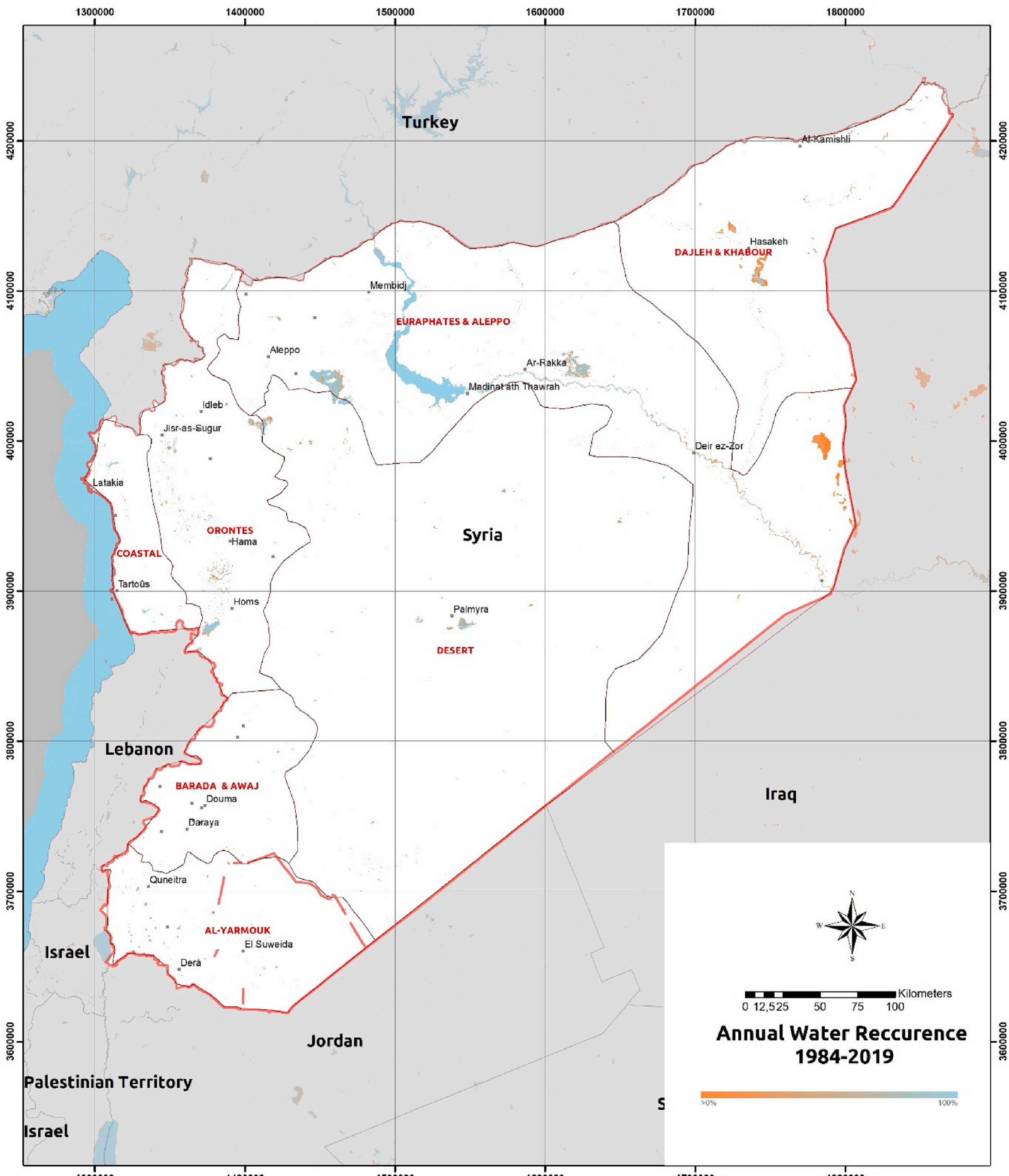

Fig. 8. Annual surface water recurrence 1984–2019.

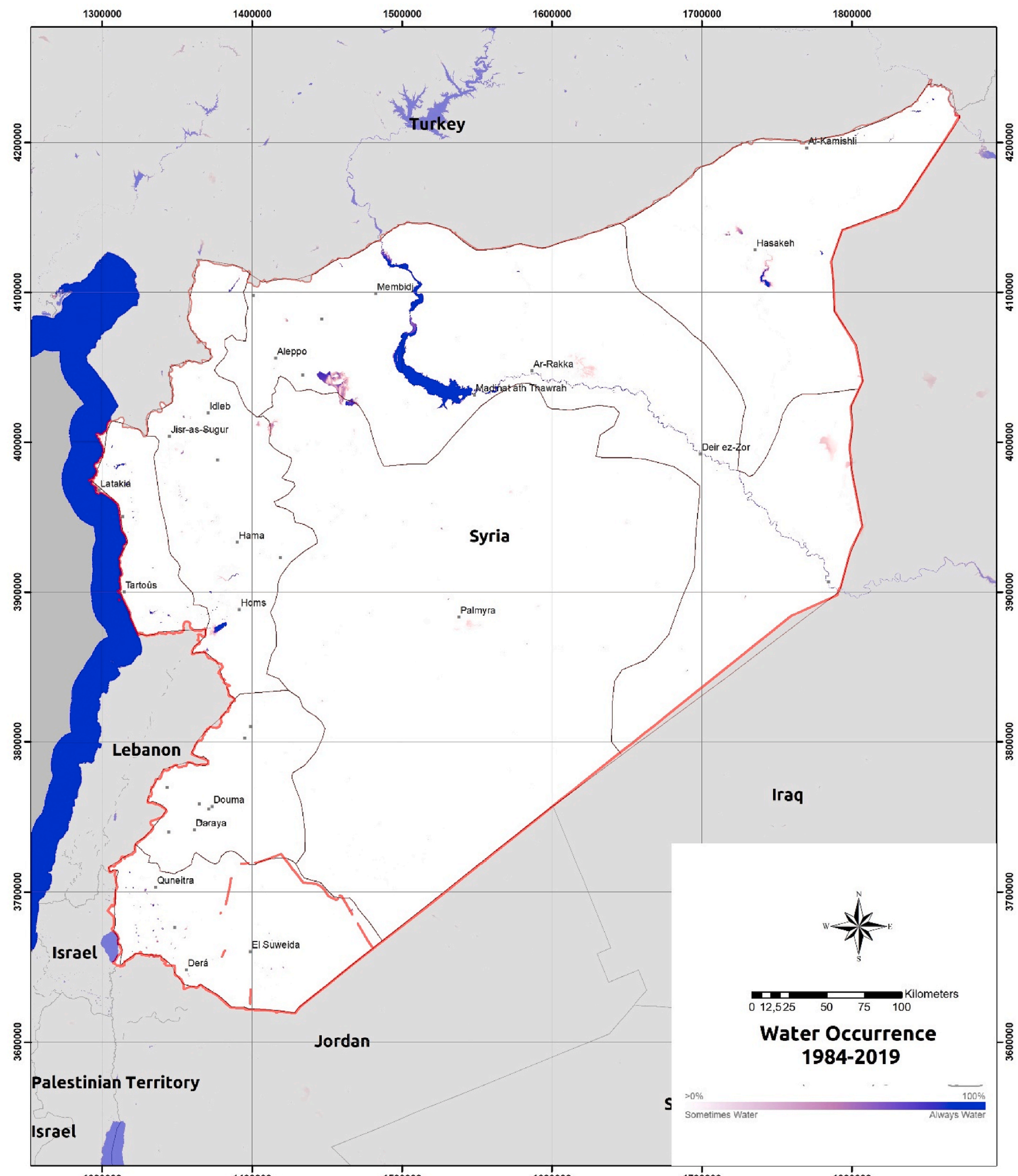

Fig. 9. Annual surface water occurrence 1984–2019.

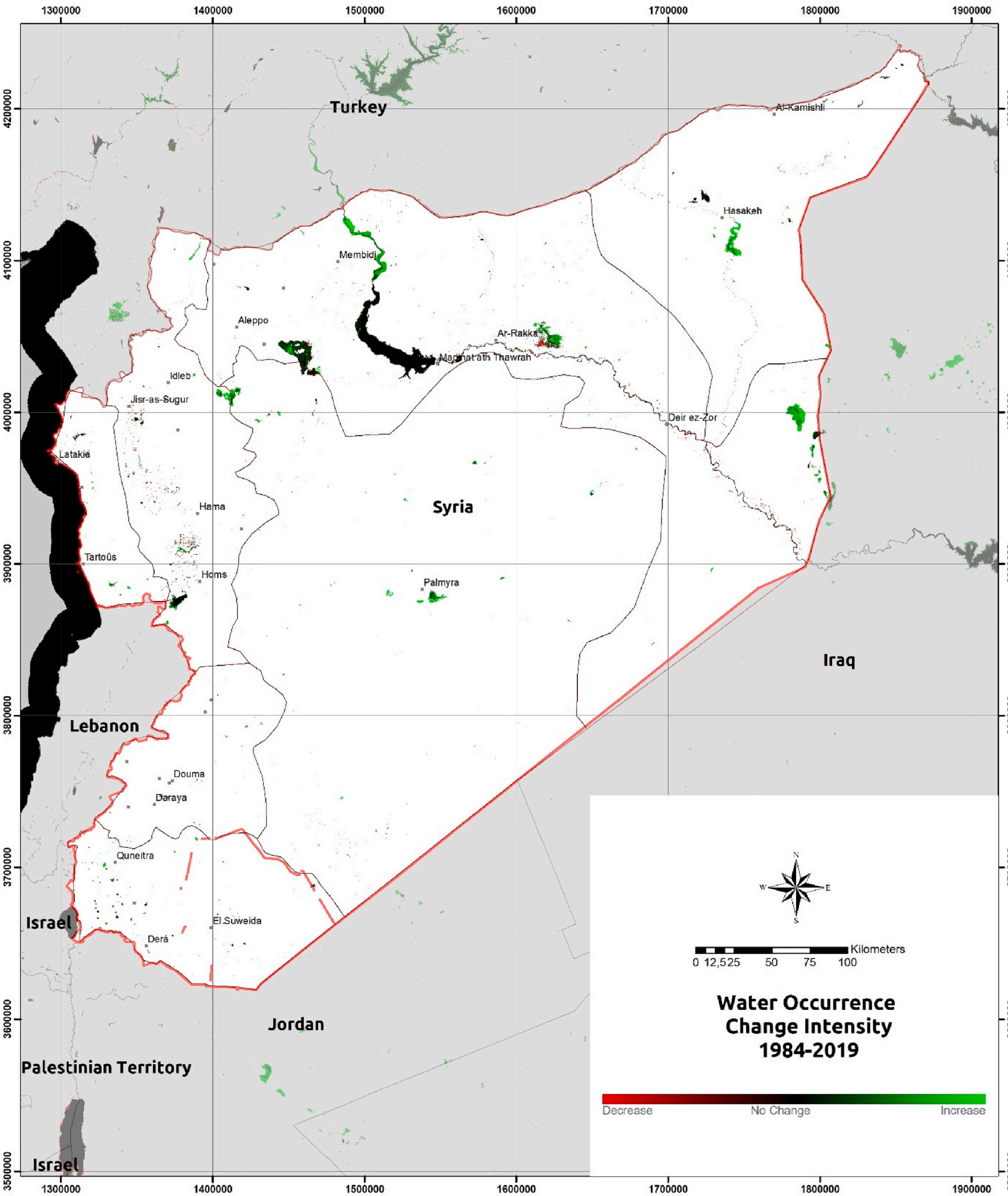

Fig. 10. Annual surface water occurrence change intensity 1984–2019.

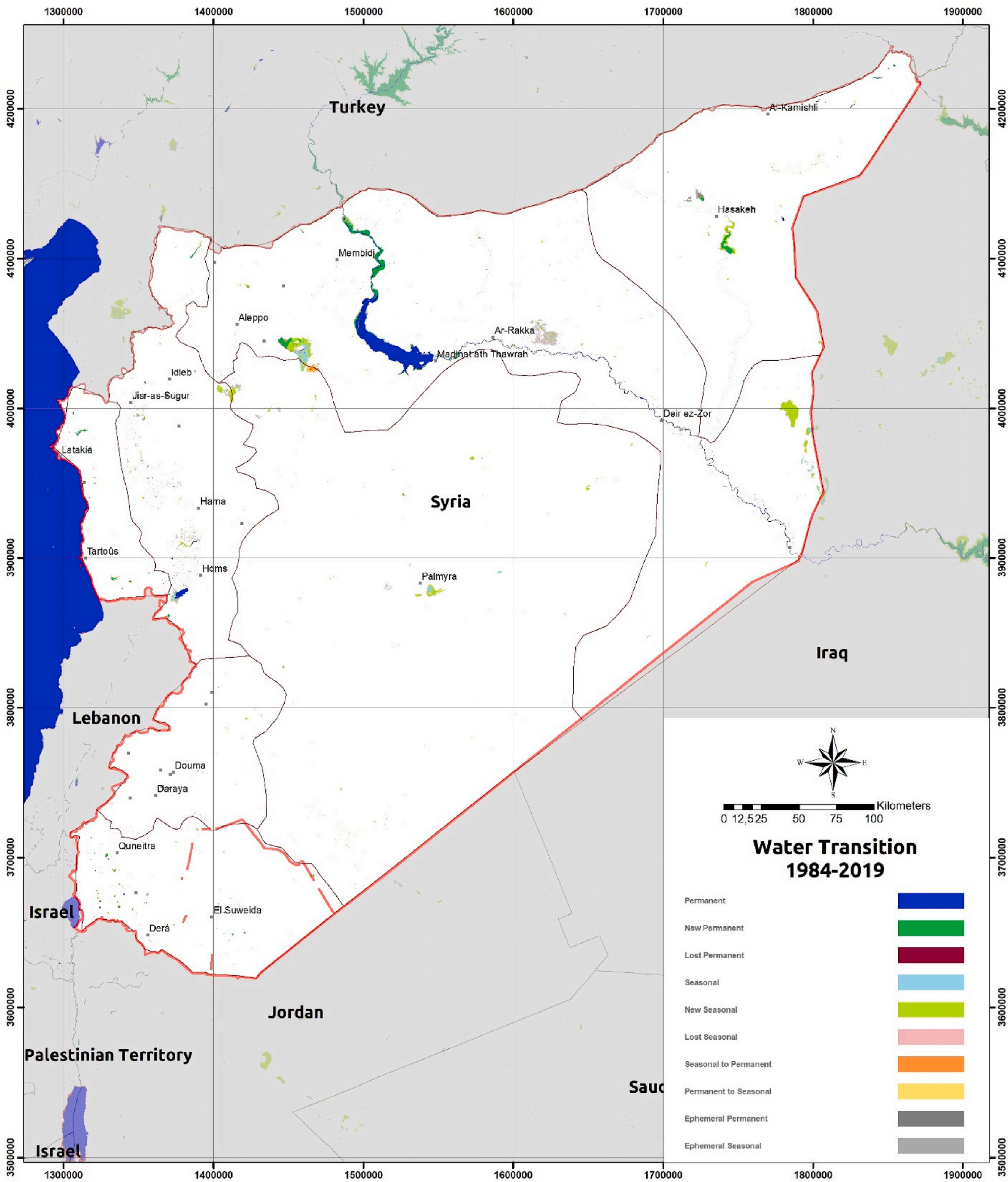

Fig. 11. Surface water transition 1984–2019.

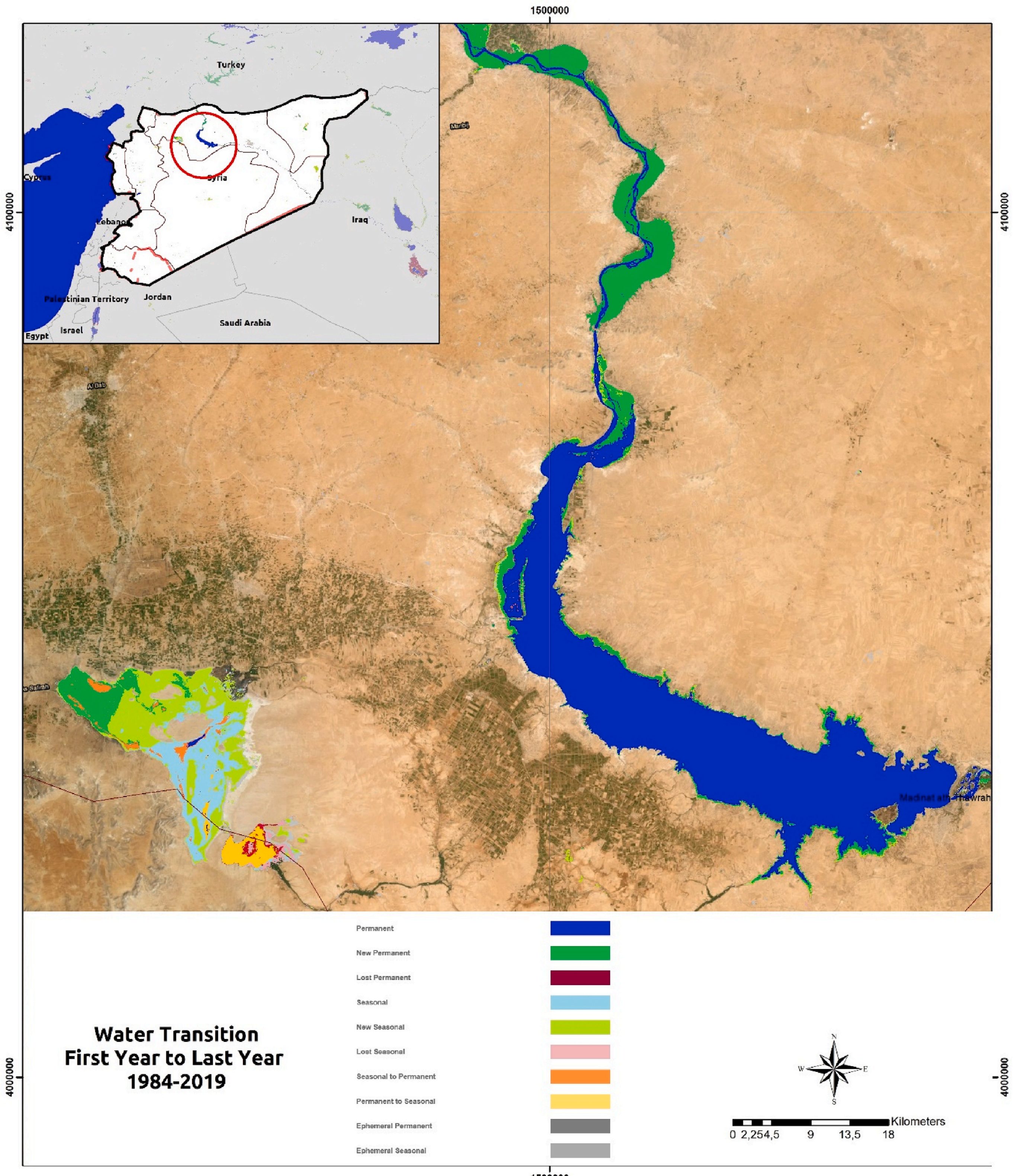

Fig. 12. Surface water transition in Aleppo 1984–2019.

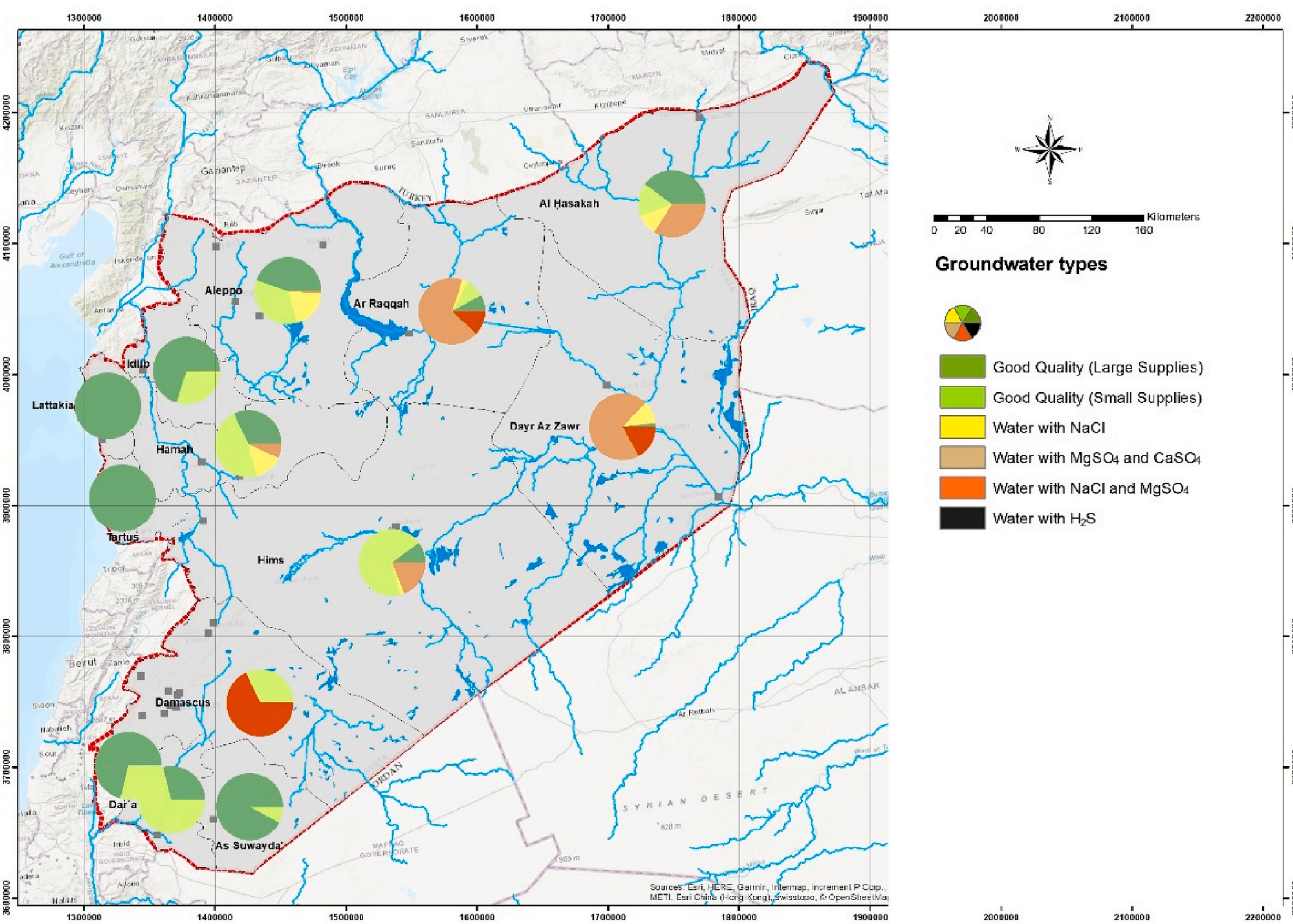

Fig. 13. Groundwater composition in Syria (Burdon et al., 1954).

dissolution of soluble salt minerals, such as halite, thenardite, mirabilite, and bloedite. Also, he mentions that the groundwater quality in the different wells in this region, which is unfortunately brackish to saline, is harmful and unsuitable for drinking water supply. In addition, the Paleogene and Quaternary formations constitute good aquifers with high capacity and hydraulic conductivity. However, the remaining aquifers are found at depths of more than 1000 m, particularly in the northern part of Syria, and have highly saline waters.

5.2. *Anthropogenic factors*

Agriculture is considered to be the main reason for surface and groundwater contamination. Some practices by farmers might lead to adverse contamination and a high concentration of nitrates in the soil due to their use of untreated sewage water for the irrigation of their plants. According to Kattan (2018), the Euphrates River water quality in Syria at all sites is generally good and suitable for drinking water supply. Contrary, the groundwater quality in the different wells, unfortunately with high nitrate concentrations, is harmful and unsuitable for drinking water supply. A similar case was assessed by Abou Zakhem and Hafez (2015) in Damascus Oasis, and they concluded that the use of direct sewage water for irrigation leads to a high concentration of zinc (Zn) and copper (Cu), which exceeded the standard limits defined by World Health Organization (WHO) and the Syrian Standards (MCL) (Fig. 19).

Warfare has impacts on water availability and human lives, too. Over 250,000 people have been killed, and the number is still increasing to the present, while others have been severely injured or are missing (Guha-Sapir et al., 2015). Direct impacts include people displaced internally and externally, which creates a hard environment for them, noticeable reductions in public health, and more people that have low or no safe access to drinking water (Elsafti, 2016). Due to the ongoing war in Syria, residents are both directly and indirectly affected. Direct influences include internal and external displacements of people due to warfare, which leads to refugees facing difficulty meeting their basic needs, such as safe access to drinking water. Additionally, internal displacement accentuates the presence of an unbalanced concentration of population, which leads to the unsustainable use of water resources in some parts of the country, such as the Hama region. Fig. 20 illustrates the percentage of Internally Displaced People (IDP) in October 2014 (Doocy et al., 2015).

Doocy et al. (2015) found that 26.2% of 2979 displaced people and 29.8% of 711 non-displaced people have poor access to water. Another indirect influence is the possible deterioration of groundwater quality due to the leachate of contaminants into groundwater, especially contaminants related to chemical weapons used in some parts of the region. Especially two agents of blister agents and nerve agents were used in Syria. Blister agents, such as sulfur mustard, have a disastrous effect on the eyes, respiratory system, and internal organs. Even very low concentrations of the mustard agent can cause serious injuries. Nevertheless, mustard agents decompose into harmless products by means of hydrolysis but have a low solubility in water which reduces its decomposition (Ivarsson et al., 1992). Nerve agents, such as sarin and VX, are extremely toxic and rapidly react when absorbed by the skin or through respiratory systems. They prevent the transmission of nerve impulses to muscles in the nervous system, which makes them horribly toxic not just to humans but to other mammals as well. Sarin is relatively a volatile

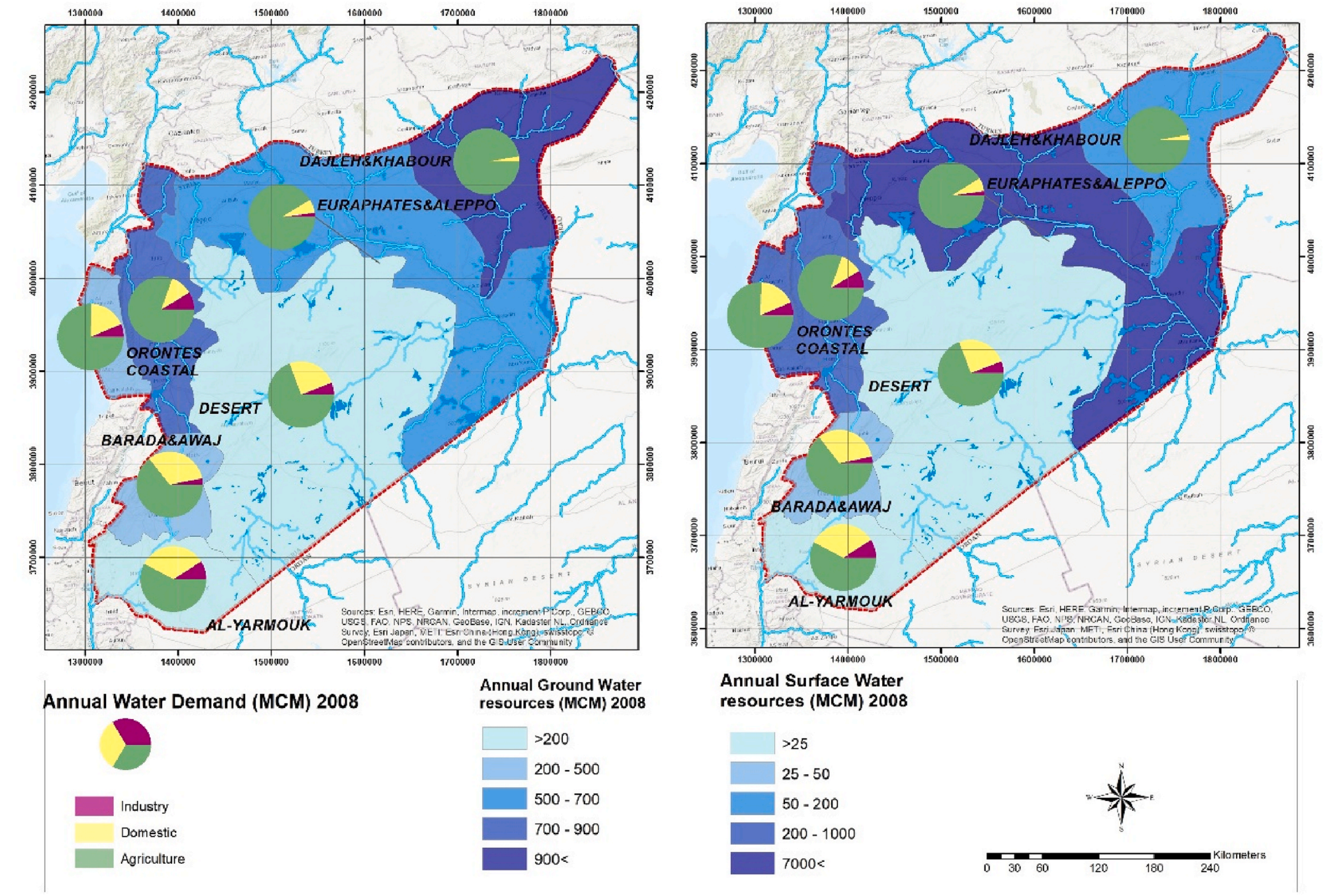

Fig. 14. Water usage in different sectors in Syria (data from Mourad and Berndtsson, 2012).

Table 2
Data for drilled wells in Syria's regions from (FAO, 2012).

REGION	PRIVATE WELL	GOVERNMENT PROJECT
DAAR'A	13075	20992
DAMASCUS	44543	–
HOMS	22655	27518
HAMA	55798	7979
IDLEB	44515	11164
ALEPPO	101213	89358
AL RAQQA	51407	93128
DEIR EZZOR	25420	38173
AL HASSAKE	313248	–

liquid, while VX is not, which increases the likelihood of it percolating into groundwater. Additionally, nerve agents such as sarin have a high solubility in water, while VX is less soluble, especially in warm water. Resembling blister agents, nerve agents can decompose by means of hydrolysis with high alkalinity. In the presence of neutral pH, however, they decompose slowly (Ivarsson et al., 1992). These, along with other by-product chemicals such as disopropyl methylphosphonate (DIMP) and isopropyl methylphosphonic acid (IMPA), were identified by the Organization for Prohibition of Chemical Weapons (OPCW) laboratories when samples were taken from Syria after the renowned 21 August incident that took place in Ghouta near Damascus. Groundwaters are vulnerable to DIMP and IMPA contamination (Moore et al., 2000).

Table 3 shows temporal and spatial data of CW attacks that took place in Syria during the ongoing civil war (Pita and Domingo 2014), and Table 4 provides the geological and hydrogeological properties of these regions. In addition, groundwater quality in these regions is mentioned in Table 4.

It can be observed that most of the areas with attacks have permeable soil, which helps with the chemicals percolate into soil and groundwater. This can be hazardous, especially for groundwater that has insufficient supplies, as this will slow down the dilution of the contaminants in groundwater systems that naturally take place due to groundwater flow, just as the case in Qasr Samrah (or Abo Samrah) in Hamah (Fig. 21). The CW effect is not limited to groundwater but can also contaminate surface water as well. Ein Tarma, one of the sites attacked in the August 21 incident in Damascus countryside, is almost 400 m from the Barada River. There is a potential that the river conveyed some chemical contaminants downstream and distributed the contamination even more.

6. Results and conclusion

Groundwater resources are one of the most important parameters for sustainability in Syria, where the regional Deep Cretaceous Aquifer is the major aquifer. The most important water resources outcrop in the uplands of Anti-Lebanon, Coastal, and Palmyrides mountains. Groundwater pumping in the semi-arid regions of Syria has increased significantly over the last two decades due to the development of groundwater-based irrigated agriculture (Luijendijk and Bruggema, 2008). Almost 60% of all irrigated sites in Syria depend on groundwater. Areas that are irrigated by groundwater have increased each year. But groundwater resources have been affected by natural and anthropogenic factors. Salinization is one of the important problems for sustainable agricultural activity. This problem, which is of particular concern because it can limit

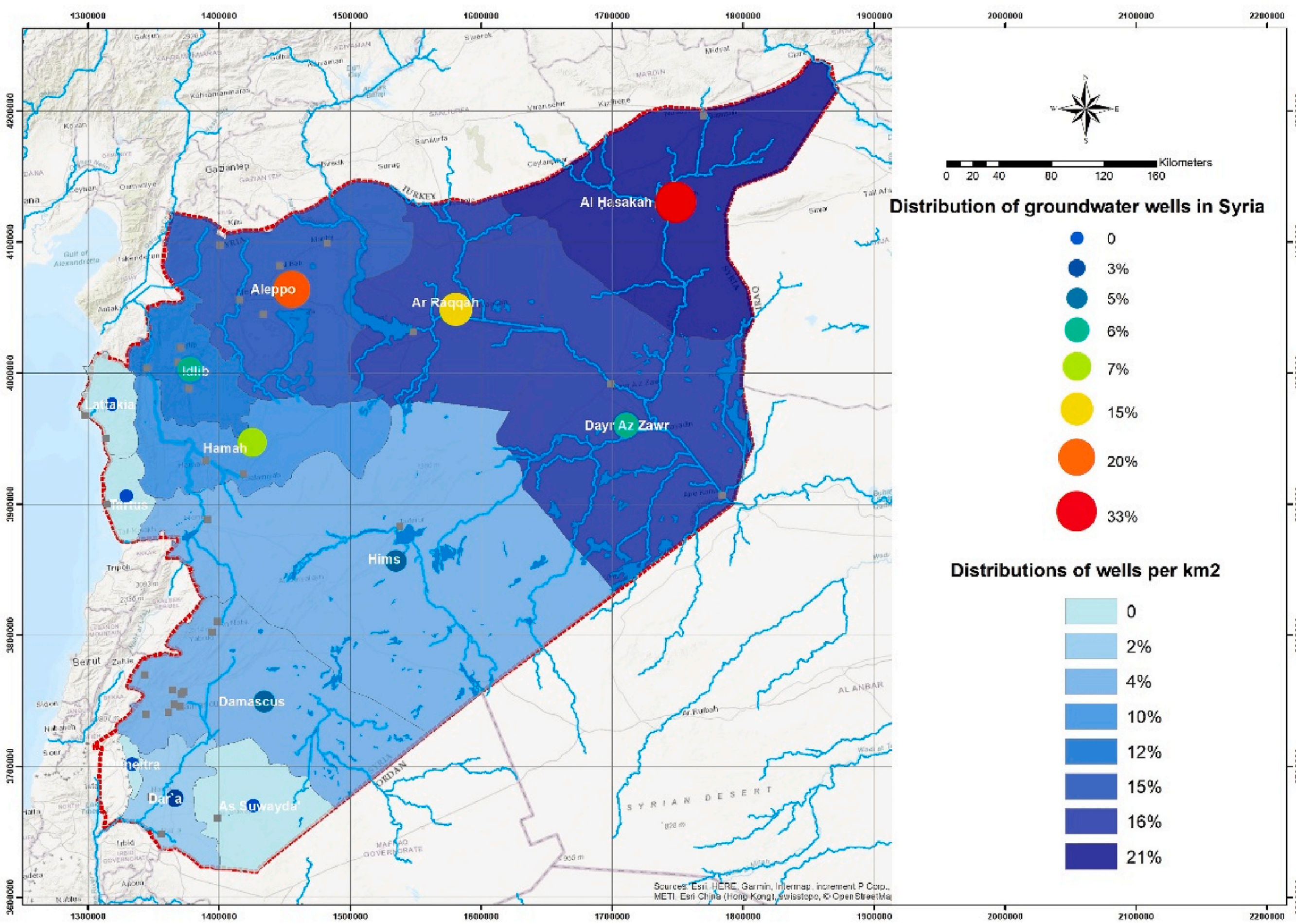

Fig. 15. Distribution of groundwater wells in Syria and Distributions of wells per km^2 in clockwise descending order (data from FAO, 2012).

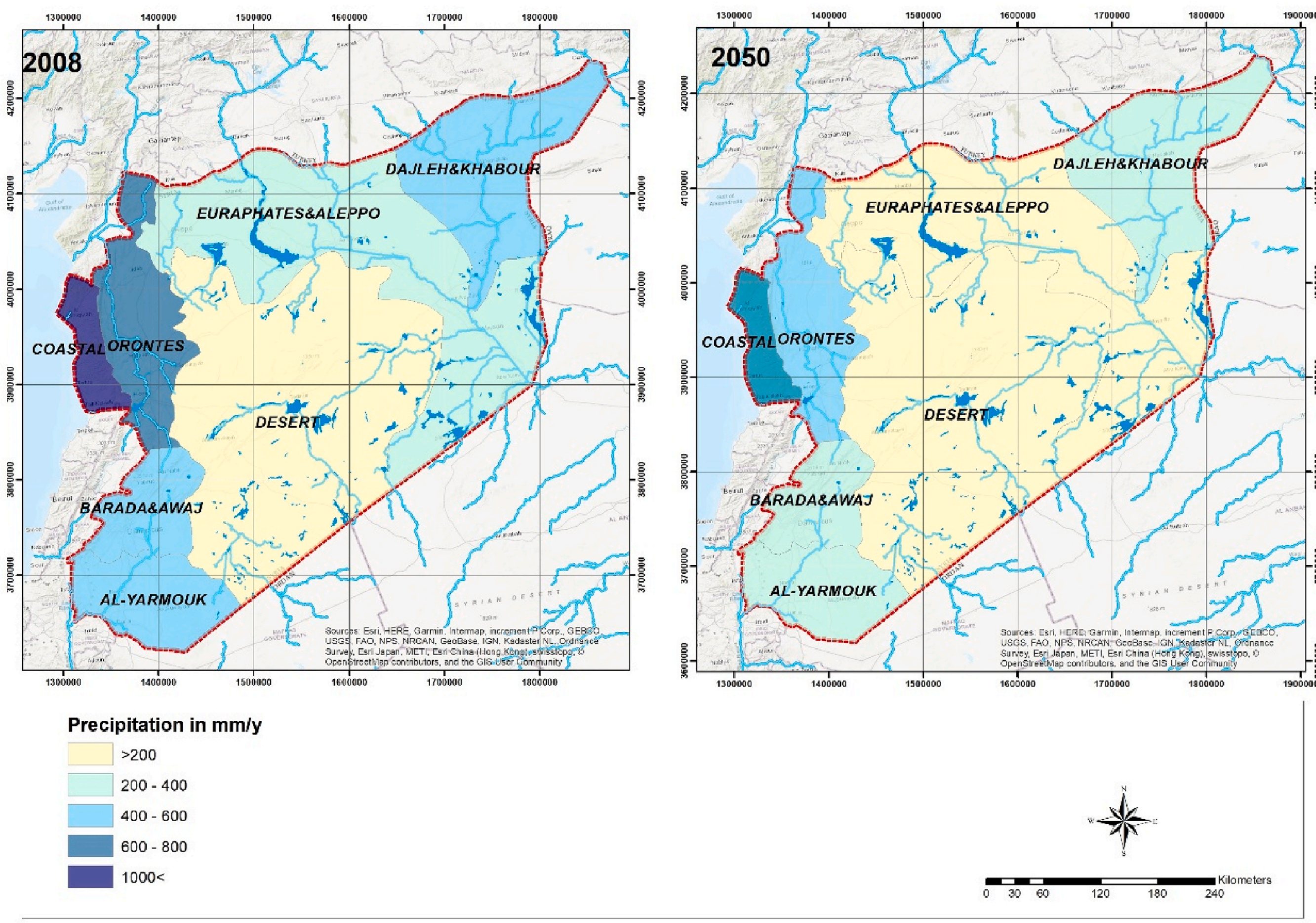

Fig. 16. Anticipation of precipitation levels in mm in Syria's basins in 2008–2050 (Based on Trondalen's 2009 study).

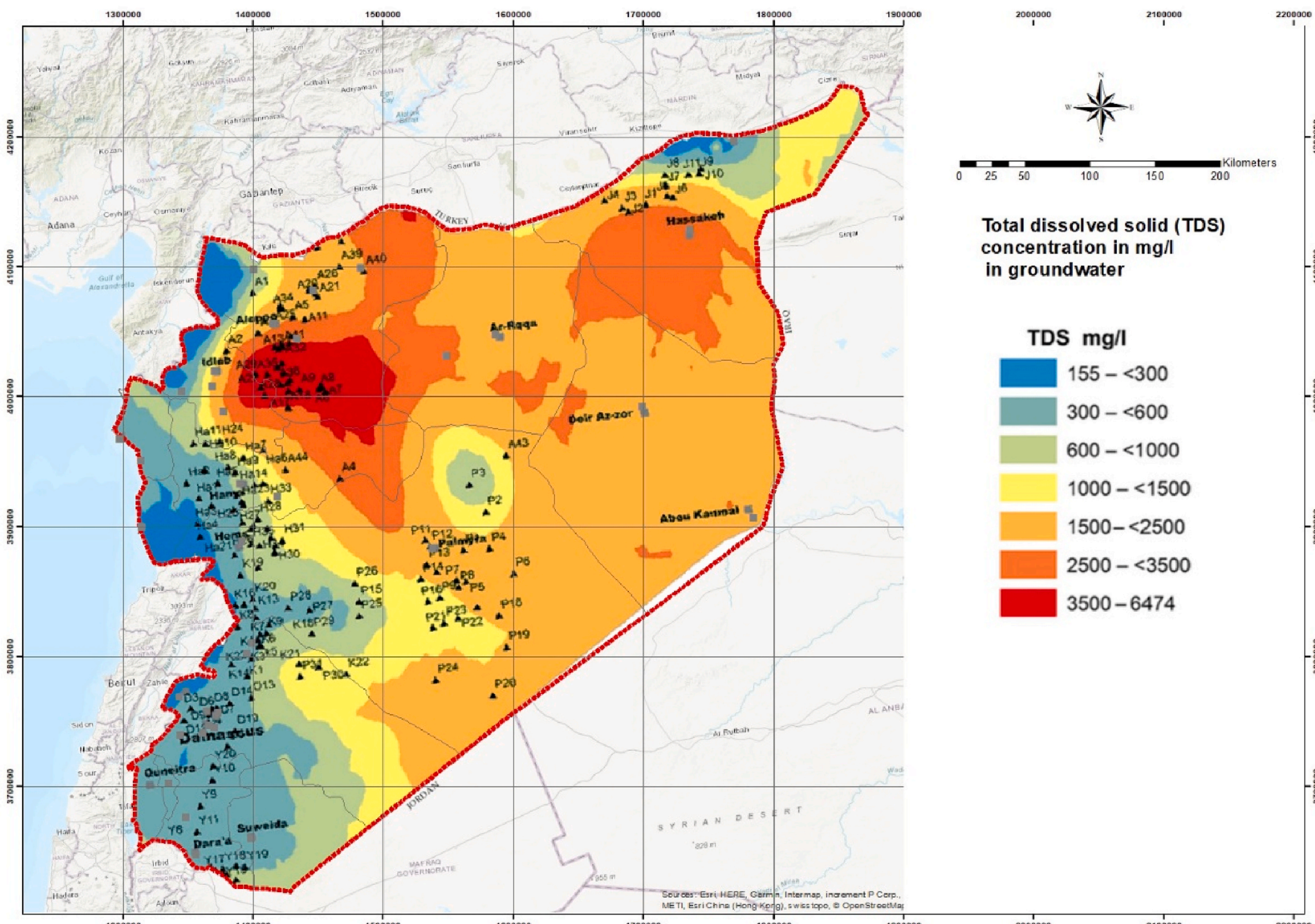

Fig. 17. Total dissolved solids (TDS) concentration in mg/l in groundwater in Syria (A. Al-Charideh and Kattaa., 2016).

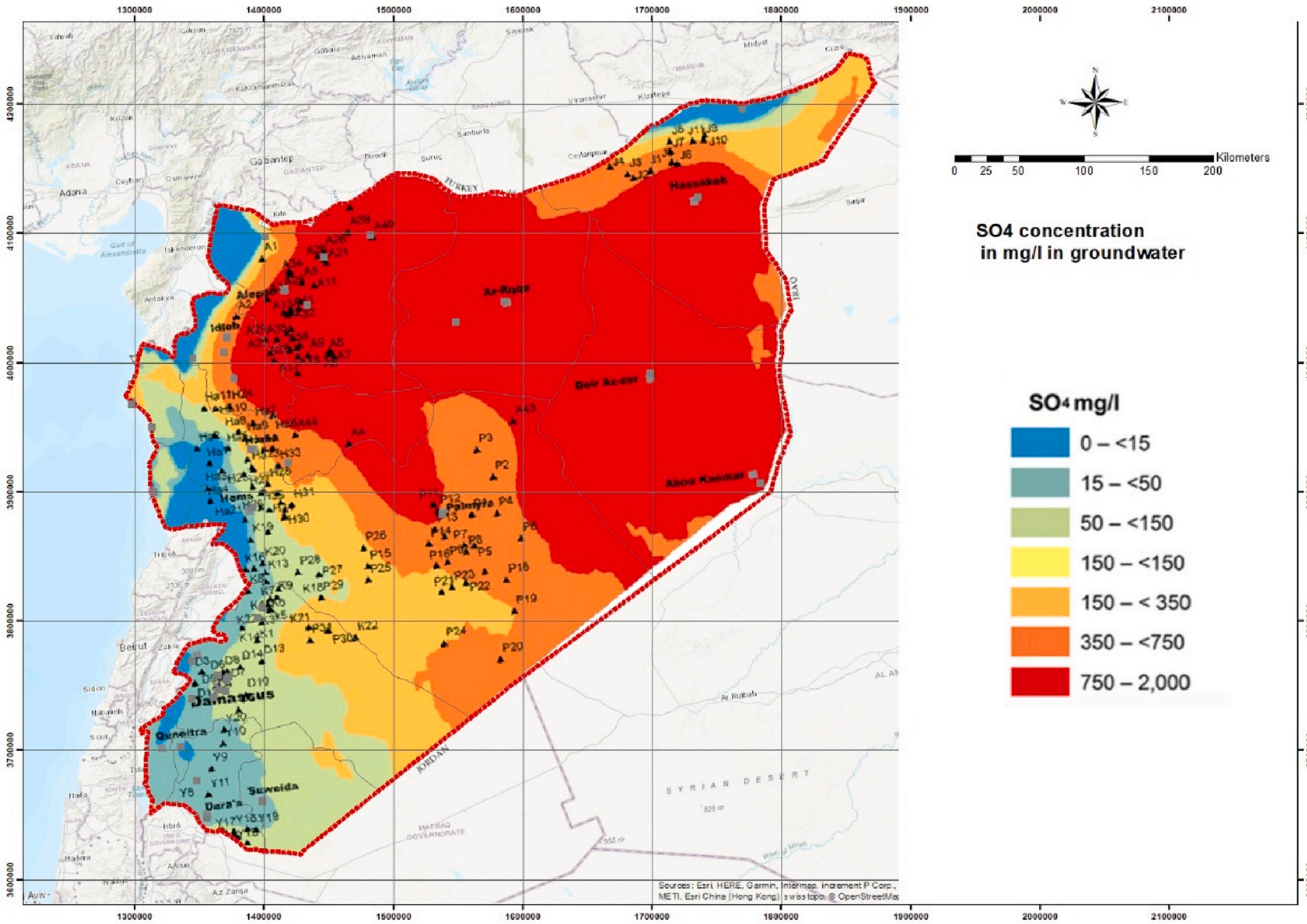

Fig. 18. SO_4 concentration in mg/l in groundwater, Syria (A. Al-Charideh and Kattaa., 2016).

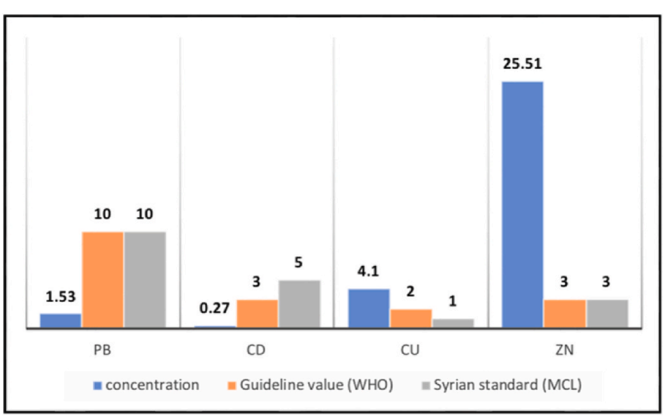

Fig. 19. The average concentration of heavy metals from 26 wells in Damascus Oasis (all units are in $\mu g/L$).

socio-economic development in many areas, continues to attract scientists' attention to preserve and protect groundwater quality. Also, global warming and climate change will continue to affect the region. In addition, anthropogenic factors affect water quality in Syria. As for the effect of warfare, it could be claimed that most of the damaged regions are based on permeable soil such as limestones, which increases the probability of groundwater contamination due to CW used, not to mention their spatial importance. Ghouta, for instance, was renowned as a place used for irrigation from groundwater. Since it is close to Damascus, people in the capital and other areas rely on Ghouta's irrigation products as their main source of food. If the groundwater is polluted, pollution could transfer to residents easily whether polluted groundwater is directly absorbed by trees or withdrawn by farmers to water their crops, without even considering people's reliance on this water for drinking. CW used in warfare is also examined. Chemicals used can produce harmless by-products when hydrolyzed. Therefore, they might not be hazardous. However, contamination might occur due to pollutants traveling through the soil. Consequences might be observed in the long term, assuming low concentrations of chemical pollutants. Therefore, thorough analyses of groundwater and soil quality are needed after the crisis in damaged areas. If such analyses are successful in proving higher concentrations of contaminants than the accepted standards, awareness must be raised in the community, and solutions for water and soil remediation must be taken seriously. Additionally, more sustainable water management must be established to preserve water quantities in the region since unsustainable withdrawing of groundwater will deplete the aquifers further. In Al Hassake and Der-ez-Zor regions particularly, groundwater has been unsustainably exploited, and with the absence of recharge of resources, this will worsen the situation quantitatively and qualitatively.

Groundwater exploitation in the Neogene aquifer system is limited by low aquifer productivity and water quality problems. A number of surface water irrigation projects initiated over recent decades in Syria have contributed to the artificial recharge of the aquifer. It is important to manage and control groundwater resources well. Improvements in the agriculture sector are needed for the sustainability of both surface water and groundwater, such as providing more wastewater treatment plants

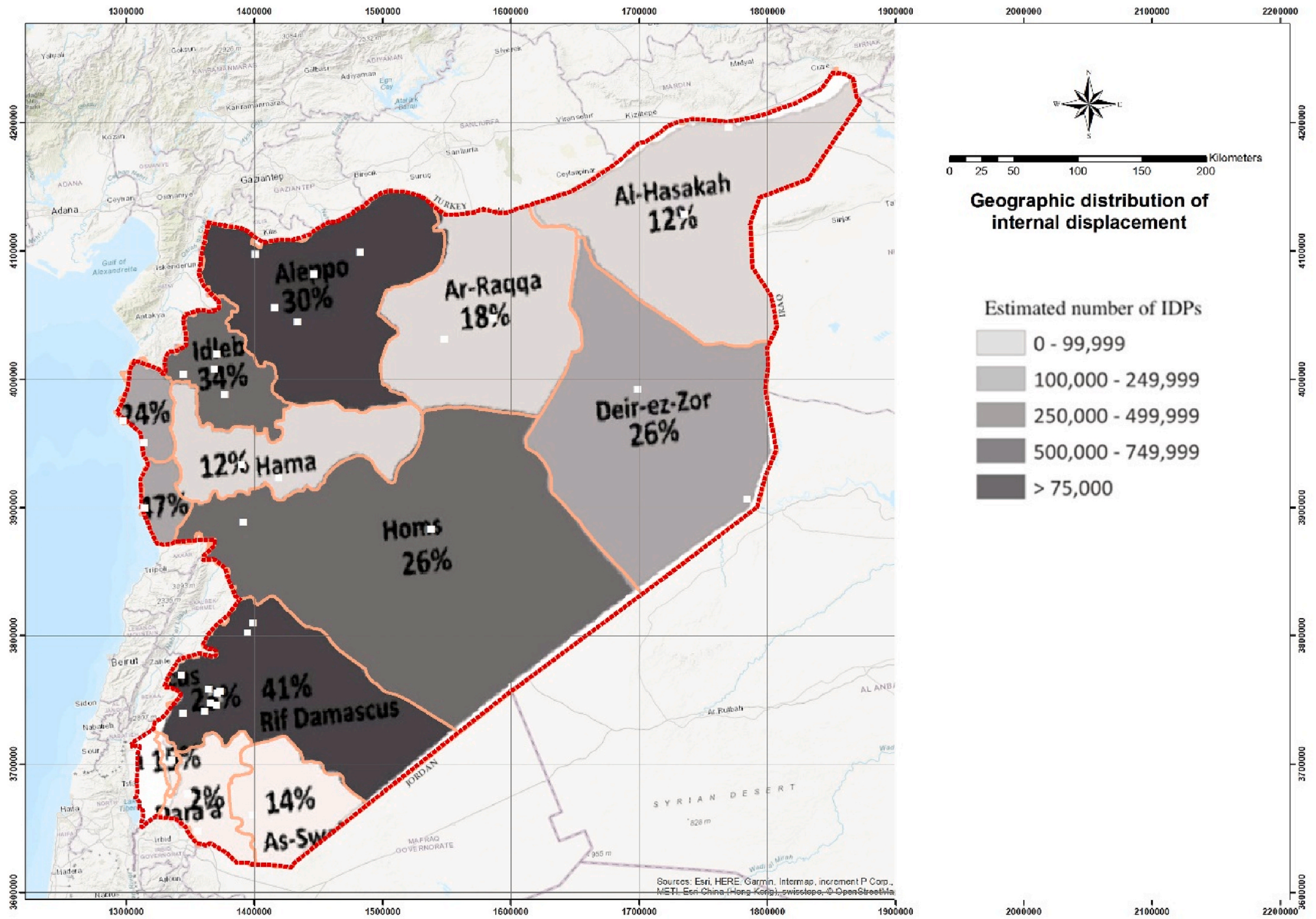

Fig. 20. Geographic distribution of internal displacement over time (Shannon Doocy et al., 2015).

Table 3
Areas exposed to CW attack.

Province	County	Date
Aleppo	Khan Al Asal	March 19, 2013
Damascus	Otaybah	March 19, 2013
Homs	Homs	December 23, 2012
Idlib	Salquin	October 17, 2012
Damascus	Darayya	March 13, 2013 and April 25, 2013
Damascus	Adra	March 24 and May 23, 2013
Damascus	Jobar	April 12 to 14 2013
Aleppo	Sheik Maqsood	April 13, 2013
Idlib	Saraqib	April 29, 2013
Hamah	Qasr Samrah	May 14, 2013
Damascus	Ghouta	August 21, 2013

Table 4
Geological and hydrological properties of groundwater (Paver and Roberts, 1947; Ponikarov and Mikhailov, 1989).

Region	Soil Type	Groundwater quality
Aleppo	Detrital limestones. The eastern slope of Kurd Dagh-conglomerates, sandstones, marls.	Good quality water (large supplies)
Damascus	Alluvial pebble beds and conglomerates, sandy loams; lacustrine clays and marls; marine calcareous sandstones.	Good quality water (large supplies) except for: Otaybah: Water with much NaCl and $MgSO_4$.
Homs	Continental conglomerates, sandstones, limestones, clays, marls, marine clays, tuff and breccia.	Good quality water (large supplies)
Hamah	Middle Eocene, soft chalky and firm nummulitic limestones, marls.	Good quality water (small supplies)
Idlib - Salquin	Continental conglomerates, sandstones, limestones, clays, marls, marine clays, tuff-breccia.	Good quality water (large supplies)
Idlib-Saraqib	Alluvial pebble beds and conglomerates, sandy loams; lacustrine clays and marls; marine calcareous sandstones.	Good quality water (large supplies)

and sustainable irrigation techniques. With the increase in water contamination and with the absence of poor water management, access to drinking water will be more of a problem than it is now.

After studying the geological and hydrogeological properties of regions that were affected by CW attacks in Syria and identifying the chemical agents and their by-products, it is very likely that the groundwater in the mentioned areas is contaminated with chemical leachate. Therefore, more studies to experimentally measure groundwater quality should be completed, as this does not just influence people's health today but also for generations in the future.

Groundwater quality is significant for people's health. In recent years, there has been a considerable growth of interest in environmental issues, including groundwater quality. This brings with it an enormous social responsibility to sustain and safeguard our environment by monitoring and solving risk factors that may be potentially threatening health. Therefore, a comprehensive protection and control system must be developed, including the establishment of a groundwater monitoring

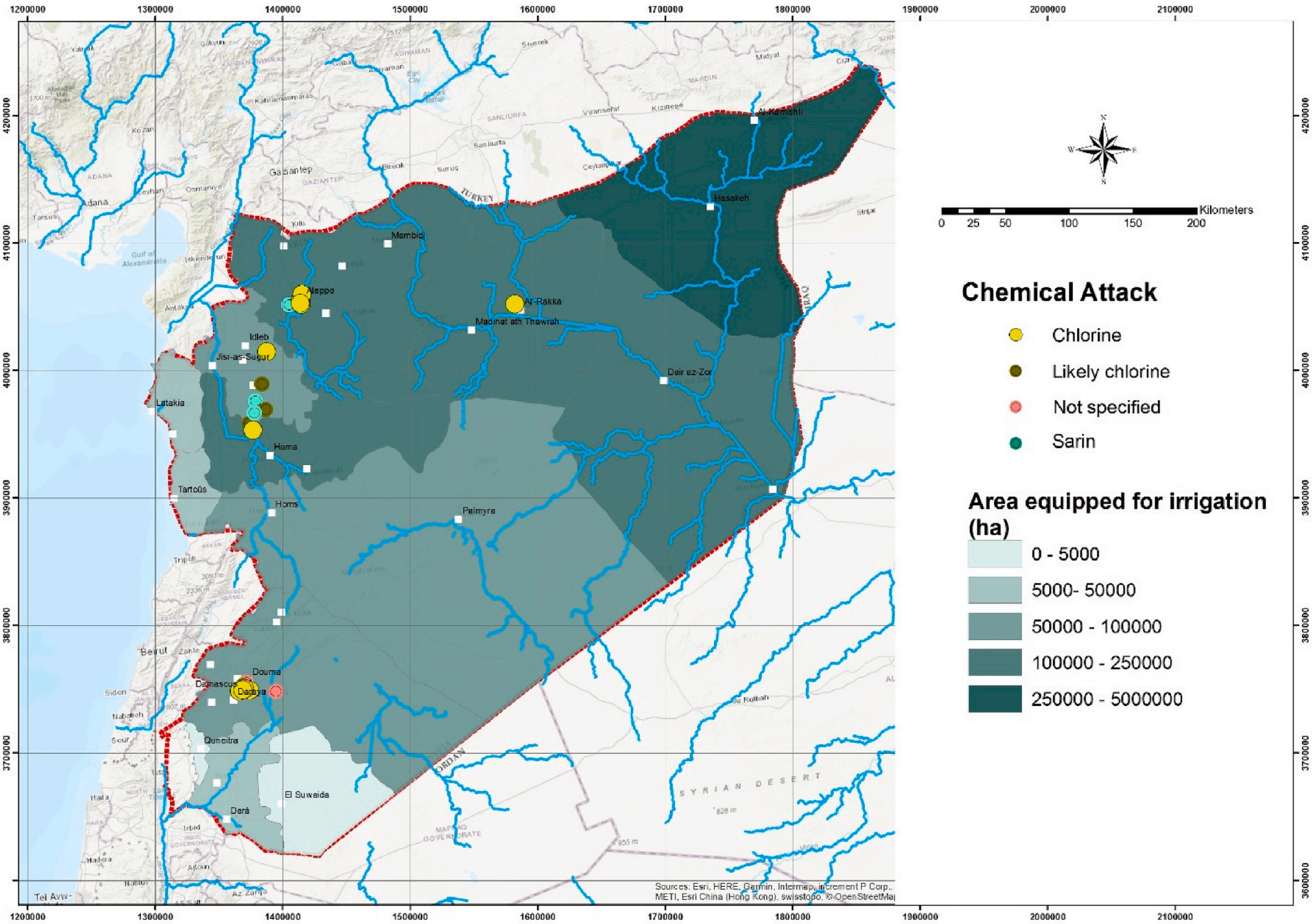

Fig. 21. The closeness of one of the chemically attacked regions to Rivers, irrigated areas.

system, the delineation of critical protection zones, and the control and elimination of sources of pollution. It is also increasing public awareness of the value and vulnerability of aquifers in Syria.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gsd.2021.100617.

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