Hydrogeology of Afghanistan and its impact on military operations

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ABSTRACT

Afghanistan is a mountainous, arid country with limited surface water supplies. The complex geology in this country includes active tectonics and mountain ranges. Afghanistan is subdivided into three distinct hydrogeological areas: the Central Highlands, the Northern Plain, and the Great Southern Plain. Most groundwater is located in the Central Highlands, where water of sufficient quantity to meet the needs of the population is available primarily by digging wells into unconsolidated alluvial aquifers located in mountain valleys. A lack of sustainable, high-quality water supplies can have a negative impact on the ability to conduct military operations. An understanding of hydrogeological conditions is required in order to minimize exposures to natural and anthropogenic sources of contamination that may pose either acute or chronic health risks to military forces. This same scarcity of potable water can have a negative impact on the local population. Projects that improve the quantity and quality of water available to both military forces and the local population are important to improve the overall stability of Afghanistan.

INTRODUCTION

In response to the terrorist attacks of September 11, 2001, the United States initiated military action against the Taliban-controlled government of Afghanistan in October of that year. After the Taliban were removed from power and replaced by a democratically elected government, U.S. and Coalition Forces remained in Afghanistan in order to promote stability and security in the face of a continuing Taliban insurgency.

The number of U.S. troops in Afghanistan has increased significantly since 2001. By mid-2011, U.S. troop levels reached a peak of ~100,000 before declining to ~38,000 by early 2014. Providing logistical support for these large numbers of troops is problematic in the landlocked, mountainous, and arid country of Afghanistan.

United States and Coalition military forces in Afghanistan conduct a wide range of missions that include providing security, rebuilding infrastructure, training Afghan military and police forces, and defeating Taliban forces that seek to prevent these efforts. Missions take place across the country with troops operating from both large and small base camps. Logistical support for these base camps and the troops operating therefrom includes the supply of large quantities of potable water.

Water is essential to many aspects of military operations, especially in arid locations with limited surface water sources. Groundwater must be evaluated as the primary water source in these situations (Gellasch, 2012). Groundwater typically is the preferred source of water in terms of logistics and security, if accessibility and cost factors are comparable to utilizing surface water or imported bottled water (Gellasch, 2004). Surface water sources are difficult to protect from intentional contamination, and imported bottled water requires the use of convoys that may be subject to attack. When planning for base camps with water provided by groundwater wells, it is preferable to drill wells

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within the camp perimeter for logistical and security reasons (Willig, 2006).

Groundwater is therefore an important part of the logistical support for U.S. and Coalition troops in Afghanistan. Monitoring water quality is one of the primary missions of a U.S. Army Preventive Medicine Detachment. To support this mission, base camp wells were inspected, and untreated (raw) well water was analyzed (Gellasch and Calix, 2007). Based on these data, it is evident that understanding the geology and hydrogeology of Afghanistan is critical to understanding how to provide an adequate quantity of high-quality water supplies to support military operations. Also important is providing potable water to the local population. Lack of access to safe and reliable water supplies by the local population is widely seen as a national health and humanitarian crisis that undermines efforts to stabilize the country (Broshears et al., 2005). This paper will provide a review of the geology and hydrogeology of Afghanistan, based in part on the author's experience during a deployment to Afghanistan as the commander of the U.S. Army 71st Medical Detachment (Preventive Medicine). The purpose is to demonstrate how groundwater is important to support military operations and also to promote stability with the eventual goal of increasing safety and security for the people of Afghanistan.

It is important to note that due to ongoing military operations, the need to maintain operational security is important. Therefore, in this study, military-derived information that is linked to specific locations will generally be either consolidated with other locations or not attributed to a location.

Terrain and Climate

Afghanistan, located in south-central Asia, is 647,500 km^2 in area, which is slightly smaller than the U.S. state of Texas. This landlocked country is dominated by the rugged Hindu Kush Mountains, with plains in the northern and southwestern portions and elevations ranging from 258 m above sea level (asl) along the Amu Darya River on Afghanistan's northern border to 7458 m asl at Nowshak in the northeastern mountains (Central Intelligence Agency, 2009). More than one quarter of Afghanistan is situated above an elevation of 2500 m (Lashkaripour and Hussaini, 2008). Although some Coalition Forward Operating Bases (FOBs) are located at an elevation as low as 500 m asl, most are situated above an elevation of 1500 m, with some FOBs at elevations approaching 2750 m.

The climate in Afghanistan is typically dry with hot summers and cold winters. The majority of central and southeastern Afghanistan is classified as a region with subtropical steppe climate, while a large portion of the southwest is subtropical desert (Palka, 2001). In the southwestern desert, the annual rainfall may be only 50 mm per year. Areas of the southeast near the Pakistan border are influenced by monsoonal weather patterns, which bring significant amounts of rain in short periods of time. Precipitation is correlated with elevation, with locations below 1000 m averaging less than 100 mm/yr, while elevations above 4000 m in the northeast have annual averages that can exceed 1000 mm/yr (Uhl, 2006). For most lower-elevation areas, the potential evapotranspiration greatly exceeds precipitation for most months of the year (Banks and Soldal, 2002).

Elevation differences also affect temperatures across the country. Although only 120 km apart, the cities of Jalalabad and Kabul have significantly different annual temperature ranges. The summer temperatures in Jalalabad exceed 40 °C with winter temperatures normally above freezing. In Kabul, cooler summer temperatures (32.2 °C) are normal, and winter temperatures are commonly below freezing (Banks and Soldal, 2002). These differences are due in part to an elevation of 553 m at Jalalabad and 1791 m in Kabul (United Nations, 1986; Palka, 2001). Many of the FOBs have a climate similar to Kabul because of their high elevations.

Geology

Afghanistan has a complex geological history. Formations ranging in age from the Archean to the Quaternary include almost all types of sedimentary, igneous, and metamorphic rocks (United Nations, 1986). Although the tectonic and geologic history of the region has been documented in some detail (Treloar and Izatt, 1993), more than two decades of war and a lack of security have prevented most geological fieldwork in Afghanistan since the late 1970s. Fieldwork conducted in the 1970s was the basis for a recent U.S. Geological Survey (USGS) publication on the lower Helmand Basin (Whitney, 2006), and Montenat's (2009) recent publication on the Mesozoic of Afghanistan is based primarily on field data collected more than 30 years ago. A study by Badshah et al. (2000) includes a detailed 1:500,000-scale geological map of southeastern Afghanistan including portions of Nangarhar, Logar, Paktia, and Paktika provinces in addition to part of northwestern Pakistan. Application of modern technologies and techniques (e.g., geophysics and remote sensing) along with new fieldwork in Afghanistan will result in a better understanding of the geology. A recent geological map of Afghanistan containing more detail than earlier versions was published by the USGS and is available online (Doebrich and Wahl, 2006).

Afghanistan has been subjected to intense tectonic forces resulting in orogenic episodes and faulting. The Hindu Kush Mountains, an extension of the Himalaya Mountains, are a result of the Indian plate being subducted under the Eurasian plate. This subduction occurred primarily in the early Cenozoic and resulted in an assemblage of structural blocks separated by strike-slip and thrust faults that comprise major tectonic features of Afghanistan (Fig. 1). The only portion of the country that is not part of the Eurasian plate is the Katawaz Basin in the southeast. Bounded to the north and west by the Chaman fault, the Katawaz Basin is interpreted as a large flexural basin on the western margin of the Indian plate (Treloar and Izatt, 1993). The Katawaz Basin sediments are over 10,000 m thick and are considered to be the proximal portion of a paleo–Indus fan deposit (Badshah et al., 2000).

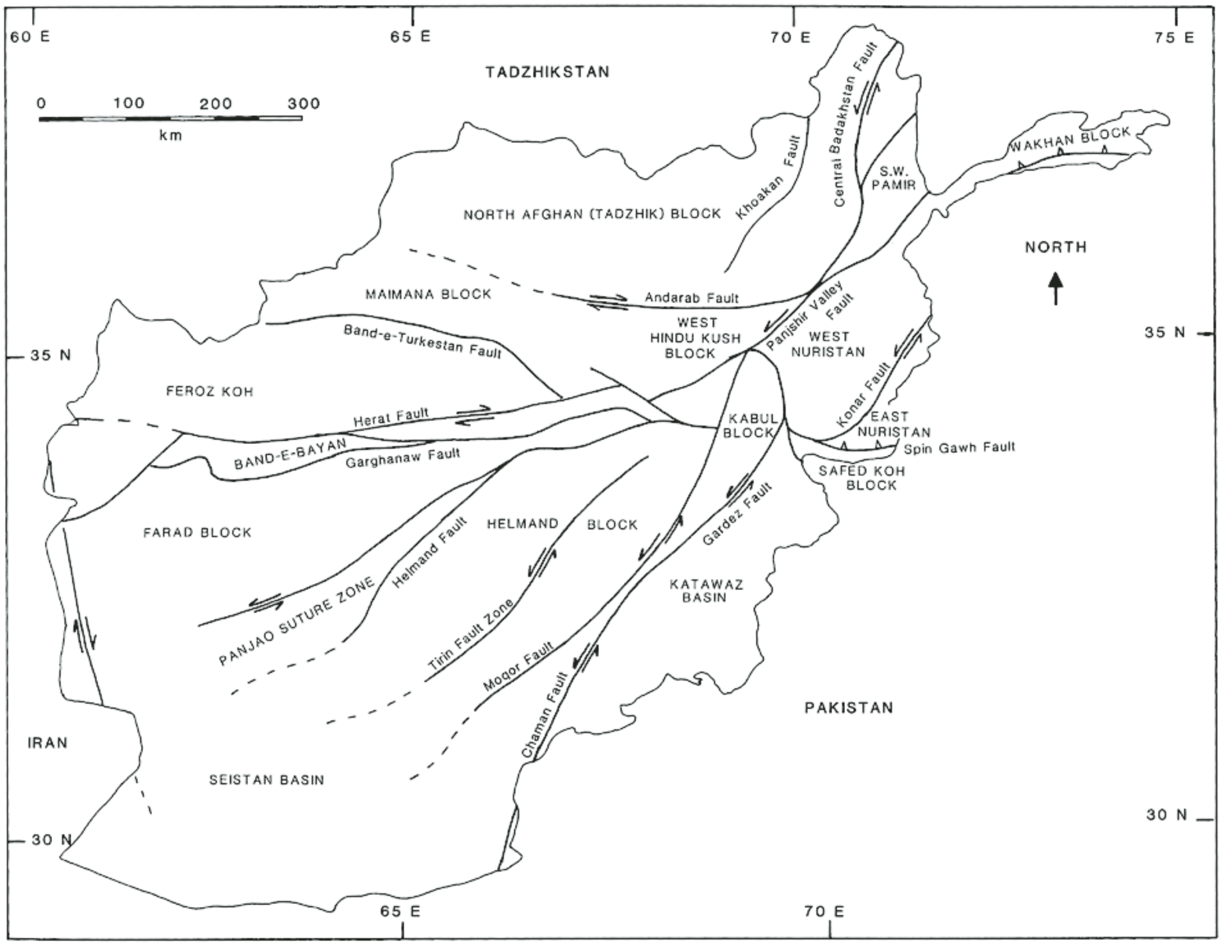

Figure 1. Map of the major crustal-scale fault blocks of Afghanistan and the strike-slip faults that separate them (Treloar and Izatt, 1993).

Another anomaly is the Kabul block, which was completely surrounded by ocean crust before the Paleocene. This is evident by the presence of the Kabul ophiolite to the west and the Khost ophiolite to the east of the block (Treloar and Izatt, 1993). Recent work by the U.S. Geological Survey (Ruleman et al., 2007) has outlined a number of Quaternary age faults in Afghanistan that indicate continued tectonic activity.

Erosion of the mountains has resulted in the valleys and lowlands being filled with Neogene and Quaternary sediments of alluvial and lacustrine origins. Deposits tend to be coarser cobble- to pebble-sized sediments proximal to the mountains owing to alluvial deposition with a general fining trend leading to distal fine sand and/or silt facies. Neogene units are generally finer grained and more lithified than Quaternary units. Total thickness of these sediments is variable but may exceed several thousand meters. Contemporary alluvial fan deposits are also present and may contain tens of meters of coarse-grained materials (Banks and Soldal, 2002). In the Kabul Basin (Fig. 2), geophysical surveying of these unconsolidated sediments has estimated a total thickness of 600 m with up to 15 m of loess present at the top of the sequence (Houben et al., 2009a). A simplified stratigraphic sequence for these deposits is contained in Table 1.

HYDROGEOLOGY

General Hydrogeology

Work by the United Nations Department of Technical Cooperation for Development (United Nations, 1986) grouped local water-bearing strata into three categories.

1. Alluvial and colluvial unconsolidated to semi-consolidated aquifers comprising ~20% of the total mapped aquifers; these aquifers contain ~70% of the available groundwater reserves.
2. Limestone and dolomite aquifers make up only 15% of the total mapped aquifers and contain ~20% of the available groundwater reserves.
3. The remaining 65% of aquifers are low permeability units that contain ~10% of the available groundwater reserves.

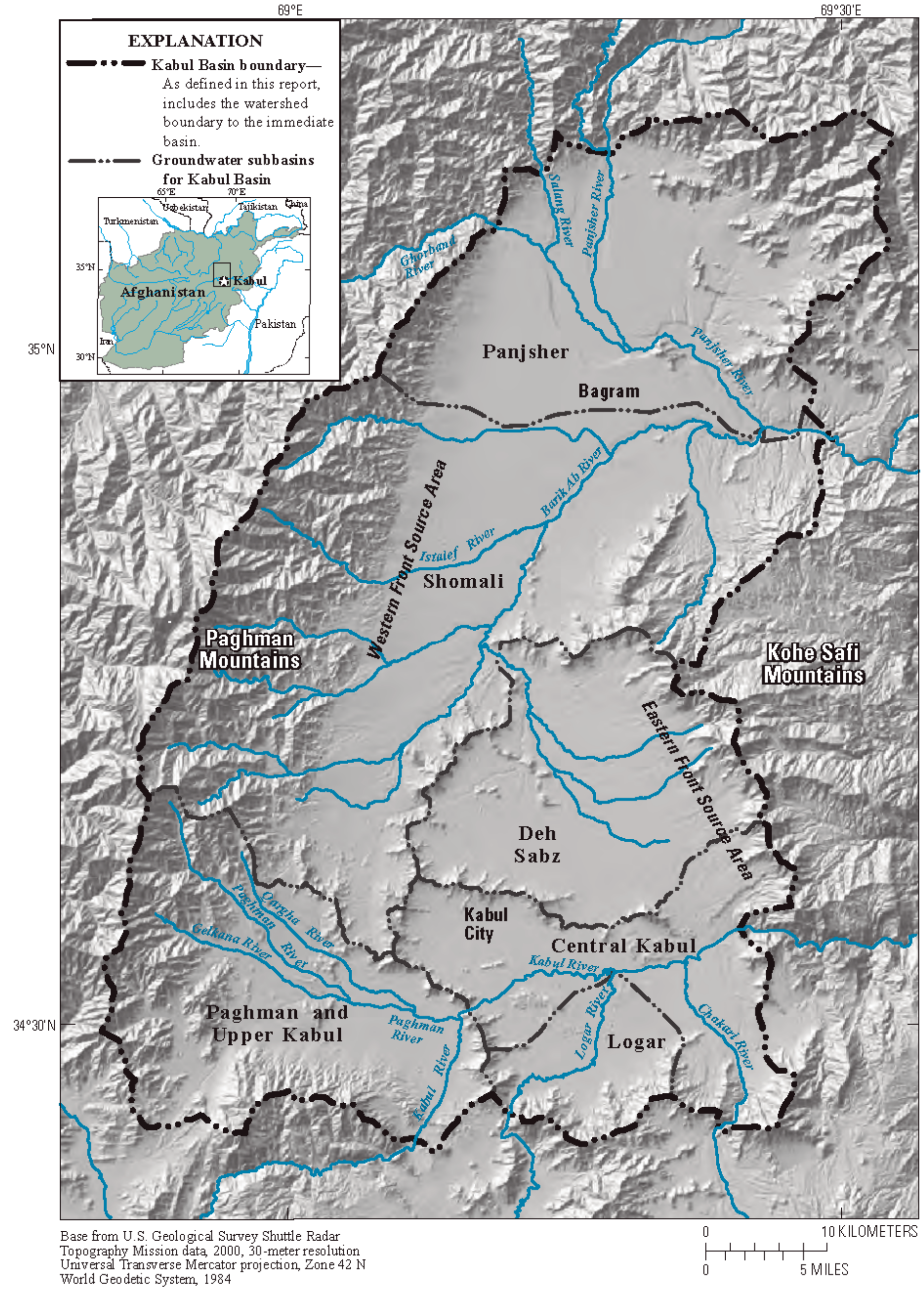

Figure 2. Map of the Kabul Basin with rivers and subbasins (Mack et al., 2010).

TABLE 1. SIMPLIFIED GEOLOGICAL SEQUENCE FOR NEOGENE AND QUATERNARY DEPOSITS IN AFGHANISTAN (BANKS AND SOLDAL, 2002)

Period	Location	Description
Quaternary		Unconsolidated fluvial, lacustrine, glacial, and alluvial sediments, with travertine and volcanics.
Pliocene (unconformably overlies Miocene)	North Afghanistan	Up to 11,000 m sandstone and conglomerate with interbedded clays and siltstone.
	Other parts	Up to 2000 m sandstone, conglomerate, clay, and siltstone. May also contain lacustrine deposits and volcanics. May be gypsum or brine bearing.
	Southwestern and western plains	Up to 100 m of lacustrine clays.
Miocene (unconformably overlies older rocks)	Northern Afghanistan	200–300 m siltstone, sandstone, and clay.
	Southern Afghanistan	100–500 m sandstone.

There are three hydrogeological regions shown on Figure 3: the Great Southern Plain (Siestan Basin) in the south, the Central Highland Region including the Hindu Kush mountain range and its associated ranges, and the Northern Plain (Amu Darya Basin) (United Nations, 1986). These regions can be further subdivided as shown in Table 2.

The intermontane stream basins of the Central Highland Region are arguably the most hydrogeologically significant in the entire country. These basins are primarily fault controlled and filled with a variety of unconsolidated materials ranging from alluvial, colluvial, lacustrine, and glacial deposits (Fig. 4). The aquifers in these basins contain a significant amount of fresh water. The most important of the intermontane basins include those near the cities of Ghazni, Khowst (Khost), Jalalabad, and Kabul (United Nations, 1986). Of these basins, the Kabul Basin has been studied the most extensively since 2001 (Broshears et al., 2005; Akbari et al., 2007; Lashkaripour and Hussaini, 2008; Houben et al., 2009a, 2009b; Mack et al., 2010). The Kunar River valley in eastern Afghanistan (Fig. 5) is another basin that contains an important aquifer system. According to Banks and Soldal (2002), these intermontane basins are similar to two other thoroughly studied locations: the intermontane trough between the Greater and Lesser Caucasus in Azerbaijan and the intermontane trough of the Altiplano, between the Cordilleras Oriental and Occidental of Bolivia.

Near the city of Kabul in the southern Kabul Basin, the three main rivers, Kabul, Paghman, and Logar (Fig. 2), share their names with the three coarse-grained, unconsolidated, interconnected aquifers that are adjacent to each other. The Kabul Basin geology consists of consolidated rocks in the mountains surrounding the basin with unconsolidated sediments in the basin serving as the principal aquifer system (Fig. 6). The Kabul, Paghman, and Logar aquifers provide most of the drinking water to the residents of Kabul. Some cementation is present in the deeper portions of the aquifer, which reduces well yield with depth. Each of these three aquifers near Kabul is capped by a loess layer that varies between 1 and 5 m in thickness and helps to protect groundwater from contaminants migrating downward from the

Figure 3. Map of Afghanistan with locations of hydrogeological provinces based on descriptions from United Nations (1986).

TABLE 2. HYDROGEOLOGICAL REGIONS AND SUBREGIONS IN AFGHANISTAN (AFTER UNITED NATIONS, 1986)

Hydrogeological region	Associated subregions and characteristics
Great Southern Plain	Registan area: Generally poorly productive with brackish to saline water except for eastern margin (Lora valley) with productive wells of slightly brackish quality.
	Dasht-e Margow area: Not hydrogeologically investigated.
	Piedmont area: Heterogeneous deposits yielding fresh to slightly brackish water. Near Kandahar, some artesian wells have been reported.
Central Highland	Carbonate massif: Limestone and dolomite, which is waterless at upper surfaces but with springs yielding significant discharge along unit contacts
	Noncarbonate complex: Pre-Quaternary formations yielding little to no water with only local importance. Comprises the majority of the region.
	Intermontane stream basins: Highest hydrogeological significance in the region.
Northern Plain	Stream valleys: Narrow belt of fluvial and delta deposits saturated with fresh water. Adequate yield and shallow depth to water.
	Eolian-proluvial complex: Shallow and deep aquifers contain brackish to saline water not suitable for consumption.

surface. The loess also inhibits infiltration and impacts recharge. Table 3 highlights some of the properties of these aquifers.

Groundwater Recharge

It is unlikely that most lowland areas receive a significant amount of direct groundwater recharge from precipitation due to evapotranspiration greatly exceeding precipitation (Banks and Soldal, 2002). These areas also contain lower-permeability, finer-grained sediment due to their distal location from the mountain alluvial fans that provide the majority of sediment to the inter-mountain basins. Some recharge may be attributed to infiltration of water through the beds of perennial streams in the valley bottoms. In the Kabul Basin, the main source of recharge along the valley bottom is from the rivers that are at their high-water stages during the spring snowmelt. Wells near the rivers experience large fluctuations in water level that coincide with river stage, indicating a strong hydraulic connection. Irrigation channel leakage and seepage from domestic sewage in urban areas may also provide some recharge to the Kabul Basin aquifers (Houben et al., 2009a).

The most likely source of groundwater recharge to the rural intermontane aquifer systems is from the mountains, where precipitation exceeds evapotranspiration for several months of the year (Banks and Soldal, 2002). Bedrock may be directly recharged by infiltration of precipitation. Snowmelt-fed streams and rivers can easily infiltrate into the coarser material at the head of alluvial fans. For most basins, it is not well understood

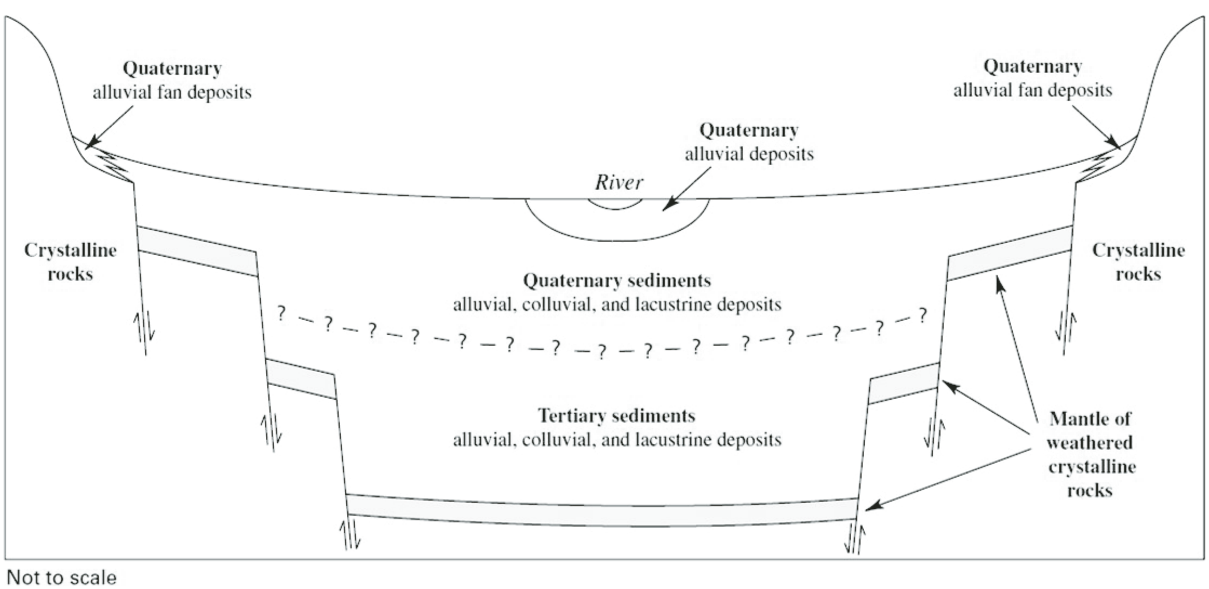

Figure 4. Generalized cross section of an intermontane basin aquifer system in Afghanistan (Broshears, 2005).

Figure 5. The Kunar River valley is an example of an intermontane basin in Afghanistan.

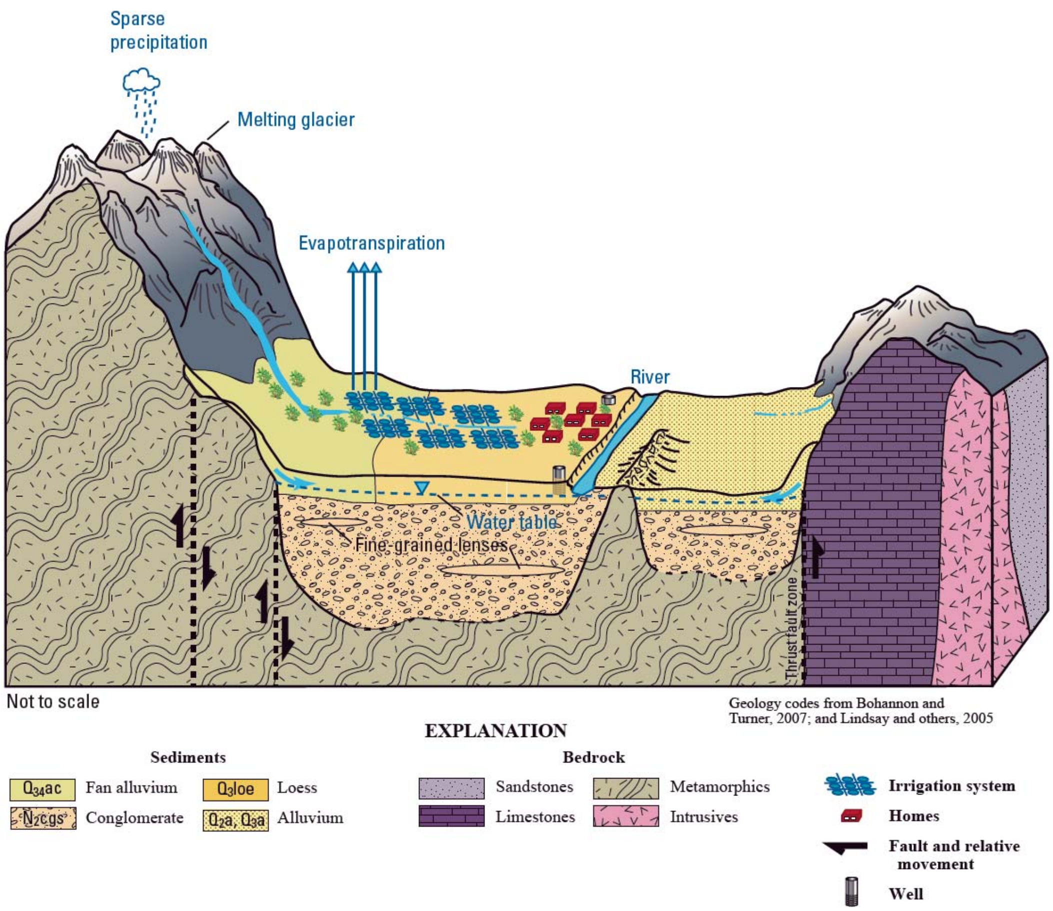

Figure 6. Geological cross section across the Kabul Basin modified from Mack et al. (2010).

TABLE 3. PROPERTIES OF AQUIFERS IN THE KABUL BASIN (AFTER HOUBEN ET AL., 2009a)

Aquifer	Thickness (m)	Area (km^2)	Hydraulic conductivity (m/s)	Notes
Paghman	45 average 70 maximum	40.0	0.2×10^{-4} to 3.0×10^{-4}	Mainly gravel and sand with some cementation. Considered best aquifer in basin with uniform permeability.
Logar	30–40 average 70 maximum	30.0	1.4×10^{-4} to 1.3×10^{-3}	Coarse grained with 10–15 m thick clay layers interbedded.
Kabul	40–80 total	22.5	0.5×10^{-4} to 7.5×10^{-4}	Conglomerate and sandstone water-bearing strata are 30–65 m thick with 2–9 m of sand and gravel above.

how much time is required for groundwater to be transported from the mountain recharge zones into the basin aquifer where it is typically utilized. Recent work conducted by the USGS (Mack et al., 2010) utilized tritium and chlorofluorocarbon (CFC) as environmental tracers that determined the ages of the shallow groundwater to be 20–30 years in the Kabul Basin. Ages were shown to increase with depth below the water table, and by using vertical age gradients, a 0.35–0.70 m/yr vertical recharge rate was calculated based on 25% porosity of the aquifer solids. These data indicate a large groundwater recharge component in the Kabul Basin that can be attributed to both river bank infiltration and anthropogenic sources (i.e., irrigation water and wastewater infiltration).

The 1998–2005 drought in Afghanistan had a negative impact on the amount of recharge to aquifers. Banks and Soldal (2002) indicated that in the previous three to four years water table levels had fallen 2 m in Zabul province, 2–4 m in Herat, 4–6 m in Kabul, and 5–8 m in the Kandahar area. Later work by Houben et al. (2009a) revealed that there was a total drop of 6–7 m from a 1965 reference datum in Kabul. Other factors impacting water table levels include increasing withdrawal of groundwater for domestic use and irrigation. Surface water was historically the primary source of water in Afghanistan, with the use of *karez* systems allowing the use of groundwater to augment the surface-water sources. A *karez* system relies on a series of mother wells that normally intersect the aquifer near the water table at the head of an alluvial fan and uses gravity to transport water through hand-dug, horizontal tunnels that are accessed by wells along their length. The design prevents the karez from removing too much water from the aquifer. If the water table drops too far, then the karez will dry up. The use of the karez dates back 3000 years to the Persian Empire, and a 2002 study indicated that more than 6700 karez systems existed in Afghanistan, although most are not currently in use (Williams, 2009). The more recent introduction of tube wells and electric pumps has enabled the population to withdraw a greater amount of groundwater from depth and subsequently increase the amount of water table decline.

Groundwater Quality

Military Water-Quality Data

The U.S. Army Public Health Command (USAPHC), formerly the U.S. Army Center for Health Promotion and Preventive Medicine (USACHPPM), is the lead organization for the collection of Occupational and Environmental Health Surveillance (OEHS) information within the U.S. Department of Defense. Part of the OEHS mission requires deployed preventive medicine personnel to collect raw (untreated) water samples from all water sources utilized by military personnel for potable water. These samples are sent to a USAPHC laboratory for comprehensive analysis. The collection and shipment of these samples from Afghanistan to the United States is logistically complicated, especially when sampling water from remote FOBs. Also, the level of water-quality analysis equipment available to deployed military units is limited (Gellasch and Calix, 2007). The OEHS samples are analyzed for dozens of contaminants including inorganic chemicals, metals, radionuclides, volatile organic compounds, semi-volatile organic compounds, pesticides, polychlorinated biphenyls (PCBs), herbicides, and various physical characteristics. Military water-quality data are evaluated using USAPHC Technical Guide (TG) 230, which utilizes Military Exposure Guidelines (MEG) as threshold levels of contamination (USAPHC, 2013). For operations in Afghanistan, the contaminant levels are based on risks associated with one year exposure assuming individuals ingest 15 L of the source water per day. This is the most conservative scenario since most troops will not drink that quantity of the source water, and, in most cases, the water will receive some level of treatment before consumption. It is also important to consider that a significant amount of water used for drinking is from imported bottled water. Based on the MEGs, risk-based recommendations concerning health and impacts to missions from drinking source water are made to operational commanders in the country.

Table 4 lists OEHS sample analytes that were detected at levels near or exceeding the 15 L/day one-year exposure MEG. In some cases, a base camp will have positive detects at multiple wells or at the same well over multiple sample rounds (generally every 6–12 months). The most common parameters exceeding MEGs are boron, magnesium, sodium, sulfate, total nitrite/nitrate as N, and turbidity. The numbers provided in Table 4 are only for raw-water samples collected between 2006 and 2009. Only samples classified as raw well water on the field data sheet are included in the data. Since dozens of preventive medicine personnel collected these samples, some samples may have been misidentified during collection. It has been observed that soldiers collecting raw-water samples from a location not immediately at

TABLE 4. GROUNDWATER QUALITY DATA FOR SAMPLES EXCEEDING MILITARY EXPOSURE GUIDELINES

Analyte	Number of base camps	Number of samples	Average concentration (mg/l)	Military Exposure Guideline (15 liters/day for 1 year) (mg/l)
Antimony	3	3	0.0082	0.002
Arsenic	1	1	0.024	0.02
Boron	6	7	2.30	0.42
Calcium	3	4	227.5	170
Chloride	2	3	1230	600
Fluoride	2	2	0.735	0.56
Iron	2	3	4.67	1.40
Magnesium	11	24	55.7	30
Sodium	10	12	158	60
Sulfate	10	16	448	100
Total dissolved solids	4	5	2441	1000
Total nitrite/nitrate, as N	8	11	11.5	7.5
Zinc	2	2	2.1	1.3
Turbidity	11	16	28.6*	1.0*

*Units are in (NTU) instead of (mg/l).
Source: Occupational and Environmental Health Surveillance database.

the wellhead may identify the sample as treated water even if no treatment has been provided. This most likely resulted in some samples not being included in the raw-water data. Well water sample collection began at some locations in 2002, but only the data for 2006–2009 were available for this analysis. These data provide a reasonable summary of which analytes exceed standards and pose a possible health risk for personnel at base camps.

Other Water-Quality Data

Several non-military organizations have collected groundwater-quality data from Afghanistan in order to assist the local population. Banks and Soldal (2002) collected data from across Afghanistan and found that the most common contaminants were nitrate, sulfate, magnesium, and sodium as compared to United Kingdom (UK) drinking water standards (DWS). Boron levels were found below the UK DWS of 2.0 mg/L, but almost half exceeded the U.S. Army MEG of 0.42 mg/L. Elevated boron levels are assumed to be linked with wastewater contamination from latrines and/or sewers. Exceedances of nitrate are attributed to contamination from wastewater in more urban settings and from fertilizer and/or manure sources in agricultural locations. The sulfate, magnesium, and sodium levels were attributed to elevated salinity levels in some aquifers, although these pose less of a health risk.

Broshears et al. (2005) and Houben et al. (2009b) conducted additional groundwater sampling, primarily in the Kabul Basin. In both of these reports water samples were found to have wide variability based on location within the basin. Water near central Kabul was of generally poorest quality in the basin with elevated concentrations of boron, dissolved solids, sodium, sulfate, chloride, nitrate, and magnesium. These elevated levels are attributed to a combination of anthropogenic sources, weathering of minerals, and evaporative concentration. The largest and most probable source of groundwater contamination is the uncontrolled release of sewage and waste. A significant portion of the wells within the basin also tested positive for *E. coli*, which is an indicator of fecal contamination.

Work done in the Kabul Basin by the U.S. Geological Survey (Broshears et al., 2005) compared water-quality parameters to U.S. Environmental Protection agency drinking water standards. Constituents with greater than 10% exceedances included *E. coli* (22.2%), nitrate as N (13%), boron (44.4%), chloride (10.6%), dissolved solids (54.2%), and sulfate (13.5%). In almost all cases, the highest values were more than an order of magnitude above the standard.

Military Hydrogeologic Work

The German Army (Bundeswehr) has deployed teams of military geologists to improve knowledge of the hydrogeology in portions of Afghanistan. In one study, the Bundeswehr purchased down-hole geophysical equipment to evaluate and log several wells in Afghanistan. The use of on-site geophysical methods improved the efficacy of percussion well drilling in northern Afghanistan near Kunduz in 2004 (Willig, 2006).

During 2006, the 521 Specialist Team Royal Engineers (STRE) (Water Development) (WD) of the British Army deployed personnel to southern Afghanistan as part of Operation Herrick in order to facilitate well construction and develop a better understanding of the local hydrogeologic conditions (Shute, 2006). Two eight-man water development sections spent four months at bases near Lashkar Gah in Helmand Province (Camp Bastion, FOB Price, and Lashkar Gah Provincial Reconstruction Team (PRT)) to ensure adequate water supplies for each location. Camp Bastion was a new base that was rapidly expanding and required seven 150 m boreholes to access the deep regional aquifer. Contractors drilled the wells under the supervision of the 521 STRE (WD) soldiers. Research conducted before the deployment indicated three shallower aquifers existed in the area, but they were not utilized by the British at Camp Bastion due to source security and the fact that the local population utilized those aquifers. The deeper aquifer was also able to supply a large quantity of water at a high enough flow rate to meet the camp's requirements. At FOB Price and Lashkar Gah PRT, the unit was required to refurbish existing wells and infrastructure.

The U.S. Army Corps of Engineers (USACE) Water Detection Response Team (WDRT) has been active in studying hydrogeologic conditions in many provinces. These studies provide detailed information on general geologic conditions, significant aquifer locations, and hydrogeologic properties. In some cases detailed inventories of existing wells are also compiled. This information is available to military well-drilling units and operational commanders to increase the likelihood of procuring adequate supplies of water for military operations. Most of this information is classified "For Official Use Only" and not available to the general public. The WDRT also provides more detailed information for military well-drilling units in order to assist them in determining the best sites to drill new water supply wells (Thomas Spillman, USACE WDRT, 2012, personal commun.).

Other Hydrogeologic Studies

The U.S. Geological Survey has worked closely with the Afghan Geological Survey to improve the understanding of hydrogeology within Afghanistan. In addition to the previously mentioned study of the Kabul Basin (Broshears et al., 2005), recent projects include studying the sources and rates of recharge within the Kabul Basin (Mack et al., 2010), sustainability of groundwater usage in the Kabul Basin (Mack et al., 2013, 2014), and a groundwater assessment of the Helmand Basin (Thomas Mack, U.S. Geological Survey, 2012, personal commun.). Other USGS efforts have resulted in the training of Afghan scientists in improved methods for assessing water quality through hands-on training (Ingrid Verstraeten, U.S. Geological Survey, 2012, personal commun.). Jack Shroder, a member of the Center for Afghan Studies at the University of Nebraska at Omaha, has been conducting research on Afghanistan for more than 30 years. The Center for Afghan Studies has provided geologic training to military units and contractors before they deploy to Afghanistan (Shroder, 2009). This training includes information on the geology and hydrogeology of Afghanistan. For units such as Provincial Reconstruction Teams and Agricultural Development Teams, this training has a direct impact on the Afghan population since these units have the mission to work with the local population in order to provide training and build capacity in many technical areas, including water supply (Stewart, 2014).

IMPACTS ON MILITARY OPERATIONS

Base Camps

There are only a few large bases in Afghanistan, but they contain a significant percentage of the troops, contractors, and other personnel deployed to the country. Although not a formal definition, included in this discussion of large base camps are U.S. and Coalition bases such as Bagram Airfield (northern Kabul Basin), Kandahar Airfield, Camp Bastion (near Lashkar Gah), and Forward Operating Base (FOB) Salerno (near Khost) with a population of more than 1500 personnel and a runway capable of supporting fixed-wing military aircraft (Gellasch and Calix, 2007). Large bases generally have significant levels of infrastructure (dining facilities, flush toilets, showers, laundry, etc.), which in turn leads to high water usage. Water treatment and distribution are normally provided by contractors, although treatment can vary from basic filtration systems to reverse osmosis depending on raw-water quality. Water is chlorinated after treatment to provide residual disinfection. Organic preventive medicine personnel living on large base camps conduct weekly water-quality analysis for basic parameters and contaminants. According to the U.S. Army Water Planning Guide, general water usage planning factors for large base camps indicate 120 L per soldier/day (U.S. Army, 2008). In order to support their populations, large bases tend to utilize multiple wells to provide the water supply.

As opposed to the large bases, small bases are more numerous but have smaller populations. Many of these sites are called Forward Operating Bases (FOBs). In general, a small base is considered to have fewer than 1500 personnel, but in many cases that number may be less than 500 or even 100 in some outposts. Most of these bases can only be reached by helicopter or ground convoy since they lack a runway for fixed wing aircraft. Infrastructure is more rudimentary in these austere bases, which results in a lower water usage. Contractor support is limited, and water treatment is more primitive—primarily chlorination of water in storage tanks—after it is pumped from the well. Preventive medicine personnel may only visit the FOB once per month to provide a check on water quality, although personnel assigned to the FOB usually monitor water quality more frequently. Due to logistical obstacles, routine Occupational and Environmental Health Surveillance (OEHS) comprehensive water sampling and analysis may not occur at more remote locations (Gellasch and Calix, 2007). According to the U.S. Army Water Planning Guide, general water consumption planning factors for smaller base camps indicate a usage of 50 L per soldier/day (U.S. Army, 2008). A FOB may only have one or two wells as the primary water source.

Well Installation for Base Camps

During a survey of base camp wells in 2005, it was apparent that no central database of wells existed at the Combined Joint Task Force 76 headquarters at Bagram Airfield. Leadership at each base camp determined water requirements and hired local Afghan well drillers to install additional wells as needed. These wells were generally not constructed to any uniform standard, and well logs were not available. Due to turnover in base camp personnel and a lack of records, no one on a base camp was likely to have firsthand knowledge of any well more than one year old. The equipment and techniques utilized by local Afghan well drillers is generally similar to what was used in Europe 60 years ago (Willig, 2006) and relies mostly on tripod-mounted percussion (cable tool) drilling methods. Figure 7 is an example of typical Afghan well-drilling equipment used to construct base camp wells and described by its owner as a "modern drilling machine." Although U.S. military well-drilling units exist in the Army, Air Force, and Navy (Gellasch, 2004), a request by the author in 2005 to deploy one or more of these units to Afghanistan in order to construct base camp wells was denied by higher headquarters. The lack of data for base camp wells, and especially a lack of well logs, complicated efforts to develop a better understanding of the local hydrogeology near these camps. Many of these wells were found to have an inadequate sanitary seal and poor wellhead protection in general.

In the autumn of 2005, the author was contacted by the facilities manager of a FOB because one of the base's two wells had stopped functioning. An onsite visit was conducted to determine the cause of the problem and to find a solution. The well had been installed by a local Afghan well driller, and no records were available. After investigating the well by utilizing a modified camera originally designed to search for explosives in small spaces, it was determined the well was cased to the water table at ~43 m below ground level but not screened below that. The coarse alluvial sediments through which the well had been drilled collapsed around the well pump, and the well had to be abandoned. After modifying a general well specification guide obtained from the U.S. Army Corps of Engineers, the author worked with a local Afghan well driller (through an interpreter) to ensure that a new well was properly constructed (Gellasch, 2012).

Figure 7. Local Afghan well driller's "modern drilling machine" during construction of a base camp well.

In more recent years, U.S. military well-drilling teams have been deployed to Afghanistan to install new base camp water supply wells. These teams have received assistance from the U.S. Army Corps of Engineers WDRT in order to determine the best locations for drilling wells. The WDRT requires all new wells to be logged and the information sent back to them for archiving (Thomas Spillman, WDRT, 2012, personal commun.). The well data collected has helped improve the knowledge of local hydrogeology in those areas.

Support to Military Forces

In almost all cases, groundwater is the only reliable, secure water source for military base camps. Although information on the local hydrogeology may be limited, the level of knowledge continues to improve. As water-quality data over longer time periods become available, they can be synthesized for a more comprehensive analysis of the health risks posed by consuming the water. Depending on the types and amounts of contaminants, appropriate water treatment technologies can be utilized to ensure the water is potable. While reverse osmosis technology is available and will remove almost all contaminants of concern, that level of treatment is not required for most groundwater sources. Reverse osmosis technology is less efficient than other technologies because it is energy intensive, requires frequent maintenance, and produces a large quantity of backwash water that is not usable. The key is to find the best technology to properly treat the water for human consumption while limiting the waste of water and energy. As efforts continue to produce more drinking water locally instead of importing bottled water from outside Afghanistan, it is important to have an improved understanding of the quantity and quality of local groundwater supplies.

IMPACT ON LOCAL POPULATION

According to the World Health Organization, only 13% of the Afghan population had access to safe drinking water in 2001, and by 2008, that figure had grown to 27% (World Health Organization, 2010), primarily due to efforts by many non-governmental organizations (NGOs). Domestic water consumption varies between 20–40 L/person/day. Efforts to improve the quantity and quality of water available to the local population have focused on drilled wells (tube wells) and the use of pumps to extract larger quantities of water than can be obtained from older methods such as a karez (Uhl, 2006). In addition to constraints posed by poor water quality in many wells that have limited sources of recharge, the increasing use of groundwater may not be sustainable.

More than 95% of the well water used by the local population is for irrigation of crops (Uhl, 2006). The over-abstraction of groundwater for irrigation purposes has a direct impact on nearby drinking water wells. In some instances, drinking water wells more than 10 m deep dry up when irrigation wells are pumping but recover when irrigation ceases (Banks and Soldal, 2002). These irrigation wells were initially developed to help local farmers deal with drought conditions. The owners of these wells report that they will continue to utilize them after the drought ends in order to increase the amount of acreage under cultivation.

One of the goals put forth by President Obama in his strategy for Afghanistan is to promote stability and security among the local population. While rapidly increasing the amount of groundwater available to the local population may further this goal in the short term, it could lead to larger problems in the long run, if the population becomes reliant on a resource that is not sustainable under greater levels of usage. The increasing extraction of groundwater by the local population and the resultant decrease in available groundwater storage may also impact military base camps accessing the same aquifer. Although concern has been raised about military base camp wells having a negative impact on nearby wells used by the local population, the opposite may, in fact, become a larger problem. If domestic consumption is only 20 L/day for the local population but that number is only 5% of the total usage (compared with 95% for irrigation of crops), the actual water extraction rate is 400 L/day/person. That is a much larger figure than the 120 L/day/person usage for Coalition forces in large bases.

In addition to concerns over depleting groundwater supplies, degradation of water quality in these oversubscribed aquifers poses challenges. This is especially true in urban areas with a significant amount of sewage infiltrating into the aquifers. It may not be practical to treat all current groundwater sources in order to maximize the protection of human health. By identifying the best sources of groundwater to use, it may be possible to minimize the amount of treatment required.

CONCLUSIONS

The geologic history of Afghanistan is complex, and with little fieldwork conducted during the past 30 years, the hydrogeology of the country is not as well understood as other parts of the world. Efforts to improve this understanding are progressing, but a lack of security still hampers efforts to conduct fieldwork. When USGS scientists conduct fieldwork in Afghanistan, they are required to wear body armor and have a security escort (Williams, 2009). The most well studied area is the Kabul Basin, and the data from that work is valuable not only for that region but also for the insight it provides to similar basins.

Since many U.S. and Coalition base camps are in remote areas where the local hydrogeology is not well understood, it is important to continue to work toward improving the understanding of the availability of groundwater and the quality of the supply. Groundwater can be seen as a low cost, relatively safe source of potable water compared to water transported by ground convoy or air. Only by improving our understanding of the water quality and the most effective way to treat it for human consumption can we reduce both the concern over the safety of the water supply and the logistical support challenges associated with importing water to base camps. Providing ample quantities of water for military operations in a landlocked, arid country such as Afghanistan is a daunting task.

In addition to ensuring that the U.S. and Coalition troops are provided with adequate quantity of water to conduct required operations, steps must be taken to ensure that the local population is also able to acquire enough water in a sustainable manner. Simply drilling more wells to tap aquifers that may soon become depleted is not in the best interest of the local population or the military forces tasked with the mission of returning the country to stability. The desired end state is for Afghanistan to once again be self-sustaining without the need for a foreign military presence. Thomas Mack at the USGS provided keen insight when he said, "If we—the U.S. and international community—curtail terrorism, we will have an increased opportunity to aid our Afghan colleagues in a very positive manner and lead them to a prosperous future. If we can build capacity for the sustainable and wise use of these natural resources, we will move Afghanistan toward a prosperous future" (Williams, 2009).

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