Military aspects of hydrogeology: an introduction and overview

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Abstract: The military aspects of hydrogeology can be categorized into five main fields: the use of groundwater to provide a water supply for combatants and to sustain the infrastructure and defence establishments supporting them; the influence of near-surface water as a hazard affecting mobility, tunnelling and the placing and detection of mines; contamination arising from the testing, use and disposal of munitions and hazardous chemicals; training, research and technology transfer; and groundwater use as a potential source of conflict. In both World Wars, US and German forces were able to deploy trained hydrogeologists to address such problems, but the prevailing attitude to applied geology in Britain led to the use of only a few, talented individuals, who gained relevant experience as their military service progressed. Prior to World War II, existing techniques were generally adapted for military use. Significant advances were made in some fields, notably in the use of Norton tube wells (widely known as Abyssinian wells after their successful use in the Abyssinian War of 1867/1868) and in the development of groundwater prospect maps. Since 1945, the need for advice in specific military sectors, including vehicle mobility, explosive threat detection and hydrological forecasting, has resulted in the growth of a group of individuals who can rightly regard themselves as military hydrogeologists.

Water is essential to life, and it is not by chance that many Palaeolithic implements, which demonstrate the antiquity of man, come from river gravels, as the lives of early human hunter-gatherers were probably conducted in close proximity to rivers and springs. The first wells may have been created as primitive man dug into the drying beds of rivers or pools, following the water as it disappeared below the surface. Subsequently, as agriculture developed, villages were built adjacent to perennial streams or around groundwater sources consisting of flowing springs or dug wells.

The sinking of such wells has a long history, with the oldest known well, discovered in China, having been dug at least 5700 years ago (Chen 2000). Even earlier examples have been claimed from the Middle East (Issar 1990). In Egypt, by c. 2980–2750 BC, the technology existed to sink shafts through weak rocks such as poorly cemented limestones and sandstones, and records exist from 2160–2000 BC of well-sinking to supply water to men cutting monumental stone (Murray 1955). Subterranean aqueducts or qanats, constructed as a series of well-like vertical shafts connected by gently sloping tunnels, originated in the highlands of western Iran, northern Iraq and eastern Turkey from c. 1000 BC. Groundwater filters into these gently sloping tunnels, and is carried from its upland source to be used for drinking and irrigation in settlements located perhaps tens of kilometres away. Subsequently, the technology spread to adjacent countries throughout the Middle East and North Africa and into Europe with the spread of Arab culture (English 1968).

Significant early written references to groundwater and wells come from the Middle East, notably from books of the Bible. Meinzer (1934) has noted that the 26th chapter of Genesis, describing events arguably dating from c. 2000 BC, reads like a water supply memoir. In Genesis the patriarch Abraham and his son Isaac (revered successively by the Jewish, Christian and Islamic faiths) are credited with ordering the digging of wells in what is now southern Israel, notably at Beersheva (Fig. 1), and both became renowned for their success in well construction (Tolman 1937). The earliest recorded tribal disputes between Abraham (Genesis, chapter 21) and Isaac (Genesis, chapter 26) with their neighbours concerned rights to groundwater use – evidence of a potential source of conflict from early times.

Humans can survive for only a short period of time without water, and it has long been the practice in time of warfare for an invading army to cut off or poison the water supply to the enemy. To cite a Biblical example, the prophet Elisha is reported to have urged the kings of Israel, Judah and Edom, to ‘stop up all the wells’ in their campaign against the kingdom of Moab in c. 850 BC (2 Kings, chapter 3, as translated in the King James Version). Beleaguered cities could be particularly vulnerable to such means of attack. In c. 680 BC, King Hezekiah averted the danger to Jerusalem by the construction of a tunnel running from the spring at Gihon outside the city...
walls to the Pool of Siloam within them (2 Chronicles, chapter 32), a tunnel that exists to this day.

Although conflicts grading into battles have doubtless been fought since time immemorial, the first recorded conflict about which historians can write with a degree of confidence (MacDonogh 2010) was the Battle of Megiddo in 1456 BC between Pharaoh Thutmose III of Egypt and Durusha of Kadesh. This battle was prolonged, becoming a seven-month siege because the fortified city of Megiddo had a secure water supply. Megiddo (approximately 100 km north of Jerusalem) had a main well outside its defences, to which its garrison had access via an 18 m vertical shaft sunk from the citadel and into a horizontal tunnel. The siege ended only when the garrison was starved into submission. Water supply has long been associated with conflict more widely in this semi-arid ‘Holy Land’ region.

Fig. 1. ‘Abraham’s Well’, Beersheva, Israel: an ancient well site re-developed for 20th-century use, arguably the site of the earliest known dispute over groundwater rights, and one of the objectives of the British military advance from Egypt in World War I (Rose 2012a). Photograph from E.P.F. Rose.
INTRODUCTION AND OVERVIEW

The military aspects of hydrogeology are therefore reviewed here in terms of five distinct fields:

(1) The provision of adequate water supplies both to combatants and to support personnel, either close to or away from the point of conflict.
(2) The influence of near-surface water on the cross-country movement of personnel and vehicles, the placing of mines and the detection of explosive ordnance threats.
(3) The impact of the manufacture, testing, use and disposal of munitions on groundwater and the consequent remediation of contamination.
(4) The training of military personnel in hydrogeology, technical innovation and the cross fertilization that may take place between the military and civilian sectors.
(5) Groundwater as a potential source of conflict.

This review puts work described in all subsequent papers in this volume into a broader context. In so doing, it provides a comparative account of groundwater use by armed forces of both the UK and USA and those of Germany/Austria–Hungary, while outlining the historical development of ‘military hydrogeology’ as the technology of warfare has become increasingly sophisticated.

 provision of water supplies

Historically, as human population densities rose, our ancestors increasingly chose defendable positions for their settlements: earthworks dating from the first millennium BC are still a common and sometimes spectacular feature of the landscape of much of Europe, particularly England. These hill forts needed a water supply, but there is little evidence of groundwater exploitation. Few were built more than one mile (1.6 km) from a surface water supply, and it has been suggested that natural ponds, dew ponds or rainwater from hut roofs channelled into clay-lined storage pits may have provided short-term alternative sources (Dyer 1992). Later, stone-built forts were constructed in Europe, North Africa and the Middle East by the Romans, and subsequently in circum-Mediterranean regions by the Byzantine and Islamic empires, and many of these are known to have obtained water from wells.

In England, following the departure of the Roman legions in 410 AD, there was a lull in the construction of stone fortifications until the Norman conquest of 1066. After this, castles became a feature of the landscape, changing over the next 500 years to reflect advances in weapon technology. To survive a lengthy siege, each castle garrison required a secure water supply, commonly provided by one or more wells within the confines of its defences (Neaverson 1947; Ruckley 1990; Halsall 2000). As England became less prone to internal dynastic strife, and especially after union with Scotland to form the United Kingdom in 1707, fortification was concentrated on coastal areas to repel a potential sea-borne attack. Potable water is not always readily available at coastal sites and the provision of a secure supply may not be a straightforward undertaking. Mather (2012a) describes such an example, in which the water supply to British garrisons on both sides of the Thames estuary was enhanced, at considerable expense, to improve the defences of London against amphibious attack from Dutch and later French forces in the 18th century. Robins et al. (2012) include a reference to another notable example, Fort Regent on the Channel Island of Jersey, where a well was excavated through granite to a depth of 72 m in 1806–1808, yielding a supposedly inexhaustible supply.
of water. Later in the 19th century ‘Palmerston Forts’, built on the recommendation of a Royal Commission in 1860 to protect important Royal Navy bases from attack (Crick 2012), were typically provided with their own wells or storage tanks, holding water from civilian sources, sufficient for a 14-day supply. As part of the scheme, three forts were built offshore on shoals in the Solent (the strait separating the Isle of Wight from the English mainland) to protect the eastern approaches to Portsmouth Harbour. Each had a fresh-water well in the centre of its core (Mitchell & Moore 1993; Moore 1997), the construction of which posed considerable problems. Cylinders, 6 ft (1.8 m) in diameter were sunk to the base of the recent marine deposits, and borings were then continued into rocks of the underlying Bracklesham Group of Middle Eocene age (Whitaker 1910). Water in sands to a depth of 150–200 ft (46–61 m) was brackish, but an underlying greenish sandy clay, some 200 ft (61 m) in thickness, confined water in deeper sands that yielded a supply of excellent, though very soft, fresh water.

In modern conflicts, combatants, whether deployed in defence or attack, require potable water for drinking and cooking, but may utilize water of lesser quality for washing and non-personal uses such as mixing concrete, cooling engines and servicing laundries. In the Gallipoli campaign during World War I, troops of the 1st Australian Division sometimes operated at an extreme of as little as 1.5 l/day/man of potable water (Rose 2012a). However, under normal conditions, and especially in non-arid regions such as the Western Front across Belgium and northern France, demand was much higher. For the British Army in France, the scale adopted was 45 l/day/man for all purposes – drinking, cooking and ablution – and the same per horse or mule. In World War II, the German Army worked on the basis of a potable water ration of 7.5 l/day for soldiers in the field, which could be reduced to 2.0 l/day for a limited period under emergency conditions (Willig & Häusler 2012b). Methods of securing such supplies depend to a large extent on whether conflict is essentially mobile or static.

In the initial stages of conflict, troops may sweep rapidly through populated country where they are able to use existing water supplies. Under such conditions, the military requirement is for detailed information on existing facilities so that these can be secured rapidly before defenders have had an opportunity to destroy or pollute them, thus denying their use to the enemy. This latter policy was implemented by the Russians to help counter the invasion by the French Emperor Napoleon I towards Moscow in 1812. It was implemented also by the Germans in World War I, when they made a strategic withdrawal in northern France in 1917, devastating a 30 km strip of land as they went (Willig & Häusler 2012b).

The need for information prior to an invasion or the initiation of hostilities requires a detailed examination of existing water resource data. Primary data sources include published geological maps and memoirs, as well as topographical maps that show rivers and may indicate the position of springs, wells and water works. The initial task of W.B.R. King, when appointed the first British military geologist soon after the start of World War I, was therefore to study information available at the Geological Survey of Great Britain on the geology and hydrogeology of Belgium and Northern France, with particular regard to borings for water (Rose 2012a). Similarly, in preparation for Operation Sea Lion, the invasion of England planned for September 1940 but eventually abandoned, German geologists compiled a large number of ‘water supply’ maps and explanatory leaflets based on British topographical and geological maps published by the Ordnance and Geological Surveys (Willig & Häusler 2012b). Such surveys are still required today. For example, the US Army Corps of Engineers provided water resources information to units preparing to deploy to Kuwait following its invasion by Iraq in 1990 (Gellahch 2012), and British Territorial Army geologists provided similar advice to units deploying to Iraq in 2003 and Afghanistan in 2005 (Dow & Rose 2012).

Arid regions create particular problems because they are sparsely populated, and potable water resources are scarce and often confined to scattered oases. Water supply was a problem to combatants in the Palestine Campaign of World War I (Rose 2012a; Willig & Häusler 2012b). More extensive problems were encountered by forces on both sides campaigning in North Africa during World War II. These were acute for mechanized German–Italian troops as they advanced rapidly across Libya in 1941 and, with the ebb and flow of battle, into Egypt in 1942, before defeat at El Alamein and retreat to eventual surrender in Tunisia in May 1943 (Willig & Häusler 2012b). It was calculated initially that 75 trucks each carrying 85 jerry cans with a capacity of 20 l were required for transporting the daily requirements of just one army division between water supply points. However, both British and German forces came to make significant use of drilled boreholes to reduce the need for long-distance water transport, and wells sited with geologist guidance were progressively developed as the conflict oscillated across North Africa (Rose 2012b; Willig & Häusler 2012b).

Once areas are occupied or warfare becomes static there is time to improve existing water supply facilities or develop new sources. This is where hydrogeological advice becomes essential...
INTRODUCTION AND OVERVIEW

in order to maximize the use of resources and prevent the drilling of dry wells. Papers in this volume report on the work of earth scientists attached to German, US and British forces in World War I (Gellasch 2012; Rose 2012a; Willig & Häusler 2012a), World War II (Gellasch 2012; Robins et al. 2012; Rose 2012b; Willig & Häusler 2012b) and subsequent conflicts (Dow & Rose 2012; Gellasch 2012; Willig 2012).

The emphasis here has been on land forces, as these have provided by far the greatest demand. However, naval forces are sustained by land bases that also require adequate water supplies, for themselves and the ships they provision. This requirement has sometimes generated innovative use of potential resources, for example on Gibraltar (Rose et al. 2004). From their beginnings in World War I, the development of air forces has been a major feature of the 20th century. In the UK, since the formation of the Royal Flying Corps (later re-named the Royal Air Force) in 1912, c. 1250 sites have been developed at various times as military airfields, with a peak of 856 active airfields and the occupation of nearly 0.67% of the national land surface in 1945, at the end of World War II (Blake 2000). Criteria for peak-time site selection included ground permeability (facilitating swift drainage of surface water, reducing the costs of installing drains and avoiding hazards such as aquaplanning) and diurnal and seasonal temperature and soil moisture content changes (influencing susceptibility of the ground to cracking, heave and subsidence due to freeze–thaw and swell–shrink cycles). As airfields increased in size as well as numbers, so did the number of associated troops and the local requirement for water. During World War II, the German air force included serving geologists who guided the siting and construction of airfields and anti-aircraft gun sites and the provision of adequate water supplies (Rose & Willig in press). Similar tasks for British and US air forces were included amongst those dealt with by geologists and engineers serving under army command (Gellasch 2012; Rose 2012b).

World War I

World War I, the Great War of 1914–1918, was warfare on an unprecedented scale, and served as a catalyst for the adoption or development of new technologies by the armies of both sides in the conflict, especially on the Western Front across Belgium and northern France. As millions of troops were concentrated into a relatively narrow and static zone of operations, groundwater locally became an essential source of water supply and its contamination a hazard to health. Rose (2012a) shows how, at the start of the war, the British Army lacked the means to exploit groundwater from deep aquifers under operational conditions, but unprecedented high troop concentrations led to the importation of ‘portable’ drilling rigs from the USA to equip units of Royal Engineers for this purpose. With the means to exploit deep aquifers it looked to the Geological Survey of Great Britain (since re-named the British Geological Survey) for help (Mather 2012b; Rose 2012a), leading to the appointment from 1915 of Lieutenant (later Captain) W.B.R. King as a geologist to advise on water supply with the headquarters staff of the British Expeditionary Force in France. The British Army deployed pre-existing civilian well-drilling technology to new geographical areas, generated considerable quantities of new data on groundwater locations in northern France, parts of the Middle East and the Balkans, and also pioneered the compilation of a number of groundwater prospect maps for parts of western Europe.

US troops became involved in the conflict on the Western Front only in the last year of the war, and therefore deployed only a few geologists before the end of hostilities, led by Major (later Lieutenant-Colonel) A.H. Brooks, recruited from the US Geological Survey (Gellasch 2012). US military geological work on the Western Front has been extensively documented by Brooks (1920), and examples of US hydrogeological maps for their part of the Western Front, to the south of the British-held area and on older bedrock, have been illustrated by Rose (2009).

Although British and US armed forces made use of only a few military geologists during World War I, the Germans and their Austro-Hungarian allies made use of significantly more, seemingly at least 250–300 in total. Most were concentrated on the Western Front, and were assigned tasks relating to water supply, both the provision of potable water and the avoidance of contamination of ground or surface waters. Not only were there far more hydrogeologists serving with the German Army than with the British and US (and indeed French) armies combined, but they were operational across a greater geographical area and range of geological terrains from the early months of the war, so achieving technical results far more extensive than those of the Allies (Willig & Häusler 2012a). Rose et al. (2000) have compared the military use of geologists on opposing sides in the war, and Rose (2009) has illustrated and described examples of several British, German and US military hydrogeological maps from this period.

World War II

Both sides demobilized their military hydrogeologists following the end of hostilities in 1918, and
the expertise had to be acquired anew from 1939 at the beginning of World War II. However, unlike World War I, where the battle lines and so troop concentrations were relatively static for long periods, World War II was more a war of manoeuvre. Water supplies had to be provided for mechanized armies capable of swifter movement than in World War I, and for armies operational across much wider geographical areas and climatic regimes.

The British mobilized both military hydrogeological and well-drilling expertise only on the outbreak of war, deploying exactly the same geologist (W.B.R. King) to the same area (the Western Front) in the same role as in World War I (Rose 2012b). However, this time the British Expeditionary Force was soon defeated and evacuated, and for much of the war the Middle East became the focus of British military well-drilling and so military uses of hydrogeology. F.W. Shotton, recruited from the University of Cambridge and based in Egypt, used his geological knowledge from 1941 to guide deployment of the Royal Engineers’ well-boring sections operating in the Middle East, and was well placed to draw on the resources of the Geological Survey of Egypt. Additional hydrogeological expertise was contributed by the South African Engineer Corps and by a small number of geologists serving as officers within the Royal Engineers’ boring sections. Techniques were generally those in standard use, but geophysical prospecting methods were widely applied. Subsequently, planning for the Allied landings in Normandy on D-Day, 6 June 1944, was partly guided by groundwater prospect maps for the coastal areas of northern France, prepared as tracing overlays for use with the corresponding 1:50 000 topographical maps. Thirteen maps similar in style but 1:250 000 in scale were later compiled for northern France, Belgium and Luxembourg, and nine sheets extended coverage across northern Germany. These maps guided the emplacement of over 20 military boreholes in Normandy, a similar number in Belgium, and were used to initiate British military well drilling in northern Germany. Moreover, within the UK, rapid wartime growth in the size of the armed forces and the arrival of contingents of Allied troops from overseas generated a considerable demand for water to service the growth in number and/or size of airfields, camps and base installations (Mather 2012b).

After the USA entered the war in December 1941, the amount of military work carried out by the US Geological Survey (USGS) increased rapidly, leading to the formation of a Military Geology Unit in June 1942. Its work focused primarily on strategic and operational planning, particularly terrain intelligence reports for designated areas, which included sections on water supply. The latter listed groundwater sources together with data on quantity and quality (Gellasch 2012). Notably, water supply maps were compiled for the whole of Italy and printed in theatre by the British Royal Engineers. Hydrogeologists from the USGS also enlisted in the army to work on the development of groundwater supplies, and by 1943 some 10 hydrogeologists were working in Europe and North Africa. In contrast, professional geology in Britain was treated as a reserved occupation from which combatants could not be drawn and the experience of Survey geologists could not be utilized in the same way (Mather 2012b).

The military geological service formed within the German Army during World War I was disbanded at the close of hostilities, but re-founded in 1937 and included many veteran geologists of the earlier conflict. Germany thus began the war with a military geological heritage significantly greater than that of the Allies (Willig & Häusler 2012b). During the war it developed the largest organization ever to be dedicated to military applications of geology, with problems of water supply forming a significant proportion of its work. With the expertise it developed, the German Army was equipped to make use of groundwater under conditions that ranged from the extreme cold of the Eastern Front to the heat of North Africa. German geologists predicted water supply conditions in scheduled future combat zones (Willig & Häusler 2012b) and undertook more detailed studies of occupied territory (Robins et al. 2012). They produced a variety of ‘water supply’ maps at scales from 1:500 000 to 1:50 000 depending on the scale of the operation and the amount of published data accessible. Of all the countries taking part in the conflict, Germany made most use of military geological expertise in guiding the search for water supplies.

Post World War II

Following the end of World War II in 1945, most geologists providing technical advice to the military returned to civilian life. It was only in the USA that the subject of military geology was not abandoned. The USGS continued to provide assistance to US forces. Its Military Geology Unit was renamed the Military Geology Branch and incorporated into the formal structure of the USGS. However, work on water resources assumed less importance than during the two World Wars (Gellasch 2012). In the UK, after a period during which the military had no in-house geological support, from 1949 onwards a few geologists were commissioned to serve as part-time specialists within the reserve army, including a notable Geological Survey water supply geologist, Austin Woodland (Rose
Their successors occupy a similar role today. Since 1964 a specialist well-drilling and water development team within the regular army has provided expertise in the abstraction, storage, treatment and distribution of water (Dow & Rose 2012). An army was re-formed in the Federal Republic of Germany in 1956 and from the early 1960s has been supported by full-time geologists employed as civilians but with reserve army ranks. This group reached a peak in number of about 20 in the 1980s, with the provision of emergency water supplies for military sites among its principal tasks (Willig 2012).

Geologists from the main combatants in World War II, now allies, have worked on water supply problems in most of the areas in which conflicts have since developed. These include Vietnam (Gellasch 2012), the Persian/Arabian Gulf (Knowles & Wedge 1998), Bosnia (Nathanail 1998), Somalia and Kosovo (Willig 2012) and currently Iraq and Afghanistan (Dow & Rose 2012; Gellasch 2012; Willig 2012). Highlights of their work include the use of remote sensing to determine the location of active wells in denied areas of Iraq at the time of the Gulf War, the use of borehole geophysical measurements to support well drilling, and the use of down-the-hole-hammer drilling in Afghanistan. One feature has been the recognition that military units may not be appropriately equipped for drilling in new conflict zones. Thus the US Army deployed seven well-drilling detachments to base areas in Saudi Arabia at the time of the Gulf War. Although their drilling rigs were new, they were designed for use in Germany and so to drill only to 180 m, whereas the target aquifer in northern Saudi Arabia was found to lie at a depth of more than 450 m. Moreover, a typical well completion time was 60 days, too long to provide the water needed for military operations. This problem was resolved by hiring civilian contractors (Gellasch 2012).

Influence of near-surface water

In addition to its importance in providing secure water supplies for combatants, groundwater influences military campaigns in other ways. Ground made unexpectedly muddy following rainfall can affect the strength of soils and the mobility of troops, tanks and other vehicles (Fig. 2). For example, just after mid-day on 18 June 1815, near Waterloo in Belgium, a French army commanded by the Emperor Napoleon finally pressed an attack delayed for several hours by ground too wet to allow the deployment of supporting artillery. The delay proved disastrous, as it allowed time for Prussian forces to join the opposing British army led by the Duke of Wellington. In consequence, Napoleon’s last military thrust, one of the great battles of history, died on the fields of Waterloo, as much the result of wet ground as the tenacity of the coalition troops (MacDonogh 2010; cf. Priddy et al. 2012).

Surface water has long been recognized as a barrier to the movement of land forces. Castles were protected where feasible by a moat, a water-filled ditch, outside their perimeter walls. Rivers and their crossings (bridges or fords) and/or the presence of marshy or boggy ground have frequently influenced the site and outcome of battles. Examples from Britain, described by Younger (2012), illustrate how subtle landscape features associated with groundwater discharge affected the

Fig. 2. Tanks bogged in mud near Ypres, Belgium, in World War I. Water associated with Cenozoic clays and sandstones created problems for cross-country movement and the excavation of tunnels and ‘dugouts’. From Anon. (1922b).
outcome of two battles fought between the English and Scots. In 1513, despite outnumbering their English foes, the Scots lost the battle of Flodden Field in northern England a few kilometres south of the Anglo/Scottish border, because they failed to identify the presence of marshy ground, in which their columns of pikemen floundered. Over 200 years later, at the battle of Prestonpans a few kilometres east of Edinburgh, a Jacobite army consisting mainly of Gaelic-speaking Scots defeated a mixed English/Scots army raised by the Hanoverian Crown of the United Kingdom by finding a way around marshland upon which the Hanoverian commander had been relying as a natural defensive feature. Younger’s paper indicates that hydrogeologists preparing for military duty would be well advised to include studies of groundwater geomorphology!

Tanks first appeared on the battlefield in 1916 when they were used by the British Army. However, problems were apparent from the outset, particularly with respect to bogging in soft ground (Fig. 2). Such problems became more acute in the more mechanized conflict of World War II. Bogging by soft sand led to the development of ‘going’ maps by both sides in North Africa, with which tracked or wheeled vehicles were guided to avoid cross-country routes across unsuitable ground (Greenwood 2012; Willig & Häusler 2012b). Following the Allied landings in Normandy on D-Day, 6 June 1944, armoured units contested one another over ground in which conditions varied markedly with the weather, periods of rainfall producing significant changes in soil moisture and so ground trafficability. Factors influencing the movement of tracked vehicles over water-softerned ground were therefore studied in the USA and notably by a ‘Mud Committee’ established by the British Army in 1944 (Greenwood 2012). This made use of the then new science of soil mechanics to develop a method of classifying soils for military purposes. Research initiated in the heat of conflict during World War II has since been carried forward, in particular by the US Army, aimed at equipping soldiers with the knowledge needed to account for the impact of near-surface hydrogeology on mobility (Priddy et al. 2012). Among other things, such work has concentrated on developing methods for quickly assessing soil conditions to ensure adequate bearing capacity for roads and airfields, which need to be designated for rapid construction or repair as armies advance.

Military mining became a major feature of World War I, rapidly adopted by both sides on the Western Front. Tunnels were driven under enemy positions, packed with explosives, and detonated to breach the overlying trenches and fortifications. At the peak of operations, some 25,000 British and Commonwealth troops were assigned as tunnellers in efforts to breach German lines. Locally high water tables in Cenozoic clastic sediments, and especially their seasonal fluctuation (up to 9 m) in parts of the country underlain by Cretaceous Chalk (Branagan 2005), had considerable influence on mine construction and on the excavation of underground facilities (‘dugouts’), built to shelter troops from artillery, mortar and aerial bombardment. Geologic guidance was given to British tunnellers by Major (later Lieutenant-Colonel) T.W. Edgeworth David, Professor of Geology at the University of Sydney in Australia, who enlisted at the age of 57 and arrived in Europe with the Australian Mining Corps in May 1916. Together with the British geologist W.B.R. King (based at the same headquarters in France), he prepared tables for the Tunnelling Companies showing how much the water table would rise, assuming maximum rainfall over the winter months. These tables proved of great practical value.

Doyle (2012) gives examples of British mining operations in Flanders, which began in late 1914. The Cenozoic geology of this area features interbedded sands and clays. Mine galleries could be driven with relative ease (and silence) in clay, but needed to be supported to prevent crushing and collapse as a result of swelling clay minerals. Water-bearing sands were negotiated using a technique known as ‘tubbing’, in which cast steel sections, and later concrete rings, were driven to reach the clays beneath. The Germans also used this technique (Willig & Häusler 2012a), but failed to countermine British tunnelling at Messines in 1917, where near-simultaneous detonation of 19 mines became the most successful example of mine warfare in history (Doyle 2012).

In more recent conflicts, ‘mine’ as a military term has come to mean not a deep tunnel filled with explosive for major detonation, but a smaller explosive device, buried only shallowly in the ground, to be detonated by the unwary foot or vehicle. The detection of such explosive devices by remotely sensed imagery, and the differentiation of real threats from false alarms, depends to a significant extent on a scientific understanding of the near-surface hydrogeological properties of soils. Hydrogeology controls several of the critical processes that contribute to the complex sensor images that can currently be obtained from aeroplanes and/or satellites (Howington et al. 2012). To enable a better understanding of the various components that contribute to images, a computational test bed has been developed in the USA to produce realistic synthetic imagery from remote sensors operating in the visible and infrared portions of the electromagnetic spectrum. This is being used to isolate the phenomena behind the detection
physics and is a striking example of the expanding role of the ‘military hydrogeologist’ from someone who can find water to one able to apply knowledge of hydrogeological processes to a range of other problems.

Groundwater contamination and remediation

As with any other industry, the manufacture, testing and disposal of munitions, and the hazardous chemicals used in tasks such as degreasing, deicing and defoliation, give rise to waste products, the thoughtless disposal of which can result in land and water contamination. For example, in 1992 the US Department of Defense estimated that, as a result of its waste disposal practices, about 11 000 individual sites required some form of remedial action. Much of this contamination involved the land disposal of waste related to explosives, petroleum, oils and lubricants, industrial solvents, heavy metals and other military-unique chemicals (Miller & Foran 2012).

Arguably the best known example, quoted in many hydrogeological textbooks (e.g. Freeze & Cherry 1979; Fetter 1993) is that of the US Army’s Rocky Mountain Arsenal at Denver in the USA. Here, wastewater from the manufacture of nerve gas and pesticides was discharged into evaporation ponds from 1942. Contamination of nearby farm wells was first detected in 1951 and was especially severe in 1954, a drought year when irrigated crops died. Groundwater contamination extended at least 8 miles (12 km) from the ponds, indicated by elevated chloride concentrations. Eventually it was demonstrated that groundwater beneath and close to the ponds contained dozens of synthetic chemicals. A cut-off wall was constructed, across a bedrock valley containing permeable unconsolidated deposits, to stop further spread of the contaminant plume. Contaminated water was pumped from the up-gradient side of the cut-off wall, treated, and then returned to the aquifer through injection wells on the down-gradient side of the wall. Later, contaminated wastewater was injected, under pressure, into a 3671 m borehole through sedimentary rocks into underlying fractured schist and granite gneiss. One month after the first injection of wastewater an earthquake occurred and was followed by some 710 small tremors during the period April 1962 to September 1965. The epicentres of the majority of the shocks were located within a circular area centred at the Rocky Mountain Arsenal. Increases in fluid pressure created by the injections had the effect of triggering small movements on a pre-existing fault at depth in the vicinity of the injection borehole.

Many of the problems associated with contamination at military and defence sites are not dissimilar to those found in equivalent non-military sites and in urban and industrial areas. Thus, similar problems arise from the spillage and/or leakage of fuel at a military airfield to those that arise at a commercial airport such as London Heathrow (Clark & Sims 1998). Often, differences are those of scale, with traditional pump-and-treat technologies suitable for small industrial spillages being impractical to renovate aquifers contaminated with hundreds of millions of litres of fuel at a defence site (Miller & Foran 2012). However, some contaminated sites are unique to the military. These include grenade ranges as well as burning grounds and detonation sites for old ammunition where released chemicals can leach into groundwater.

Miller & Foran (2012) describe some of the research currently in progress in the USA, where environmental restoration programmes previously pursued by the individual services were rationalized in 1989 to address the cleanup of sites contaminated by past military use. Current efforts are concentrated in four main areas: site investigation, groundwater modelling, treatment technologies and the fate/impact of potential contaminants. Cleanup technologies are increasingly moving towards in situ solutions and away from methods that remove sediment or groundwater. An example is the use of lime at grenade ranges, where results show that mixing hydrated lime with soils to maintain a pH above 10.5, can reduce, by 70%, the concentration of RDX in pore waters. RDX, an acronym for hexahydro-1,3,5-trinitro-1,3,5-triazine, is the primary explosive in hand grenades and is a likely groundwater contaminant because of its slow dissolution rate and low adsorption onto soils. In Korea, quicklime, in this case derived from waste oyster shells roasted at high temperature, has been used to stabilize copper-contaminated soils on an army firing range (Moon et al. 2011). Such work has demonstrated that the addition of lime to raise pH can be a simple and effective treatment for ranges contaminated with metal fragments and munitions constituents such as RDX.

Training, research and technical developments

In the UK, the provision of an adequate water supply is such a basic requirement that the skills of identifying sites and digging wells were presumably passed down through the generations by early military engineers. However, digging wells was an expensive and time-consuming process: for example, a 330 ft (101 m) deep well at Sheerness on the southern side of the Thames Estuary took
some 13 months to complete (Mather 2012a). Drilled boreholes are normally much quicker and more cost-effective and by 1723 they were being used to deepen existing dug wells. These early boreholes were drilled using hand augers and so were only viable in poorly consolidated ground. In Britain it was not until the early 19th century that percussion rigs began to be employed by military engineers, being introduced c. 1835 (Jebb 1842; Bromehead 1942) by Colonel Charles William Pasley (later to become General Sir Charles Pasley and Europe’s leading expert on demolitions and siege warfare) (Porter 1889). In 1812, as a major, he was appointed the founding Director of the Royal Engineer Establishment (later to become the [Royal] School of Military Engineering), Chatham. He remained Director until promoted to major-general in 1841. Training was soon provided at the School on the siting and drilling of water supply boreholes from both engineering and geological perspectives.

Another Royal Engineer officer, Major Joshua Jebb (later Sir Joshua and Surveyor General of Prisons) soon published a guide to the theory and practice of sinking artesian wells (Jebb 1842). A few years later, a massive three-volume textbook, *Aide Mémoire to the Military Sciences*, was published to advise members of the ‘scientific corps’ (artillery and engineers) of the British and East India Company’s armies on technical aspects of their work (Lewis *et al.* 1846–52). This quickly went to a second edition (Lewis *et al.* 1853–62). Both editions included brief articles by the civilian civil engineer G.R. Burnell on water supply and wells. Courses of lectures, which included water supply, were given subsequently at the [Royal] School of Military Engineering, in 1873 by William Henry Corfield (1874) and later by Alexander Binnie (1878) and James Mansergh (1882). Corfield was then Professor of Hygiene at University College London and the others were distinguished civilian engineers, both serving in time as Presidents of the Institution of Civil Engineers.

The *Aide Mémoire* also included a substantial article on geology by Joseph Ellison Portlock, a Royal Engineers officer, who rose to the rank of major-general and served as President of the Geological Society of London. His article (Portlock 1848) included a description of the principles of hydrogeology, of boring apparatus for well drilling (e.g. Fig. 3) and summarized techniques then in use. Portlock may have influenced the decision to introduce geology into the curriculum at the Royal Military College, Sandhurst, in 1858. However, there is little evidence to suggest that the geology of water supply was of other than a passing interest to the British Army. Geological teaching at officer-training establishments in the UK was always at an elementary level and was largely discontinued before the end of the 19th century (Rose 2012a).

The lack of any real training in either geology or hydrogeology amongst British military engineers, or appreciation of the significance of the subject amongst field commanders, became evident after the start of World War I, as opposing armies...
expanded to an unprecedented size. Boring plant was first ordered for the British Army in the spring of 1915, and five Water Boring Sections of the Royal Engineers were created subsequently. W.B.R. King sited boreholes and developed specialist water supply maps for British areas of the Western Front in Belgium and northern France, roles for which he had no pre-war experience. Both geologist and drilling crews had to learn mostly ‘on the job’. At the end of the war, both the few British military geologists and the Boring Sections were demobilized. However, lessons learned during the conflict were distilled into a textbook on water supply (Anon. 1922a), which provided the basis for training of Royal Engineers officers between the wars. Although demonstrating the importance of geology for guiding emplacement of deep boreholes, even the revised edition of this book (Anon. 1936) advised that the employment of dowsers might save time and possibly fruitless labour in well sinking, suggesting that after 100 years of lectures and manuals only limited progress had been made in teaching British military engineers the value of geology. However, following the outbreak of World War II, the British Army was quick to deploy a geologist officer to guide well drilling in France, soon deployed one in this role to the Middle East, and included geologists among the officers of the [Water] Boring Sections progressively raised during the conflict (Rose 2012b). Military textbooks describing applications of geology published after World War II (Anon. 1949, 1976a) and a revised textbook on water supply (Anon. 1976b) were even more explicit in their description of geology as of prime importance in dealing with groundwater.

In the German-speaking nations, the importance of clean drinking water and good hygiene to soldiers was also recognized by the mid-19th century. At the start of World War I, responsibility for the supply of drinking water to German troops was in the hands of army physicians. Medical regulations introduced in 1907 specified principles for such things as the exploitation of groundwater in river plains and the construction of driven wells (Willig & Häusler 2012). Whether or not army physicians were given any training in the geology of water supply is yet to be established, but by late 1914 it was thought necessary for geological advice to be provided to support the consulting hygienic officer working inland from the Belgian coast. Initially, geology teams were incorporated into the surveying branch of the German Army, but, as the war drew to a close, geologists were put under the control of their main customer, the engineer branch. The teams included 126 ‘geological experts’, supported by technical staff, and developed overall into an organization making use of some 250 ‘geologists’. A significant proportion of their work involved guiding the provision of water supplies and the disposal of wastewater through the preparation of specialist reports, maps and manuals. The military geology service was disbanded at the end of World War I but the experiences of the officers, many of whom obtained academic or geological survey appointments, was distilled into several textbooks, which included sections and sometimes whole chapters on military aspects of hydrogeology. These formed useful manuals to help train a new generation of military geologists in the build up to World War II.

A German military geological organization was re-founded in 1937, and developed during World War II largely by recruitment or conscription of geologists of doctoral status from university teaching staffs or geological survey departments (Willig & Häusler 2012b). On the outbreak of war, the German Army thus had immediate access to experienced staff, some of whom had served as military geologists in World War I. In order for the geologists to learn from each other as the war progressed, a series of conferences was held, five during the quiet winter months of January and February 1940 and a sixth, more substantial course, in December 1940. Notable amongst the publications was a pocket guide for military geologists, issued during the latter stages of the war, which contained a chapter on water supply. Guidance on best practice was set out, including sections on the construction of boreholes and wells and the location of supplies in arid areas. There is no doubt that Germany began World War II with an ‘Army High Command’ that appreciated the value of geology and a group of trained personnel, including graduate hydrogeologists, capable of making an immediate impact. The influence of senior geologists is apparent from the decision, in October 1939, to ban the use of dowsers in all parts of the German Army and encourage the use of geophysical survey equipment rather than a pendulum or hazel twig.

The USA, guided to some extent by British experience, appointed two experienced geologists to serve with the American Expeditionary Force in France soon after entering World War I in April 1917, and a final increase in their number to 18 was in progress when the war ended. Among the hydrogeologists was Captain O.E. Meinzer, head of the USGS Groundwater Division from 1912, who was en route to France when the war ended. Although a number of authors subsequently highlighted the contribution of geologists to the military planning process, their message was completely ignored by the superintendent of the US Military Academy at West Point, General Douglas MacArthur, who eliminated courses in geology...
from the curriculum (Gellasch 2012). World War II brought a new approach, with the USGS and the US Army Corps of Engineers establishing a joint programme to provide geological expertise via a Military Geology Unit. Civilian hydrogeologists from the USGS contributed to intelligence reports but, by early 1943, ten survey hydrogeologists had been commissioned as army officers. Most served in water supply battalions and some commanded water supply companies. The USGS has continued to support US armed forces, although hydrogeology currently forms a less prominent part of section staff duties.

The different approaches to the provision and training of military hydrogeologists in the USA, Britain and Germany during the 20th century reflect the prevailing attitude towards hydrogeology in the three countries. In the USA, the USGS had a Division of Groundwater by 1908 with a staff of 80 by the beginning of World War II (Mather 2012b). This interest in the geology of water supply was supported by teaching and research in US universities. Similarly, in Germany, applied geology was taught in universities, and after World War I, often by teachers who had returned to academic life after service as military hydrogeologists (Willig & Häusler 2012b). In both countries there was a pool of trained personnel, particularly in the lead-up to World War II, who could be called up to support military operations. In Britain this was not the case. Little hydrogeology was taught in British universities until 1965 (Mather 2004) and there were only three members of staff in the Water Department of the Geological Survey of Great Britain at the beginning of World War II. These staff were seconded from field mapping units on the basis that hydrogeology was not a suitable career path for a Survey geologist (Mather 2012b). Thus, both the Americans and Germans were able to rapidly deploy trained geological staff with a background in water supply when required, whereas the British relied on able individuals who gained relevant experience as their tour of duty progressed.

In past centuries, advances in military engineering paralleled those in the civilian sector, and it is difficult to characterize any research and development activities in the field of hydrogeology as specifically military. Rather, military engineers contributed to the developing science and benefited from it. Thus the British military engineer Thomas Hyde Page (Mather 2012a) made significant advances towards understanding the hydrogeology of the eastern part of the London Basin, which were then followed up and developed by civilian geologists and engineers. Until the late 18th century, the discipline of civil engineering had not fully diverged from that of military engineering (West & Rose 2005).

In the 19th century, one technique in particular was used and made famous by British Army engineers. This was the Norton tube well (Fig. 4), invented in the USA but used by the British in the Abyssinian War of 1867/1868. It consisted of a pointed, partly perforated iron tube that was driven into the ground by raising and dropping a weight. These wells proved so useful in the campaign that the name ‘Abyssinian well’ was given to them by the general public and they became an indispensable item of equipment for the British Army, being used subsequently in South Africa and Egypt. In the late 19th century they were installed in many parts of Britain, particularly to supply breweries, by the civilian firm Le Grand and Sutcliff, who advertised as artesian well engineers (cf. Rose 2012b). During World War I they were widely used by both the British and German armies (Rose 2012a; Willig & Häusler 2012a) and subsequently by British consultants in developing countries, particularly in Africa (Beeby Thompson 1924).

In addition to tube wells, Robins & Rose (2009) have identified a number of other areas in which technical developments, driven by military needs, have benefited the wider water supply industry. These include the introduction into Europe in World War I of mobile drilling rigs (from the USA) and the Ashford filter (from India), the development in Europe during both World Wars of a variety of groundwater prospect maps, and the extended use of abstraction galleries, particularly in coastal dunes and arid-region wadi bottoms.

Research and development in hydrogeology directed at applications specific to the military, as distinct from hydrogeological research applied to military problems, has become significant only in the second half of the 20th century, since the end of World War II. Published research has originated mostly from the USA, but other countries are assumed to be carrying out similar work, keeping key results confidential, as is typical for most military research. Four papers in this volume describe studies directly funded by the US military. Three of these have been referenced in earlier sections of this review and show how the US Army has pursued research aimed at equipping soldiers with the tools and knowledge to account for the impact of near-surface hydrology on mobility (Priddy et al. 2012), how computer simulation has been used to explore the importance of hydrogeology in remote sensing for explosive threat detection (Howington et al. 2012), and how the Department of Defense has researched and developed technologies for environmental cleanup from past military activities (Miller & Foran 2012). A more general paper (Downer et al. 2012) discusses the need for hydrological forecasts by the US Army and the history of hydrological modelling and
model development undertaken to satisfy that need. The paper includes a description of the Gridded Surface/Subsurface Hydrologic Analysis (GSSHA™) model, which has been developed over the last 20 years. This two-dimensional, physics-based model has been successfully applied to assess a variety of problems in varied environments in many parts of the world. Research and products generated by the modelling programme are being disseminated widely to an international audience and used by public and private entities for scientific and engineering analysis. This work represents a good example of how work initiated and funded to solve problems of direct military interest can be successfully transferred to the civilian sector.

Groundwater as a potential source of conflict

Groundwater has no respect for national boundaries, and these are crossed by many significant aquifers. Implications of ‘internationally shared’ or ‘transboundary’ aquifers were largely ignored until 1997, when the International Association of Hydrogeologists, followed by the United Nations Educational, Scientific and Cultural Organisation (UNESCO), established groups to promote their study and the international cooperation needed for their management (Puri & Aureli 2005). It was recognized that conflicts might arise over the management of such aquifers, particularly if there was a lack of reliable scientific information on such parameters as groundwater abstractions, potentiometric levels, safe yields and water quality. Some observers have gone so far as to suggest that future wars might be fought over shared water, although so far the history of hydro-political relations worldwide has been overwhelmingly cooperative (Jarvis et al. 2005).

The key features of transboundary aquifers include a natural subsurface path of groundwater flow, intersected by an international boundary, such that water transfers from one side of the boundary to the other (Puri 2001). In many cases the aquifer can receive the majority of its recharge on one side, with the majority of its discharge occurring on the opposite side of the boundary. The subsurface flow system at the boundary might include both regional and local components. In legal documents, drawn up to allocate the equitable sharing of transboundary resources, the initial requirement must be agreement on the flow and movement of groundwater followed by its quantification. Conflicts can develop if socioeconomic pressures have already resulted in excessive water abstraction on one side of the boundary or relevant issues are not addressed because of institutional weaknesses and/or political pressures.

Fig. 4. ‘Experiments with Norton’s patent tube-wells’, as used by the Royal Engineers to supply water to British troops in Abyssinia: a demonstration in March 1868 near Thames Ditton on the edge of London, showing tube wells of three sizes (1.25, 2.5 and 4.0 in [c. 32, 64 and 102 mm] in diameter) being driven some 14 ft (c. 4.27 m) into the ground, one completed and pump fitted (foreground, right), and another as component parts (foreground, left). An American invention, credited as extensively used during the Civil War of 1861–1865, it was introduced into the UK and soon adopted for use by the Royal Engineers in 1867, its London patent being held by a Mr. J.L. Norton. From The Illustrated London News of 21 March 1868, pp. 272 and 280.
Since 2003, a UNESCO-led initiative on International Shared (transboundary) Aquifer Resources Management (ISARM) has worked to produce an inventory of transboundary aquifers (Puri & Aureli 2009). So far, 273 shared aquifers have been identified, 68 on the American continent, 38 in Africa, 65 in Eastern Europe, 90 in Western Europe and 12 in Africa. Some of these aquifers cover large areas, with the Guarani Aquifer System of South America extending over an area of at least 1.2 million km$^2$ of Brazil, Paraguay, Uruguay and Argentina, and the Nubian Sandstone Aquifer System, lying beneath the four North African countries of Chad, Egypt, Libya and Sudan, extending over some 2 million km$^2$. On a different scale, there are some 20 aquifers straddling the 3220 km border between Mexico and the USA, many of which serve as the main source of water for the rapidly increasing border population.

Of all the many transboundary aquifers, it is that shared between the Palestinians and the Israelis that has resulted in most tension. The Mountain Aquifer, lying beneath both the West Bank and Israel, is an important water resource. Composed of three components, the Western Aquifer crops out and is recharged in the semi-arid uplands of the West Bank, and groundwater flows west beneath Israel to discharge at springs near the Mediterranean coast (Mansour et al. 2012). The key to equitable apportionment is the determination of the long-term average recharge to the basin, but conventional estimates are difficult to make because of the complex geological structure and steeply sloping outcrop. Empirical formulae and process-based models have been used to constrain recharge to the Western Aquifer Basin, and a range of estimates is emerging. However, no single value or range can yet be selected that is justifiable and defensible. This can be obtained only by gathering relevant data (on rainfall, spring and wadi flows, and seasonal floods) to support future modelling work. Unfortunately lack of coordination and direction mean that not all of these data are being collected.

Experience suggests that if tensions already exist between countries these can be exacerbated by the challenges posed by transboundary aquifers. However, the recently signed Guarani Aquifer Agreement to regulate the sustainable use and protection of one of the world’s largest groundwater reservoirs (Foster et al. 2006) shows how an integrated approach can lead to a legal framework able to deliver effective transboundary aquifer management.

Conclusions

There are many ways in which groundwater and the science of hydrogeology are of relevance to the military. Traditionally, springs and wells provided a readily available source of water to castles and encampments, and in arid terrain the only source. If situated within fortifications, wells enabled the defenders to survive an extended siege and hold up the advance of an enemy. The skills necessary to dig wells were initially handed down through the generations by military engineers and it was not until the middle of the 19th century that the geology of water supply was formally taught at military academies, at least in the UK. One technique embraced by the British Army was the Norton tube well, which was used to such good effect in the Abyssinian War of 1868 that it was subsequently known by the name ‘Abyssinian well’.

World War I served as a catalyst for the adoption of new technologies, and both sides in the conflict pioneered the compilation of groundwater prospect maps, a concept largely unknown in the civilian sector. Germany and her allies made most use of hydrogeologists during the conflict, but at the end of the war both sides demobilized their geologists, and expertise had to be acquired anew when World War II began in 1939. However, this was more straightforward for the Germans and Americans than the British, because in both those countries, hydrogeology was by then established as a subject in its own right, taught in universities and with employment available within geological surveys. In contrast, hydrogeology was a fringe activity in the UK, with few practitioners and many water engineers often siting boreholes using water diviners rather than geologists. The latter approach was reflected in British military textbooks on water supply, which, as late as 1936, were still advising that the use of dowsers might save time! Dowising was practised by a few rogue individuals on both sides during the conflict, but with such initial official sanction only in the UK. Since the war, geologists from the main combatants, now allies, have worked on water supply problems in most conflict zones. Much use has been made of contractors to drill boreholes in non-combatant areas or where in-house equipment has proved unsuitable for work in geological situations beyond those for which it was originally intended.

As well as a welcome source of water supply, groundwater can create problems for the military engineer. Ground made muddy following rainfall or from groundwater discharge can affect the mobility of troops and vehicles. Examples from Britain show how groundwater geomorphology influenced the outcome of battles between the English and Scots in the 16th and 18th centuries, but the principle is timeless. In the 20th century, potential mobility problems led to trafficability studies in the USA and temporary establishment of a ‘Mud Committee’ by the British towards the end of
INTRODUCTION AND OVERVIEW

World War II. Since then, the US Army in particular has pursued research aimed at developing rapid methods to assess the effect of weather, and so varying soil moisture, on ‘going’. Such terrain analysis is known to be of continuing importance in many modern armies, although the most recent technical data are usually clouded in secrecy.

Groundwater also influences the construction of underground facilities, and hydrogeological advice is needed to predict water table fluctuations and the distribution of swelling clays. During World War I, both sides on the Western Front used underground tunnels to lay mines and excavated ‘dugouts’ to shelter troops. British tunnelling at Messines became the most successful example of mine warfare in history. In modern conflicts, mines are small devices often concealed just below the ground surface where, under certain conditions, they may be detected by remotely sensed imagery. The hydrogeological properties of soils are important in interpreting these images and distinguishing threats from false alarms, a topic of continuing research.

The manufacture and testing of munitions and hazardous chemicals for use on the battlefield can result in the contamination of groundwater and remedial action has often been necessary. Most problems are similar to those characteristic of non-military sites, but some contaminants, such as RDX, are unique to the military sector.

Groundwater does not respect international boundaries, and 273 shared aquifers have been identified that cross such boundaries. Although potentially a source of conflict, experience worldwide has been overwhelmingly positive, leading to some significant management agreements. A current exception is the Mountain Aquifer, which lies beneath the West Bank and Israel and where tension is likely to continue until accurate estimates of long-term average recharge are available. Unfortunately, current lack of coordination and direction mean that not all the relevant data are being collected to enable resources to be allocated equitably.

Prior to World War II, it is difficult to distinguish a separate subject of military hydrogeology. Rather, military engineers, and the geologists recruited as needed during times of conflict, applied existing techniques to problems encountered on the battlefield. In some fields, such as the widespread use of Norton tube wells and the preparation of groundwater prospect maps, significant advances were made, but no specific subject of military hydrogeology developed. This situation has changed since 1945 and, particularly in the USA, work has been directed towards problems (such as mine detection, remediation of contaminated land and groundwater, and battlefield mobility) specific to the military. There are now individuals who can more legitimately describe themselves as military hydrogeologists. As conflicts extend into the 21st century, demand for their services is likely to increase, in parallel with the development of sophisticated Geographic Information System (GIS) technology linked to developments in satellite and remotely sensed images, and process-based models.

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INTRODUCTION AND OVERVIEW


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