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Prepared in cooperation with the Afghanistan Geological Survey and the U.S. Department of Defense Task Force for Business and Stability Operations

Hydrogeology and Water Quality of the Chakari Basin, Afghanistan

Scientific Investigations Report 2014–5113
USGS Afghanistan Project Product No. 263

U.S. Department of the Interior
U.S. Geological Survey

Cover. View of the Chakari Basin in the Khaki Jabbar District, Afghanistan, from the north looking south. Photograph courtesy of Drew Craig, SRK Exploration Services, used with permission.

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By Thomas J. Mack, Michael P. Chornack, Sarah M. Flanagan, and
Ann T. Chalmers

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SALLY JEWELL, Secretary

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Conversion Factors, Datum, and Abbreviations

International System (SI) to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	328.1	foot (ft)
centimeter (cm)	32.81	foot (ft)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)
meter per day (m/d)	3.281	foot per day (ft/d)
meter per year (m/y)	3.281	foot per year (ft/y)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per second per square kilometer [(m^3/s)/km^2]	91.49	cubic foot per second per square mile [(ft^3/s)/mi^2]
cubic meter per day (m^3/d)	35.31	cubic foot per day (ft^3/d)
liter per second (L/s)	15.85	gallon per minute (gal/min)
liter per minute	0.2642	gallon per minute (gal/min)
liter per day	0.2642	gallon per day (gal/d)

Vertical and horizontal coordinate information is referenced to the World Geodetic System of 1984 (WGS 84).

Elevation, as used in this report, refers to distance above the vertical datum.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Delta notation for reporting of isotope data.—Stable isotope data are reported as a ratio relative to the ratio of a standard. For example, $^{18}O/^{16}O$ of a sample is compared with $^{18}O/^{16}O$ of a standard by the relation: $\delta^{18}O$ = (Rsample/Rstandard – 1) × 1,000, where Rsample = $^{18}O/^{16}O$ in the sample, Rstandard = $^{18}O/^{16}O$ in the standard, and $\delta^{18}O$ = relative difference in concentration, in parts per thousand (per mil). Delta ^{18}O ($\delta^{18}O$) is referred to as delta notation and is the value reported by isotopic laboratories for stable isotope analysis. Deuterium, designated as δ^2H, can be derived by analogy to $\delta^{18}O$ where the ratio ^2H:H replaces $^{18}O/^{16}O$ in Rsample and Rstandard. The standard used for determining $\delta^{18}O$ and δ^2H in water used in this report is Vienna standard mean ocean water (VSMOW). If $\delta^{18}O$ and δ^2H samples contain more of the heavier isotopes (^{18}O or ^2H) than the reference material, the samples have positive per mil values and are referred to as heavier than the reference material or as being enriched in the heavier isotope. Conversely, if the samples contain more of the lighter isotopes (^{16}O or H) than the reference material, the samples have negative per mil values and are referred to as lighter than the reference material or as being depleted in the heavier isotope. For example, a $\delta^{18}O$ value of –18.15 per mil can be referred to as lighter than VSMOW or depleted in ^{18}O relative to VSMOW.

Place names given in this report are anglicized translations from the Dari language; however, there may not be a universally accepted English language translation for many names. This report attempts to use the most commonly used translation where possible, but the reader is cautioned that other variants of names may be in use.

Abbreviations

AGS	Afghanistan Geological Survey
DOD	U.S. Department of Defense
NGO	nongovernmental organization
TFBSO	Task Force for Business and Stability Operations
USGS	U.S. Geological Survey

Hydrogeology and Water Quality of the Chakari Basin, Afghanistan

By Thomas J. Mack, Michael P. Chornack, Sarah M. Flanagan, and Ann T. Chalmers

Abstract

The hydrogeology and water quality of the Chakari Basin, a 391-square-kilometer (km^2) watershed near Kabul, Afghanistan, was assessed by the U.S. Geological Survey and the Afghanistan Geological Survey to provide an understanding of the water resources in an area of Afghanistan with considerable copper and other mineral resources. Water quality, chemical, and isotopic samples were collected at eight wells, four springs, one kareze, and the Chakari River in a basin-fill aquifer in the Chakari Basin by the Afghanistan Geological Survey. Results of water-quality analyses indicate that some water samples in the basin had concentrations of chemical constituents that exceeded World Health Organization guidelines for nitrate, sodium, and dissolved solids and some of the samples also had elevated concentrations of trace elements, such as copper, selenium, strontium, uranium, and zinc. Chemical and isotopic analyses, including for tritium, chlorofluorocarbons, and carbon-14, indicate that most wells contain water with a mixture of ages from young (years to decades) to old (several thousand years). Three wells contained groundwater that had modeled ages ranging from 7,200 to 7,900 years old. Recharge from precipitation directly on the basin-fill aquifer, which covers an area of about 150 km^2, is likely to be very low (7×10^{-5} meters per day) or near zero. Most recharge to this aquifer is likely from rain and snowmelt on upland areas and seepage losses and infiltration of water from streams crossing the basin-fill aquifer. It is likely that the older water in the basin-fill aquifer is groundwater that has travelled along long and (or) slow flow paths through the fractured bedrock mountains surrounding the basin. The saturated basin-fill sediments in most areas of the basin are probably about 20 meters thick and may be about 30 to 60 meters thick in most areas near the center of the Chakari Basin. The combination of low recharge and little storage indicates that groundwater resources are likely to be limited. Groundwater use in the villages of the basin is generally supplied by hand-pumped wells, whereas agricultural needs are met by surface-water flows. New or increased water uses in the basin, or activities that may affect water quality, should be carefully evaluated to avoid affecting existing uses.

Introduction

Afghanistan's mineral resources are a potential means of achieving economic growth that may greatly benefit the country's stability. Water is needed not only to process the minerals but also to supply existing communities and the associated community growth that may accompany a developing mining economy. For the development of the mineral resources of an area to be sustainable and have minimal adverse effects, the quality and quantity of water in the streams and aquifers in the area must be assessed relative to the needs of both the local population and potential future mining activities. The Chakari River Basin is a 391-square-kilometer (km^2) area about 20 kilometers (km) southeast of the city of Kabul (fig. 1). The basin contains considerable copper, cobalt, and chromium minerals in addition to other deposits (Peters and others, 2011). Thus, the Chakari River Basin was well suited as a pilot mineral resource area for the Afghanistan Geological Survey (AGS) to develop and demonstrate capabilities for conducting geologic and hydrologic investigations.

In 2012–2013, the U.S. Geological Survey (USGS), in collaboration with hydrologic engineers at the Afghanistan Geological Survey (AGS), conducted hydrogeologic investigations of the Chakari Basin under an agreement supported by the U.S. Department of Defense Task Force for Business and Stability Operations (TFBSO). The hydrogeologic investigations compiled existing data from nongovernmental organizations (NGOs), Afghan ministries, and geologic studies together with field data collected by the AGS to provide an understanding of the hydrogeology of the basin. The investigation of the Chakari Basin focused on the basic aquifer properties of the basin-fill aquifer, including aquifer boundaries, recharge, discharge, direction of groundwater flow, saturated thickness, and storage. A team of hydrologic engineers from the AGS conducted field investigations in the study area that included inventorying wells, identifying water quality and isotopic sampling locations, collecting surface and groundwater samples, and making hydrologic observations on the discharges of springs and karezes. This report presents results and interpretation of the hydrogeologic and field investigations.

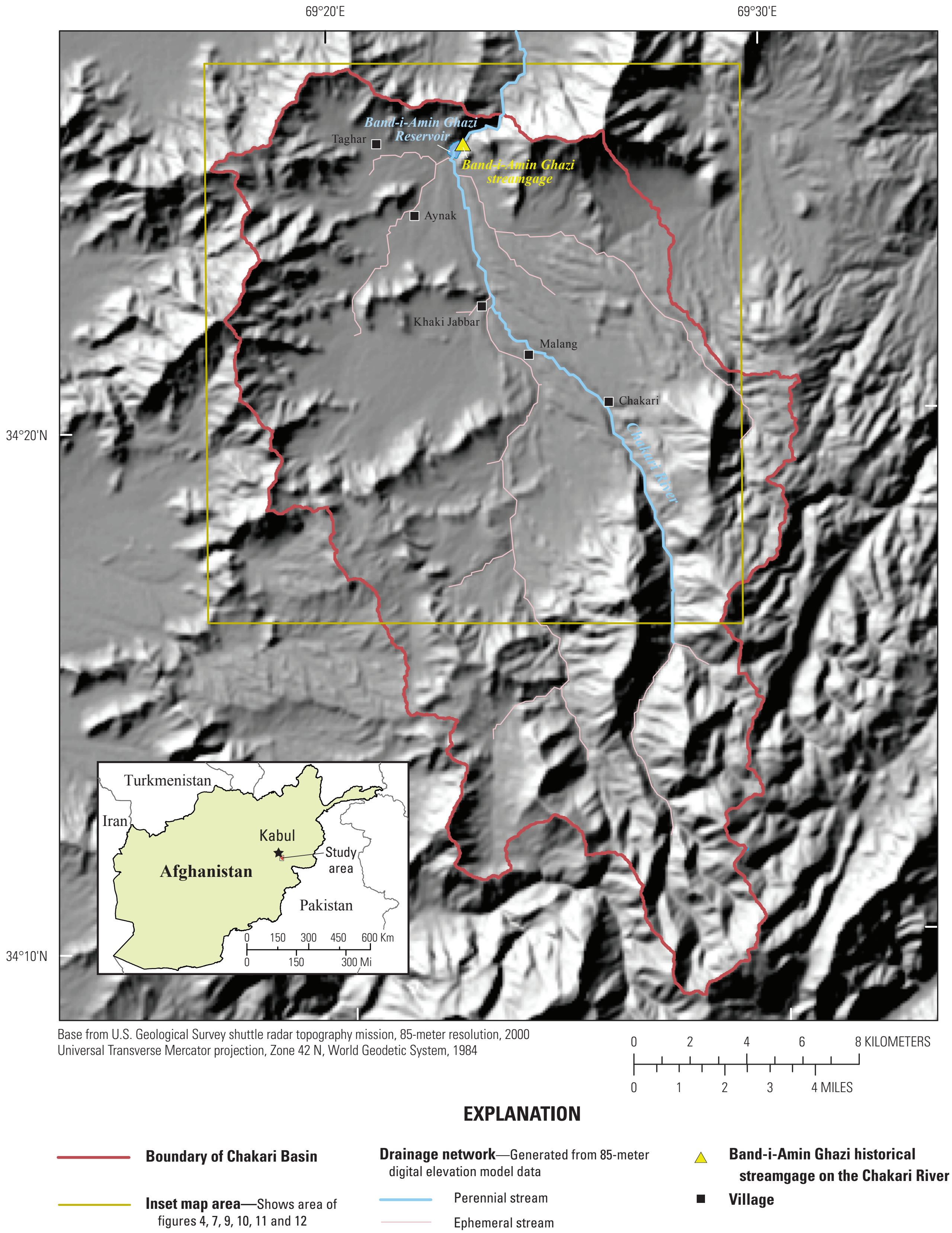


Figure 1. Major geographic features of the Chakari Basin, Afghanistan.

Description of Study Area

The study area, herein described as the Chakari Basin, encompasses a 391-km^2 watershed formed by the Chakari River in the western half of the Khaki Jabar District (fig. 1). The North Aynak-Taghar mineral investigation recently (2013) undertaken by the AGS, the TFBSO, and the USGS was conducted in an area along the southern slope of the mountain ridge that forms the northern boundary of the Chakari Basin, near the villages of Aynak and Taghar (fig. 1). Known mineral deposits, including numerous copper and cobalt ore bodies and several ore bodies containing chromium, talc and magnesite, and asbestos are hosted in sedimentary rocks surrounding and within the Chakari Basin (Peters and others, 2011).

Geographic Setting

The Chakari Basin is surrounded by steep mountain ridges, except for a section about 6 km in length along the northeastern boundary of the basin, adjacent to the eastern part of the Khaki Jabar District. The only drainage outlet is the Chakari River, which flows northward out of the basin in the center of the northern ridge (fig. 1). A few ephemeral streams drain the surrounding hills and ridges and are tributaries to the Chakari River. The average elevation of the hills and ridges surrounding the basin is 2,900 meters (m) above World Geodetic System of 1984 (WGS 84), with a few peaks rising above 3,300 m (Bohannon, 2010). The lowest point in the basin is 2,050 m at the Band-i-Amir Ghazi Reservoir (coincident with the streamgage symbol on fig. 1). The floor of the basin can be defined approximately by the 2,350-m topographic contour line (Bohannon, 2010). The transition from the basin floor to the surrounding hills and ridges is marked by variously sized alluvial fans with angles of repose from 3 to 9 degrees. The best developed alluvial fans are on the hills and ridges that form the northern boundary of the basin. The hills and ridges that surround the basin have steep slopes, have very narrow peaks and are dissected by incised ephemeral drainages. The southern upland areas of the Chakari Basin are extremely rugged (cover and fig. 1).

Climate and Vegetation

The climate in the study area is semiarid. The summers are typically hot and dry, and the winters are cold with rain and snow. The Afghanistan Agrometeorological Project (Agromet) operates a meteorological station in the city of Kabul approximately 20 km northwest of the study area. The Kabul Agromet station is close to the study area, but the elevation of the valley floor in the Chakari Basin is more than 300 m higher than the city of Kabul. The precipitation patterns between the two areas may be similar, but the higher elevation of the Chakari Basin likely results in lower temperatures that could affect the amount and type of precipitation. The study area is in the Capital region of the Agromet network; this region includes several precipitation stations (Afghanistan Agrometeorological Project, 2010). The annual observed total precipitation for water year[1] 2010 for the Capital region ranged from 221 to 300 millimeters (mm; Afghanistan Agrometeorological Project, 2010, Seasonal Bulletin map 2). Summary statistics for the Kabul Agromet station are listed in table 1. Monthly mean precipitation is shown in figure 2 for two periods of record, 1957 through 1977 (Favre and Kamal, 2004) and 2003 through 2012 (Afghanistan Agrometerological Project, 2013). The two short-term records are similar, with higher precipitation amounts in the late fall through early spring, although precipitation appears to be higher in recent summer months (fig. 2).

[1]The Afghan water year is the 12-month period from September 1 through August 31 designated by the calendar year in which it ends.

Table 1. Annual and long-term average precipitation and temperature at the Afghanistan Agrometeorological Project station in Kabul, Afghanistan.

[Station is about 20 kilometers northwest of the Chakari Basin, Afghanistan. Elevation refers to distance above the World Geodetic System of 1984 vertical datum. Long-term averages are based on data from 1942 through 1993 and 2005 through 2010 as reported in Afghanistan Agrometeorological Project (2010). Agromet, Afghanistan Agrometeorological Project; km, kilometers; m, meters; mm, millimeters; °C, degrees Celsius]

Agromet station	Distance from study area center, in km	Elevation, in m	Precipitation, in mm				Temperature, long-term average, in °C		
			Annual, water year 2010[a]	Long-term average			Minimum and month	Mean	Maximum
				Annual	Minimum and months	Maximum and month			
Kabul	24	1,810	304.3	317.5	1.2 June and August	83.2 April	-2.6 January	9.8	24.8

[a]Water year is the 12-month period September 1 through August 31 designated by the calendar year in which it ends.

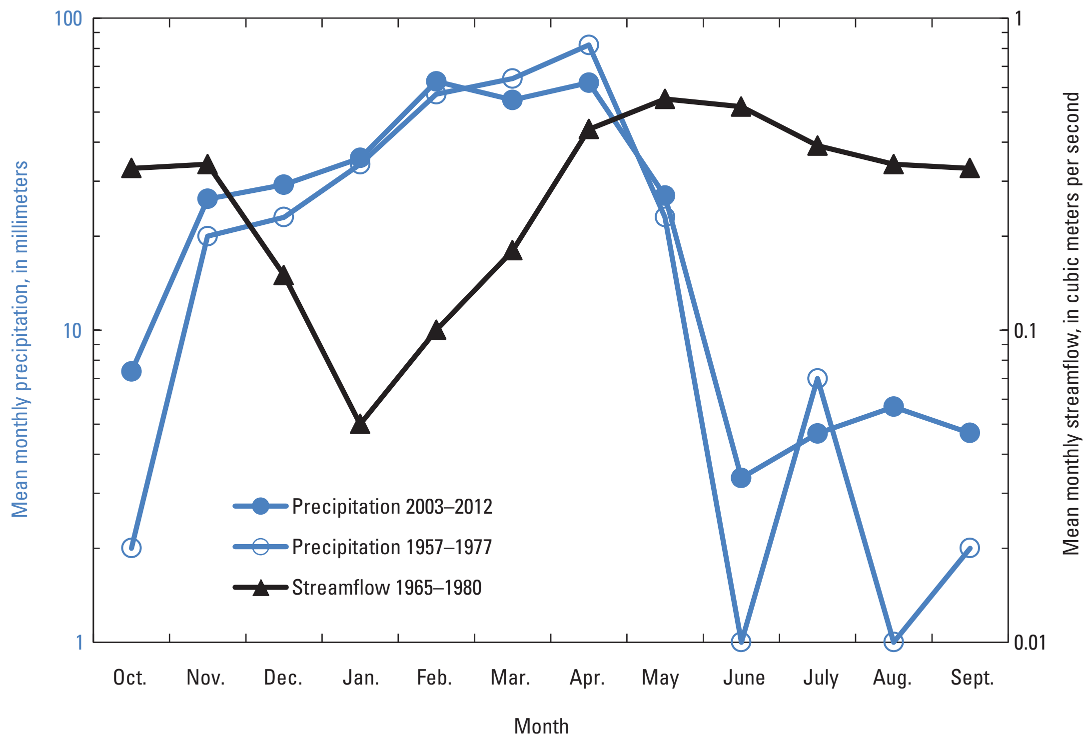


Figure 2. Mean monthly precipitation in Kabul, Afghanistan, from 1957 through 1977 (Favre and Kamal, 2004) and from 2003 through 2012 (Afghanistan Agrometeorological Project, 2013) and mean monthly streamflow at the Chakari River between 1965 and 1980 (Olson and Williams-Sether, 2010).

The natural vegetation in Afghanistan has been degraded during the past several decades by overgrazing and harvesting for fuel and building materials (Breckle, 2007). In the study area, the lower elevations are classified as Pistacia atlantica (pistachio) and Amygdalus (almond) woodlands. However, there is very little actual woodland in the basin apart from some stands of small trees where the Chakari River flows into the Band-i-Amir Ghazi Reservoir (coincident with the historical Band-i-Amir Ghazi streamgage symbol on fig. 1). Irrigated fields, small orchards, and pastures are present in the valleys in the study area wherever water can be accessed. The study area above the valley floor has very sparse vegetation.

Population and Water Use

Currently there is no formal population count in Afghanistan; however, the Central Statistics Organization (2013) estimated the population of the Khaki Jabar District, which is the least populated district in the Kabul Province, to be 13,900. The 2011 population estimated by LandScan (Oak Ridge National Laboratory, 2012), which uses population indicators such as nighttime lights, roads, and buildings, was 21,556 for the Khaki Jabar District and 10,703 for the study area. The population density shown in figure 3 has a pixel resolution of about 1 km^2 (Oak Ridge National Laboratory, 2012). The high, rugged mountains in the study area are likely uninhabited regardless of the estimates in figure 3. About one third of the population is in about 10 villages with estimated populations of 200 to more than 300 people in the northern half of the basin. The extreme southern upland, area of the basin is rugged and much less populated.

Most villages have several dug wells and one or more tube wells installed in unconsolidated sediments by NGOs. Most wells have hand pumps; therefore, per capita water use in the study area is likely to be minimal and may be on the order of 20 to 30 liters per day (L/d; Mack and others, 2010). Given the estimated population and per capita use rates, total drinking-water use in the basin may amount to only 200 to 300 cubic meters per day (m^3/d). Irrigation water use in the study area is likely to be an order of magnitude or greater than drinking water use and generally is served by seasonal flow from springs, karezes, or streams.

Some villages may also be served by karezes. Before the Afghan revolution (1980), nearly all water supply in the Chakari Basin was from either dug wells or karezes; few, if any, small-diameter cased wells were installed in the Chakari Basin. A kareze is a hand dug, gravity-fed water-supply tunnel conduit system that accesses the groundwater table and

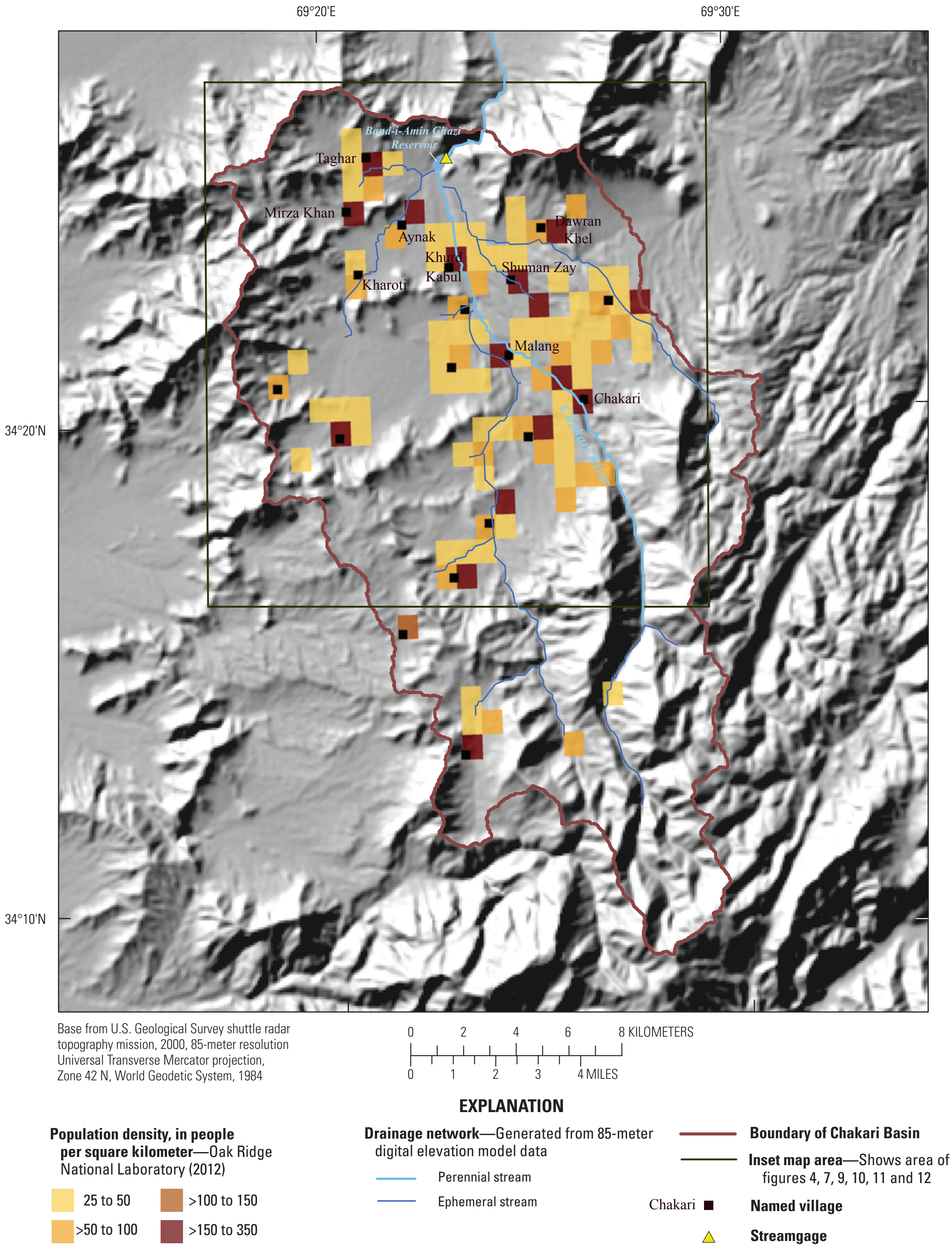


Figure 3. Villages and estimated population in the Chakari Basin, Afghanistan. Population density data are from Oak Ridge National Laboratory (2012).

works consistently in stable climates. However, the kareze supply conduit requires periodically removing fine-grained sediment, which may represent a considerable effort and can be hazardous because of unstable tunnel walls. Additionally, drilled wells near the source of a kareze may lower the local water table and cause karezes to become dry. Since the 1980s, the population in the Chakari Basin, similar to many areas of Afghanistan, has become more reliant on drilled wells and less so on karezes. At least seven karezes can be identified, primarily in western areas of the study area, using aerial photography (fig. 4). The karezes have lengths, from the outlet to the furthest visible upgradient access hole, of approximately 100 to 1,250 m. Two of the larger karezes are still functioning as agricultural water supplies, whereas the others appear to be inactive. Based on aerial photography, kareze K1 appears to have a source in an ephemeral drainage about 700 m west of its outlet.

Purpose and Scope

The purpose of this report is to (1) describe the hydrogeologic characteristics of the basin-fill aquifer, including areal extent of the basin-fill aquifer, water-table elevations, general directions of groundwater flow, and saturated thickness; (2) provide a general estimate of water availability; and (3) assess the general quality of the water resources in the Chakari Basin.

Methods of Investigation

The hydrogeology and water quality of water resources in the Chakari Basin were characterized through the use of geologic mapping, information contained in well records, historical streamflow and groundwater-level data, and recent water-quality sampling. Geologic maps in combination with data contained in well completion and borehole logs provide information on extent, composition, thickness, and saturation of the unconsolidated sediments of the aquifer. Historical streamflows, groundwater-level data, and chemical and isotopic tracers were analyzed to assess recharge in the basin. Water quality was described through the use of recently collected surface-water and groundwater samples.

AGS engineers examined the study area for accessible wells, springs, karezes, and streams for investigation in the more populated northern areas of the Chakari Basin. Eight wells, one kareze, four springs, and one stream were inventoried and sampled for this study (fig. 4). The locations, depths to water, well depths, and other information are provided in table 2. The wells and kareze investigated were in villages shown on figure 3.

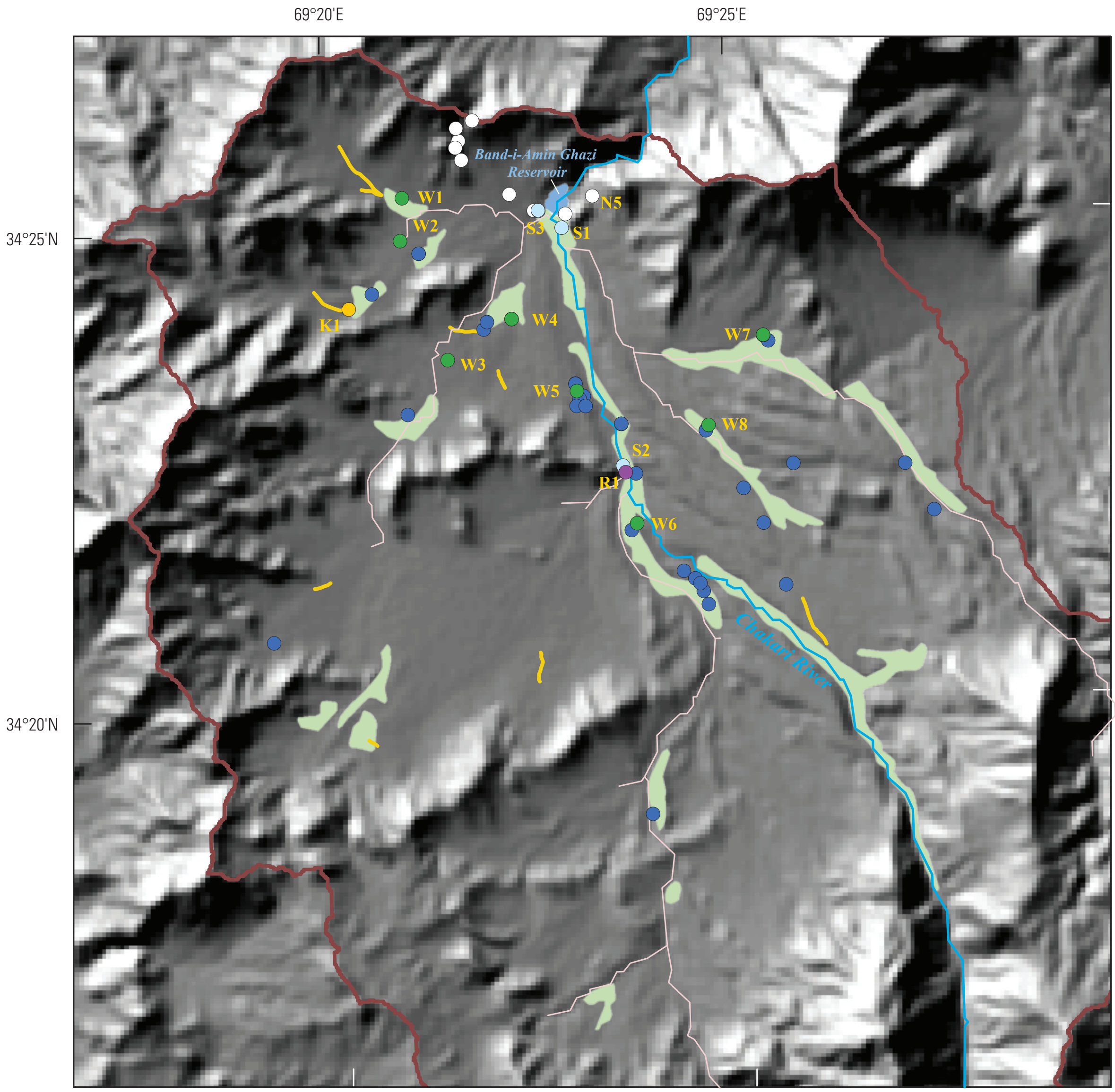
Security concerns greatly restricted the time that AGS and USGS personnel could spend in the field and the locations that they could access. Because of these limitations, existing spatial, mapping, and well data were used as much as possible.

Hydrogeologic Data

Hydrogeologic data and information used in this study were also obtained from geologic maps and from wells and boreholes in the basin. Boreholes drilled for the North Aynak-Taghar mineral investigation (SRK Exploration Services, written commun., 2013) provided insight into the hydraulic properties of bedrock in the area (fig. 4). Additionally, water-supply well data compiled by the NGO Danish Committee for Aid to Afghan Refugees (DACAAR) provided information on distribution of drilled wells, depth to water, and well depths in the basin (Danish Committee for Aid to Afghan Refugees, 2011). No hydraulic tests have been conducted in the study area; however, hydraulic properties from other investigations (Böckh, 1971; Abdullah and Chmyriov, 1977; Mack and others, 2010), inferred from drillers logs of wells in Kabul (Jaron Andres, U.S. Army Geospatial Center, written commun., 2013) and boreholes (fig. 4) for the North Aynak-Tahgar mineral investigation (Drew Craig, SRK Exploration Services, written commun., 2013) or from literature (Freeze and Cherry, 1979, table 2.3) are used for hydraulic characteristics in this study. The DACAAR has been monitoring groundwater levels (depth to water) and specific conductance at well W5 (fig. 4; also known as DACAAR groundwater monitoring well 4) in Khurd Kabul village since 2005 (Danish Committee for Aid to Afghan Refugees, 2001). Historical streamflow measurements collected by the Afghanistan Ministry of Energy and Water (MEW) (Olson and Williams-Sether, 2010) were used to assess recharge to the Chakari Basin.

Water-Quality Data

The AGS engineers collected a variety of water samples that were shipped to the United States for analysis at several USGS laboratories. Water temperature, pH, and specific conductance were measured in the field and provided general information about basic properties. Major ion, nutrients, and trace elements were determined from filtered samples and provided information on general water chemistry. Water samples also were collected for total coliform and *Escherichia coli* (*E. coli*) bacteria, which also are useful indicators of general water quality. Additional water samples for chemical and isotopic analysis were collected to provide supporting evidence of hydrogeologic processes, such as the time elapsed since recharge or the degree of evaporation of groundwater recharge. Generally, AGS engineers followed USGS procedures for the collection of water samples. In some cases, these procedures were modified to reflect challenging field conditions, such as the lack of ice to chill samples. Security issues greatly limited the time that project personnel could spend in the field, the locations they could access, and the number of samples that could be collected; therefore, the number and types of quality-control samples were limited. The lack of ice for sample preservation likely affected only the nutrient and carbon-14 samples. Thus, the nutrient values from this study are reported as estimated values because samples were not



Base from U.S. Geological Survey shuttle radar topography mission, 85-meter resolution, 2000
Universal Transverse Mercator projection, Zone 42 N, World Geodetic System, 1984

0 2 4 KILOMETERS
0 1 2 MILES

EXPLANATION

Irrigated or cultivated area

Boundary of Chakari Basin—From Afghan Information and Management Service (1997). See figure 1 for full extent.

Drainage network—Generated from 85-meter digital elevation model data

Perennial stream

Ephemeral stream

Kareze path

Data collection site and identifier

R1 Chakari River

K1 Kareze

S1 Spring

W2 Well, sampled as part of this study

Well, data provided by Danish Committee for Aid to Afghan Refugees (DACAAR) (2011) (no identifier)

N5 Exploratory borehole (N5 identified only)

Figure 4. Locations of wells, springs, karezes, and streams in the Chakari Basin sampling network, Afghanistan.

Table 2. Wells, kareze, springs, and stream sampled in the Chakari Basin, Afghanistan.

[W, S, K, and R in identifiers denote wells, springs, kareze, and the Chakari River site, respectively. Elevation refers to distance above the World Geodetic System of 1984 vertical datum and is from advanced spaceborne thermal emission and reflection radiometer (ASTER) global digital elevation model (U.S. Geological Survey, undated). m, meters; --, not applicable or not measured]

Identifier	Location	Elevation, in m	Type	Well depth measured, in m	Depth to water, in m	Measurement or sample date
W1	Taghar Sofla Mosque	2,135	Drilled well	55	14.70	23 Dec 2012
W2	Taghar Sofla School	2,144	Drilled well	41	22.79	24 Dec 2012
W3	Kharoti High School	2,141	Drilled well	30	--	30 Dec 2012
W4	Aynak Mosque	2,093	Drilled well	37	4.07	01 Jan 2013
W5	Khurd Kabul	2,150	Dug well	40	37.80	02 Jan 2013
W6	Malang Pain	2,194	Drilled well	60	42.49	07 Jan 2013
W7	Dawran Khel	2,241	Drilled well	36	17.46	08 Jan 2013
W8	Shuman Zay Pine	2,206	Drilled well	51	21.00	14 Jan 2013
S1	Band Ghazi	2,060	Spring	--	--	22 Dec 2012
S2	Khurd Kabul	2,139	Spring	--	--	06 Jan 2013
S3	Band Ghazi	2,067	Spring	--	--	15 Jan 2013
S4	Band Ghazi (adjacent to S3)	2,067	Spring	--	--	19 Jan 2013
K1	Mirza Khan Kareze	[a]2,198	Kareze	--	--	25 Dec 2012
R1	Chakari River (also known as Malang Stream)	2,149	River	--	--	22 Jan 2013

[a]Elevation is at outlet.

chilled and laboratory hold times were exceeded. The dissolved gas bottles remained sealed in transport and appeared to be well preserved, although denitrification (where available nitrate is converted to nitrogen gas) may have occurred. However, samples were collected during the winter with average daily temperatures of about zero degrees Celsius (°C) and stored in a cool location before shipping. Samples that required filtration and preservation were processed in the field at the time of sample collection. Water samples collected for the analysis of major ions, trace elements, tritium, helium, chlorofluorocarbons (CFCs), sulfur hexafluoride (SF_6), and oxygen and nitrogen isotopes were not affected by the lack of ice preservation. Bacteria samples were processed and incubated at the end of each field day.

The USGS National Water Quality Laboratory analyzed water samples for nutrients, major ions, and trace elements. The USGS Chlorofluorocarbon Laboratory analyzed sequential duplicate water samples for dissolved gases, CFCs [trichlorofluoromethane (CFC–11), dichlorodifluoromethane (CFC–12), and trichlorotrifluoroethane (CFC–113)], and SF_6. Dissolved gas concentrations of nitrogen, argon, carbon dioxide, and methane were analyzed by gas chromatography (U.S. Geological Survey, 2014b). CFC and SF_6 concentrations were analyzed by purge-and-trap gas chromatography (Busenberg and Plummer, 1992, 2000; International Atomic Energy Agency, 2006; U.S. Geological Survey, 2014a,c). The USGS Stable Isotope Laboratory analyzed water samples for nitrogen and oxygen isotopes in nitrate and deuterium and oxygen isotopes in water (U.S. Geological Survey, 2014d). Carbon isotopes (carbon 13 [^{13}C] and carbon 14 [^{14}C]) were determined at the National Ocean Sciences Accelerator Mass Spectrometry Facility (National Ocean Sciences, 2014). Water samples for tritium-to-helium (^3H:^3He) age determination and noble gases helium, neon, argon, xenon, and krypton were collected in 80-centimeter (cm)-long copper tubes and analyzed at the Lamont-Doherty Earth Observatory Noble Gas Laboratory by mass-spectrometric procedures similar to those of Bayer and others (1989) and Beyerle and others (2000). All water quality, chemical, and isotopic analyses are provided in appendixes 1 through 3.

Hydrogeology

The hydrogeology of the Chakari Basin is interpreted using information from geologic maps and investigations, various satellite imagery, historical streamflow data, historical NGO well data, and chemical and isotopic analysis of water samples.

Surface Water

The Chakari River flows north through the Chakari Basin and drains into the Kabul River north of the study area (fig. 1). Figure 1 shows a drainage network generated from a digital elevation model that delineates several of the large ephemeral streams in the basin. The Chakari River drains to the Band-i-Amir Ghazi Reservoir above a stone dam at the northern end of the basin (coincident with the symbol for the historical Band-i-Amir Ghazi streamgage on fig. 1). The dam, which is 25 m high, was built in 1918 for irrigation, and the resulting reservoir had a capacity of 12 million cubic meters (m^3). The width of the reservoir across the valley is about 100 m at the top and 20 m at the bottom; however, the reservoir is now entirely filled in with sediment and is no longer effective for water storage.

The streamgage on the Chakari River at Band-i-Amir Ghazi (fig. 1, Afghan identification number 1–9.R00–4W) was operated by the MEW from May 26, 1965, through September 30, 1980. The mean annual streamflow for the period of record is 0.31 cubic meters per second (m^3/s; 26,784 m^3/d), with a standard deviation of 0.12 m^3/s (Olson and Williams-Sether, 2010). The mean annual precipitation at Kabul between 1957 and 1977 was 330 mm (Afghanistan Ministry of Water and Power, 1981). The mean annual streamflow per unit area for this streamgage is 8×10^{-4} cubic meters per second per square kilometer [$(m^3/s)/km^2$] or, expressed as a rate over the basin, 7×10^{-5} meters per day (m/d). The month with the highest mean monthly streamflow was May with 0.55 m^3/s, and the month with the lowest mean monthly streamflow was January with 0.05 m^3/s (fig. 2). The lowest monthly mean streamflow was 0.01 m^3/s in January and February 1977 and March 1978. The Chakari River flows during December 2012 and January 2013 were observed to be small, likely much less than 0.5 m^3/s. Mean monthly streamflow is lowest in the winter months when precipitation is highest (fig. 2). This indicates that a winter snowpack generally develops and that snow meltwater is likely the dominant contribution to spring and summer streamflows. Perennial streamflow in the basin, which is primarily only in the Chakari River, is likely a combination of snowmelt at high elevations at the southern areas of the basin (see cover figure) and drainage from the underlying bedrock aquifer in those areas. The ephemeral streams in the basin likely only flow in the spring or occasionally after precipitation events.

Springs are present in the study area, particularly at low elevations near the Band-i-Amir Ghazi Reservoir. Four springs and one kareze were inventoried for this study to help assess the source and movement of water in the Chakari Basin (table 2). During a field reconnaissance visit on November 21, 2009—a relatively dry period—a spring was observed emanating from highly fractured gneiss on the north flank of the mountains bounding the study area. This spring, just outside the study area, provides insight into the nature of discharges from fractured bedrock in the area. The spring had a volumetrically measured flow of approximately 0.1 liter per second (L/s; 10^{-4} m^3/s) near its source and was managed for irrigation, which is an indication of perennial flow. The spring was less than 1 km from the topographic peak in the local area and indicates groundwater draining from highly fractured bedrock uplands. On the eastern side of the study area, an ephemeral spring was identified on the flank of a south-facing gully near a ridge. The spring was about 0.7 km below a peak consisting of fractured carbonate rocks. The spring was not flowing when it was identified during the reconnaissance trip; however, there were small orchards at its origin and a settlement downgradient along the spring channel. Both factors indicate a likely dependence on easy access groundwater resources, such as would be provided by a shallow depth to groundwater, in the area of the spring. The springs observed in the study area generally coincide with delineated lineaments (Hubbard and others, 2012).

Geology

The geology of the study area is mapped in detail in Bohannon (2010). The Chakari Basin study area is within the Aynak Syncline Zone of the Kabul tectonic block, and detailed geologic and mineral investigations are provided by Peters and others (2011). The geologic units in the study area are categorized into hydrogeologic groups of similar hydrologic properties—primarily well yields and aquifer porosity—for the purposes of this study (fig. 5; table 3). The unconsolidated sediments are grouped according to sediment particle size, particle sorting, and deposition method, all of which can affect the hydrologic properties of the resulting deposits. Unconsolidated sediments and bedrock units were each grouped into four general hydrogeologic groups as shown in table 3.

Bedrock

Limestones and dolomites form the dominant bedrock outcrop in the study area particularly, the northeastern, northwestern, and the south-central part of the study area (fig. 5). Dolomitic marble is the primary host rock for the Aynak copper mineralization. Limestone and dolomite east of the Chakari River are in contact with sedimentary rocks (sandstone) along low-angle faults; sedimentary rocks may be present beneath unconsolidated sediments in much of the study area (Bohannon, 2010). Outcrops of metamorphic rock (gneiss and migmatite, amphibolite, schist, and marble) form the ridges along the northern boundary of the study area and form some of the ridges and hills within the basin (fig. 5). Erosion has exposed metamorphic rock in the upper reaches of the Chakari River. Intrusive igneous rocks in the study area are primarily in small areas near the northwestern corner of the study area, where they have intruded metamorphic rocks.

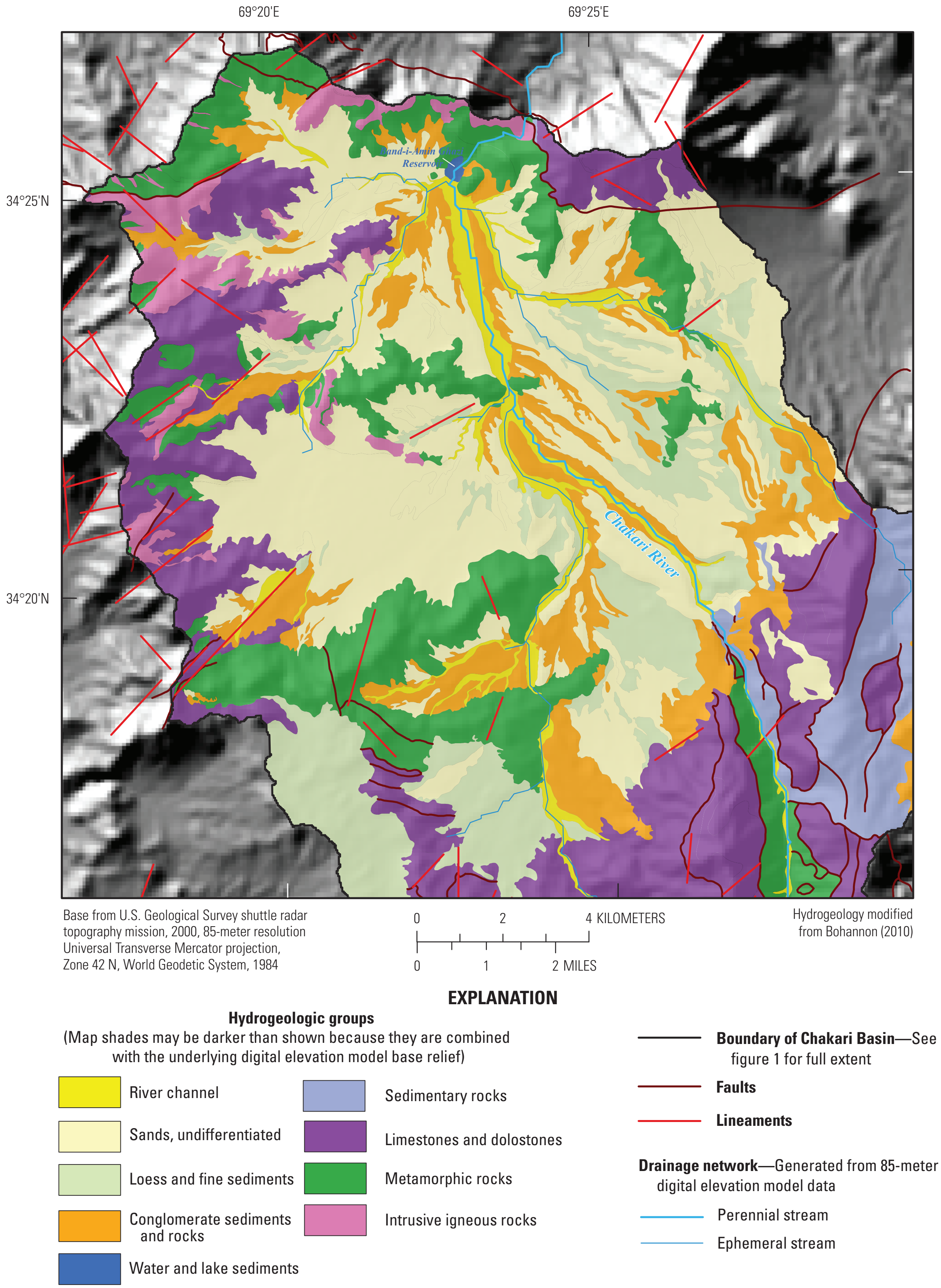


Figure 5. Generalized geology and topography in the study area in the Chakari Basin, Afghanistan. Lineaments data are from Hubbard and others (2012).

Table 3. Hydrogeologic groups in the Chakari Basin, Afghanistan.

[Hydrogeologic groups are shown on figure 5. Geologic map units and unit codes (in parentheses) are from Bohannon (2010)]

Hydrogeologic group	Relative well yield for sediments or rocks	Geologic map unit
		Sediments
River channel	Very high	Young alluvium (Qa_3)
Sands, undifferentiated	High	Colluvium and rock falls (Qcr), alluvial sheet deposits (Qas), intermediate alluvium (Qa_2), and older alluvium (Qa_1)
Loess and fine sediments	Moderate to high (where reworked)	Fine-grained deposits (Nlfw) and purple fine-grained facies (Nlfp)
Conglomerate sediments and rocks	Low to moderate	Conglomerate (Nlc) (this unit is unconsolidated to semiconsolidated and is grouped with sediments for this study)
		Rocks
Sedimentary rocks	Moderate	Undifferentiated unit (₱ɛKku), conglomerate and sandstone unit (Pkc)
Limestones and dolostones	Moderate to high where highly fractured	Belemnite unit (Jkb), undifferentiated limestone (Jku), Nerineen unit (Jkn), limestone, dolomite and tuff (ŦRklt), Ceratiten unit (ŦRkkc), reef limestone unit (Pkl), Gulkhamid Formation (Ꞓg), Gulkhamid and Loy Khwar Formations, undifferentiated (ꞒZu), Loy Khwar Formation (ꞒZlk)
Metamorphic rocks	Very low to moderate where highly fractured	Light-blue unit (₱ɛKklb), amphibolite (Zwa), undifferentiated (Zwu), gneiss and migmatite (Xsgn)
Intrusive igneous rocks	Very low to moderate where highly fractured	Peridotite unit (₱ɛKkp), brown peridotite unit (₱ɛKkpb), mafic ring dike (Ꞓmd), intrusions of Aynak district (ꞒZi), intrusive amphibolite (Zia)

The sedimentary, carbonate, and metamorphic rocks found in the study area generally are not considered to be primary aquifers because these rocks typically are low yielding. However, boreholes drilled for the North Aynak-Taghar mineral investigation (fig. 4) found the rock at the site, primarily limestone, to be highly fractured. The loss of considerable amounts of drilling fluid to the formations during drilling supports these findings. Although drillers logs did not have a record of the static water levels in the boreholes while drilling, the rocks contained water near the surface in places. A static water level of 7 m below land surface (corrected for borehole angle) was measured at borehole N5, which is about 50 m vertically above the valley floor and 300 m horizontally from the valley (fig. 4). Mapped faults (Bohannon, 2010) and lineaments (Hubbard and others, 2012) also indicate that rocks in the study area are likely to be highly fractured and may contain considerable amounts of water. Where exposed at the surface, these rocks appear to be intensely fractured, and the intense fracturing likely results in moderate hydraulic conductivities and potential for groundwater storage. Water-supply wells constructed in the bedrock hydrogeologic groups could supply limited qualities of water, provided that there is sufficient recharge to replenish groundwater withdrawals. The fracture porosity, hydraulic conductivity, and storage in these aquifers likely diminishes with depth. Persistent spring and kareze flows in or near bedrock areas of the Chakari Basin indicate slow water drainage from underlying rock aquifers.

Unconsolidated Sediments

The distribution of the unconsolidated sediments in the study area results from the sequence of erosion and subsequent sedimentation that has occurred. The oldest unconsolidated sediments outcropping in the study area are conglomerate sediments and rocks; these deposits are exposed across the region and underlie most other basin-fill sediments in the study area (fig. 5). The stratigraphic sequence of the unconsolidated sediment hydrogeologic groups in the study area, from youngest to oldest, likely follows the order (from top to bottom) of the groups listed in table 3. There are no measured sections or borehole lithologic descriptions of the conglomerate sediments and rocks group but these deposits are probably similar to the upper Neogene conglomerates of the Kabul Basin (Mack and others, 2010), which are more permeable than the thick lower Neogene conglomerates found at depth in the Kabul Basin. The positions of the mapped outcrops indicate that a loess and fine sediments group probably overlies the conglomerate group. The loess and fine sand may be deposited directly on bedrock in some parts of the study area where the conglomerate was removed by erosion.

The oldest and intermediate alluvium of the undifferentiated sand group are the most extensive sediments mapped in the study area, followed by the colluvium, rock falls, and alluvial sheet deposits (Bohannon, 2010), which are also part of the undifferentiated sand group (table 3). The youngest sediments in the study area are the sediments of the river channel group (young alluvium), which are found along the Chakari River and the larger drainages in the study area. This group consists of coarse-grained sands and gravels that are likely to be highly permeable (fig. 6). The river channel hydrogeologic group was deposited in cut-and-fill channels and could be in depositional contact with older unconsolidated sediment of other hydrogeologic groups (fig. 5). Well yield tests in river channel sediments or river reworked loess or alluvium in the Kabul Basin less than 10 km northwest of the study area indicated aquifer materials yielding tens to hundreds of liters per minute. Where sediments are fine-grained loess or cemented conglomerates, yields were considerably lower (a few liters per minute or less).

Basin-Fill Aquifer Thickness

The primary source of water for domestic or industrial water use in the Chakari Basin is likely to be groundwater in the aquifer formed by the basin-fill unconsolidated sediments. The depths of drilled wells and limited passive seismic data were used to infer a minimum thickness of basin-fill unconsolidated sediments in the study area (fig. 7). In the center of the valley, along the Chakari River, well depths of 60 m are common, and one well is 94 m deep. Farther from the valley center, well depths indicate thicknesses of 40 to 60 m in most of the basin and thinner sediments near bedrock outcrops at the valley walls. The extent of mapped conglomerates also is shown on figure 7. The degree of consolidation of these sediments is not known, but these sediments are likely to have a porosity greater than that of the consolidated rock units and thus are included in the aquifer thicknesses shown (fig. 7). Depths to water range from 4 to 42 m below land surface, based on available data, (table 2), so the saturated thickness of the basin-fill aquifer is probably less than 100 m in all areas of the basin.

Water-Level Fluctuations

The monthly groundwater levels from 2004 to 2012 in well W5 (fig. 4) were assessed, using the seasonal Kendall test (Hirsch and Slack, 1984; Helsel and others, 2006), to determine whether trends were evident. A statistically significant slope (p value less than 0.05) in the relation of depth to water and time is considered evidence of a trend. No statistically significant trend in groundwater levels is apparent across the entire period of record; however, a break in slope is apparent in 2008. Examination of the water levels before and after September 2008 (selected as an approximate midpoint in the record) indicates that there was a slight but significant water-level rise of 0.02 meter per year (m/yr) between 2005 and 2008 and no trend after 2008. This water-level rise may be attributed to the end of a multiyear drought in the region in 2005. A similar increasing trend in groundwater levels in the region before 2008 and a break in the slope of the trend in 2008 were observed in the adjacent Kabul Basin (Mack and others, 2010, 2013). The decreases in the groundwater level in the city of Kabul, however, are a result of increasing water use.

The groundwater level at well W5 did not have a consistent seasonal pattern, but some low levels occurred in late fall to winter and some high levels occurred in late spring (fig. 8). The median annual rainfall- or snowmelt-induced groundwater-level rise was 0.3 m. The mean annual precipitation for the period of record (2005–2012) at the Kabul airport was 335 mm (Afghanistan Agrometerological Project, 2013). A groundwater recharge rate of 0.07 m/yr (2×10^{-4} m/d) was estimated using the water-table fluctuation method (Healy and Cook, 2002), using a specific yield of 0.25 and a water-table rise of 0.3 m/yr. Ideally the water-table fluctuation method is used with continuous data so that all water-level rises in the time period for which the estimates are made are measured. The water-table fluctuation method as applied in the present study, using monthly water-level data, results in recharge estimates that are approximate, because not all water-level rises are captured with monthly measurements. However, a similar water-table fluctuation analysis, using monthly water-level measurements, in a closed basin in southern Australia (Ordens and others, 2012) yielded estimates of recharge that compared favorably with recharge estimates based on isotopic analysis.

The recharge estimated at well W5 in the Chakari Basin is a result of precipitation at the well and infiltration of streamflow from snowmelt in upland areas of the basin (fig. 4). The estimated recharge rate is about one order of magnitude greater than the historical rate of water leaving the basin (see "Surface Water" section). This indicates that the Chakari River likely represents a substantial source of recharge where it traverses from less permeable bedrock uplands to more permeable unconsolidated sediments. Chemical and isotopic results of surface and groundwater measurements, discussed in later sections, support a conceptual model that includes recharge of the basin-aquifer by streamflow lost from the snowmelt-supplied Chakari River. The Chakari Basin is essentially a closed basin, and the difference between the estimated groundwater recharge rate and the lower rate of discharge at the basin outlet indicates that there may be considerable water loss resulting from evapotranspiration in the lower areas of the basin, where irrigation is concentrated and the water table is near the land surface.

Groundwater Flow and Storage

A water-table map of the Chakari Basin is provided in figure 9, for the area of basin-fill sediments, showing generalized 50-m contours from 2,100 to 2,350 m. The water-table surface was contoured from the land-surface elevation minus the depth to water measured by the AGS in December 2012 and January 2013 at supply wells (table 2) or from historical static depth to water measured at the time of well construction (Danish Committee for Aid to Afghan

A

B

Figure 6. Coarse-grained sediments in a stream channel on the west side of the Chakari Basin, Afghanistan, looking *A*, north and *B*, south.

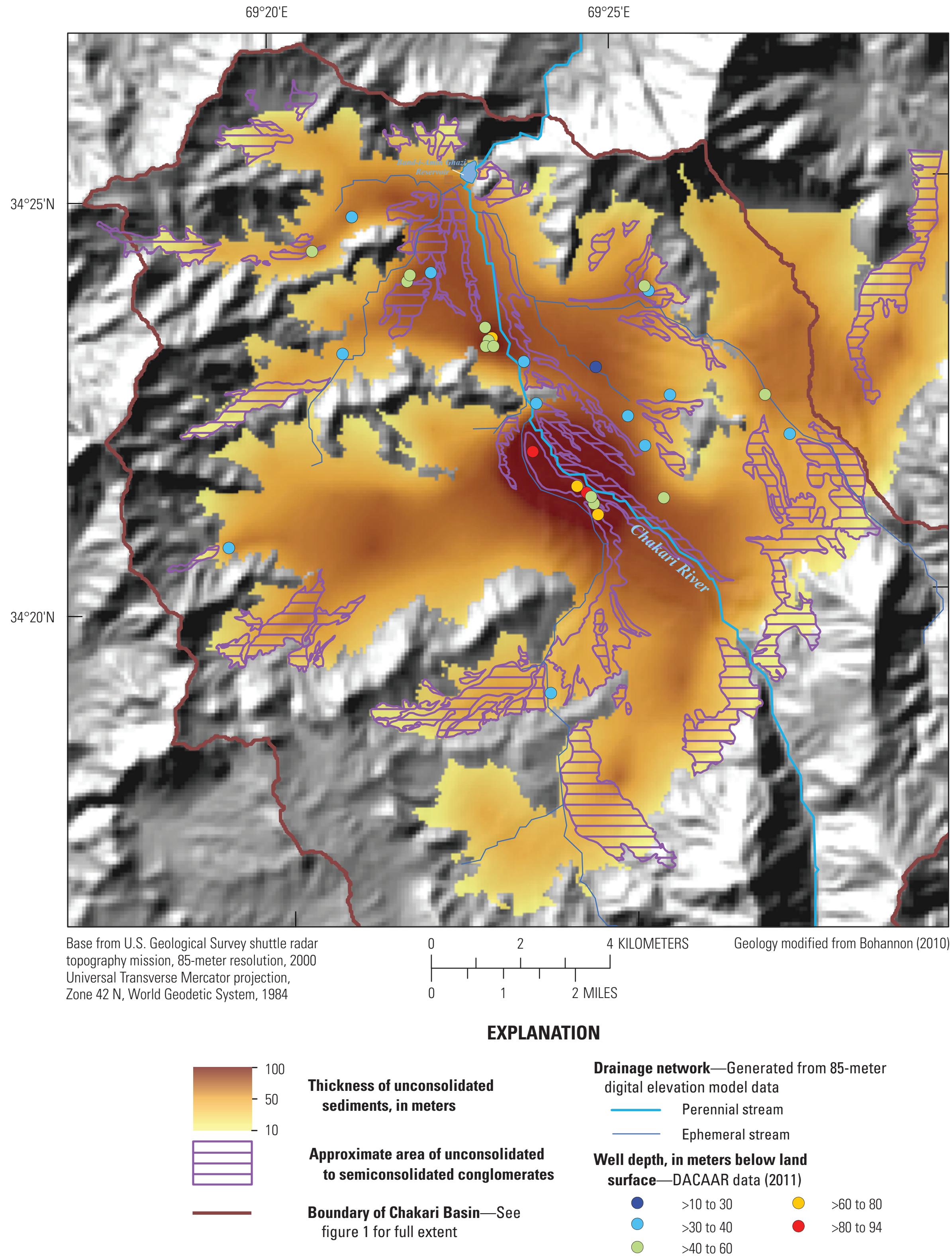


Figure 7. The thickness of unconsolidated and semiconsolidated sediments in the Chakari Basin, Afghanistan.

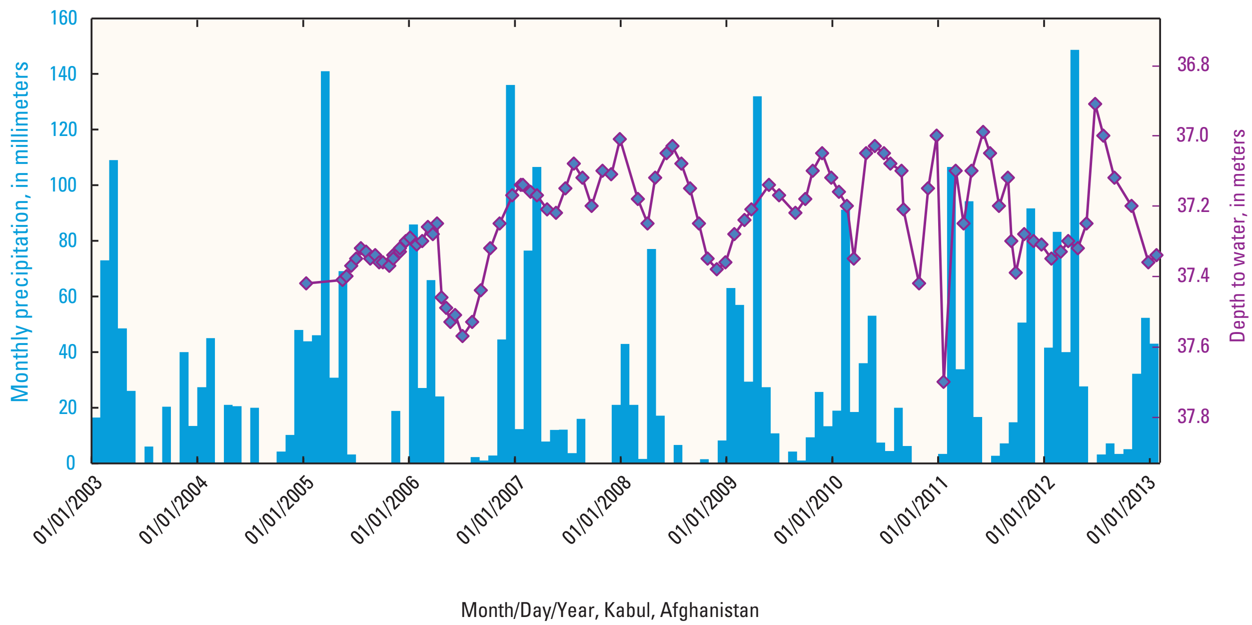


Figure 8. Hydrograph of well W5 (Danish Committee for Aid to Afghan Refugees well GMW–4) in the Chakari Basin and total monthly precipitation in Kabul, Afghanistan, 2005 through 2011.

Refugees, 2010). For the 2012–2013 measurement points (eight wells and four springs), depth to water ranged from 0 m at springs to 37.8 and 42.5 m at wells W5 and W6. The mean depth to water was 14 m. The mean depth to water at 35 historical points was 22 m. A maximum depth to water of 65 m was measured near well W6. The depth to water is 0 m at the Band-i Amir Ghazi Reservoir and assumed to be near 0 m at downstream reaches of the Chakari River.

The water table surface generally follows the land surface topography. Directions of groundwater flow are toward the center of the basin and northward toward the Band-i Amir Ghazi Reservoir. The greatest inflows to the unconsolidated aquifer are likely to occur primarily where the Chakari River loses water as it enters areas underlain by the unconsolidated aquifer (fig. 7) and secondarily where other ephemeral drainages enter areas underlain by the unconsolidated aquifer. Groundwater in the study area ultimately discharges to the Chakari River or its tributary drainages and the Band-i Amir Ghazi Reservoir. Water-table contours are widely spaced in the center of the basin where gradients are low. Gradients may be steeper in the bedrock of the surrounding hillsides, following the topography. However, the nature of the gradients is generally unknown in the bedrock, because water level data are available only from one borehole. In borehole N5, about 330 m east of and 30 m higher than the reservoir, the depth to water was measured to be 7 m below land surface (January 2013).

In a subbasin of the Kabul Basin, isotopic evidence indicated that there was regional interbasin groundwater flow across a surface-water divide into the Kabul Basin from an adjacent high-elevation basin (Mack and others, 2010). Similarly, there could be regional groundwater flow from the Chakari Basin to the lower elevation Kabul Basin (to the northwest) or to the Logar Basin (to the west) through the bedrock ridges that delineate the basins (fig. 1); the Kabul and Logar Basins are about 300 m lower in elevation than the Chakari Basin. It is not likely that there is interbasin groundwater flow to or from the basin to the east of the Chakari Basin (figs. 7 and 9) because the basins have similar elevations and there is a topographic divide between them.

Groundwater storage in the basin is expected to be greatest in the unconsolidated sediments and the unconsolidated to semiconsolidated conglomerates (fig. 7). In the lower elevation areas of the northern Chakari Basin, these sediments cover areas of approximately 120 and 30 km^2, respectively. Assuming an average porosity of 0.20 and an average saturated thickness of about 20 m, the volume of groundwater stored in these sediments would be at least 600 million cubic meters. As in any aquifer system, not all groundwater can be physically extracted, and the stored volume is much greater than the recharge (26,784 m^3/d based on average annual streamflow) that sustains groundwater in the basin. Groundwater in storage provides some buffer to the seasonal climatic variability of water resources; however, new or increased groundwater withdrawals must be carefully assessed to avoid negatively affecting existing, generally shallow water resources. Additionally, because recharge in the basin is supplied by a melting winter snowpack in the spring

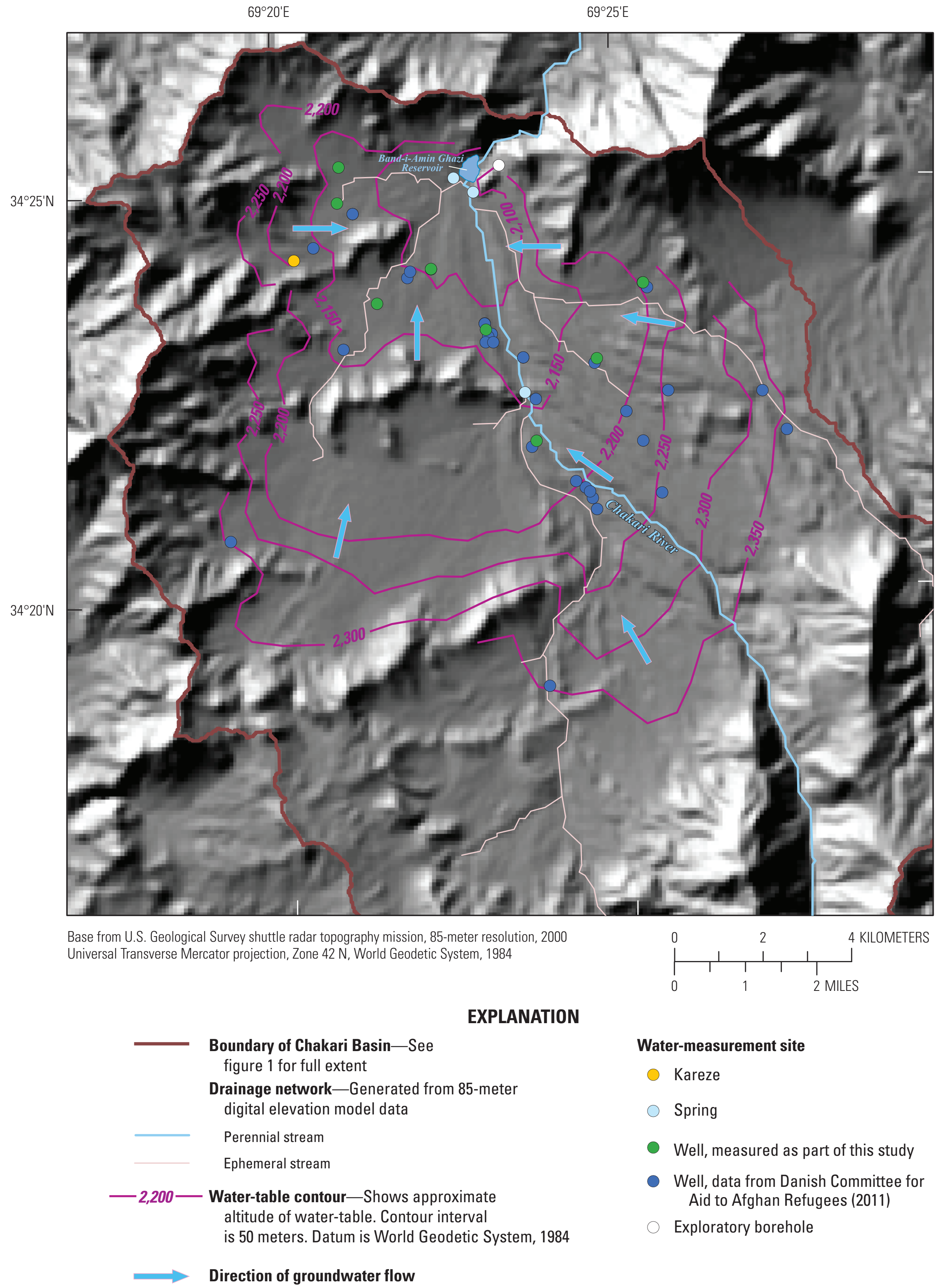


Figure 9. Water-table elevation and direction of groundwater flow in the Chakari Basin, Afghanistan.

and summer, the availability of water resources is likely to be affected by climate changes. An integrated assessment, using a groundwater flow model, of the variables involved in estimating groundwater availability and sustainability—including the physical geometry of an aquifer system, the hydraulic characteristics of the sediments (porosity and hydraulic conductivity), and the amount and timing of inflows and outflows (recharge and discharges)—would improve understanding of the aquifer system.

Water Quality, Chemistry, and Isotopes

Water quality samples were collected in the Chakari Basin during December 2012 and January 2013 from the Chakari River, eight wells, four springs, and one kareze (fig. 4; table 2; appendixes 1–3). Samples collected from the springs and kareze represent discharging groundwater and are considered groundwater for purposes of this study. Water quality in the sparsely populated Chakari Basin is generally good with dissolved solids less than 600 mg/L, although elevated nitrogen compounds were detected in some of the samples (table 4).

Surface Water

One surface-water sample was collected from the Chakari River in January 2013. The surface water sample had a specific conductance of 228 microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C), a concentration of dissolved solids (DS; defined as the amount of dried solids at 180 °C) of 250 milligrams per liter (mg/L), and a field pH measurement of 7.9 (appendix 1). Concentrations of nutrients and major ions in the Chakari River sample were similar to concentrations in other upland rivers flowing into the Kabul Basin, such as the Paghman and Istalef Rivers (Mack and others, 2010) but had higher alkalinity and concentrations of calcium, magnesium, sulfate, and strontium, reflecting the limestone, dolostone, and gypsum found in the Chakari Basin. The concentration of copper (8.4 micrograms per liter [µg/L]) in the Chakari River sample was about an order of magnitude higher than concentrations in other rivers in the Kabul Basin (Mack and others, 2010). The concentration of cobalt (1.49 µg/L) in the Chakari River sample was similar to concentrations in the Logar River (just west of the Chakari Basin), but 5 to 10 times higher than concentrations in the Paghman and Istalef Rivers (Mack and others, 2010). Concentrations of copper and cobalt in the Chakari River reflect the presence of mineral-rich deposits in the Chakari Basin.

Groundwater

Groundwater samples from the Chakari Basin were collected from relatively shallow sources (four springs, one kareze, and eight wells ranging in depth from approximately 30 to 90 m in unconsolidated sediments). Samples were collected from sources either at the water table (kareze and springs) or, with the exception of well W1 (40 m below the water table), from less than 20 m below the water table. There were no clear differences in the major ion chemistry between wells and springs. This is expected because the springs and the kareze are supplied by groundwater discharge. The kareze generally had lower concentrations of major ions than wells or springs, but similar proportions of major ions. Field specific conductance measurements in 13 groundwater samples ranged from 438 to 970 µS/cm at 25 °C and had a median value of 621 µS/cm at 25 °C (fig. 10); the median pH was 7.7, and the median value of alkalinity was 221 mg/L as calcium carbonate ($CaCO_3$) (table 4). These conductivities, pH values, and alkalinities were similar to values in other sparsely populated areas in the upper reaches of the Kabul, Istalef, Panjshir, and Paghman valleys (Mack and others, 2010). DS in groundwater samples ranged from 242 to 578 mg/L and had a median value of 365 mg/L (fig. 11; table 4). DS in one well (W7) exceeded the recommended guideline of 500 mg/L that was established by the U.S. Environmental Protection Agency (EPA) for public water supplies in the United States (table 4). The highest conductivities and DS concentrations were measured in samples from wells W7 and W5, which are in areas with a relatively greater population density than elsewhere in the basin (fig. 3). The hardness of the 13 groundwater samples (which is primarily due to calcium and magnesium dissolved in the water) ranged from 208 to 344 mg/L as $CaCO_3$. Based on the hardness scale that characterizes water from soft to very hard (Hem, 1992), all the groundwater samples from this study indicate that the water is very hard (hardness greater than 180 mg/L as $CaCO_3$).

Where DS concentrations were high, concentrations of sodium, chloride, and sulfate also were high. Major ion chemistry was dominated by calcium-bicarbonate type waters, with a few magnesium-bicarbonate water types and one sodium-bicarbonate-sulfate water type. Calcium-bicarbonate major ion chemistry also was dominant in other subbasins around the Kabul Basin (Broshears and others, 2005; Mack and others, 2010). Changes in the major ion chemistry from calcium-magnesium-bicarbonate to sodium-bicarbonate-sulfate water types may be attributable to the weathering of rock that contains gypsum (Broshears and others, 2005).

Mass-Concentration Ratios

The ratios of select ions to chloride, a conservative tracer, were compared between surface-water and groundwater samples to help determine if there are interactions between the water and rock. Similar ratios of sodium to chloride in surface water and groundwater in the Chakari Basin suggest a common source but little or no reaction between water and rock involving sodium. Ratios of calcium, magnesium, sulfate, and to a lesser extent silica, potassium, strontium, and arsenic relative to chloride were higher in surface water than in groundwater, indicating that interactions between

Table 4. Summary statistics for selected physical properties, inorganic water-quality constituents, and raw and modeled isotopes in groundwater samples collected by the Afghanistan Geological Survey from eight wells, four springs, and one kareze in Chakari Basin, Afghanistan, 2012–2013.

[MRL, minimum reporting limit; Min, minimum; Max, maximum; WHO, World Health Organization; EPA, U.S. Environmental Protection Agency; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; na, no value or not applicable; °C, degrees Celsius; mg/L, milligrams per liter; <, less than; e, estimated; µg/L, micrograms per liter; per mil, parts per thousand; TU, tritium units]

Water-quality properties and constituents	Units	Number of samples	Common MRL	Percentage of samples above MRL	Concentration					WHO drinking-water standard	EPA drinking-water standard
					Min	Quartile			Max		
						25th	50th	75th			
Physical properties											
pH, field	Standard units	13	na	100	7.5	7.6	7.7	7.8	8.0	na	[a]6.5–8.5
pH, laboratory	Standard units	13	na	100	7.7	7.9	8.0	8.1	8.2	na	na
Specific conductance, field	µS/cm at 25 °C	13	na	100	438	566	621	684	970	na	na
Specific conductance, laboratory	µS/cm at 25 °C	13	na	100	432	562	628	686	979	na	na
Water temperature	°C	13	na	100	10.8	12.2	13.9	14.3	15.5	na	na
Major ions											
Total dissolved solids, summed (as DS)	mg/L	13	10	100	249	332	365	427	578	na	[a]500
Hardness, dissolved, calculated (as $CaCO_3$)	mg/L	13	na	100	208	225	244	295	344	na	na
Calcium, dissolved (as Ca)	mg/L	13	0.04	100	34.6	45.7	47.5	66.5	81.6	na	na
Magnesium, dissolved (as Mg)	mg/L	13	0.02	100	22.5	28	29.7	33.3	38.2	na	na
Potassium, dissolved (as K)	mg/L	13	0.06	100	1.38	2.06	3.30	5.28	8.47	na	na
Sodium, dissolved (as Na)	mg/L	13	0.1	100	8.08	23.5	36.6	49.8	109	na	[b]30–60
Alkalinity, dissolved, field (as $CaCO_3$)	mg/L	13	na	100	163	194	221	228	250	na	na
Bicarbonate, dissolved, field (as HCO_3)	mg/L	13	na	100	189	232	267	276	304	na	na
Carbonate, dissolved, field (as CO_3)	mg/L	13	0.1	61	<0.1	<0.1	<0.1	1	2	na	na
Bromide, dissolved (as Br)	mg/L	13	0.01	100	0.032	0.069	0.123	0.162	0.429	na	na
Chloride, dissolved (as Cl)	mg/L	13	0.12	100	5.40	11.0	16.2	26.2	105	na	[a]250
Fluoride, dissolved (as F)	mg/L	13	0.1	100	0.19	0.32	0.35	0.38	0.55	1.5	2–4
Silica, dissolved (as SiO_2)	mg/L	13	0.06	100	10.7	13.6	17.0	18.3	20	na	na
Sulfate, dissolved (as SO_4)	mg/L	13	0.18	100	22.7	58.9	67.7	87.4	156	na	[b]250
Nutrients											
Nitrogen, ammonia, dissolved (as N)	mg/L	13	0.001	38	<0.0001	<0.0001	<0.0001	[e]0.019	[e]0.3	na	[b]30
Nitrogen, nitrite plus nitrate, dissolved (as N)	mg/L	13	0.001	100	[e]0.21	[e]2.6	[e]3.1	[e]4.1	[e]12.9	[c]10	10
Phosphorus, orthophosphate, dissolved (as P)	mg/L	13	0.001	31	<0.0001	<0.0001	<0.0001	[e]0.003	[e]0.033	na	na

Table 4. Summary statistics for selected physical properties, inorganic water-quality constituents, and raw and modeled isotopes in groundwater samples collected by the Afghanistan Geological Survey from eight wells, four springs, and one kareze in Chakari Basin, Afghanistan, 2012–2013.—Continued

[MRL, minimum reporting limit; Min, minimum; Max, maximum; WHO, World Health Organization; EPA, U.S. Environmental Protection Agency; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; na, no value or not applicable; °C, degrees Celsius; mg/L, milligrams per liter; <, less than; e, estimated; µg/L, micrograms per liter; per mil, parts per thousand; TU, tritium units]

Water-quality properties and constituents	Units	Number of samples	Common MRL	Percentage of samples above MRL	Concentration					WHO drinking-water standard	EPA drinking-water standard
					Min	Quartile 25th	Quartile 50th	Quartile 75th	Max		
Dissolved gases											
Carbon dioxide (as CO_2)	mg/L	13	na	100	3.6	9.5	10.8	17.2	21.9	na	na
Nitrogen (as N_2)	mg/L	13	na	100	12.7	13.3	14.3	14.5	19.1	na	na
Argon (as Ar)	mg/L	13	na	100	0.47	0.49	0.51	0.52	0.6	na	na
Methane (as CH_4)	mg/L	13	0.001	23	<0.001	<0.001	<0.001	<0.001	0.1	na	na
Trace elements											
Aluminum, dissolved (as Al)	µg/L	13	2.2	77	<2.2	2.4	3.3	3.7	13.7	na	[a]50–200
Antimony, dissolved (as Sb)	µg/L	13	0.027	85	<0.027	0.03	0.05	0.07	0.38	na	6
Arsenic, dissolved (as As)	µg/L	13	0.04	100	0.12	0.30	0.43	0.67	1.9	10	10
Barium, dissolved (as Ba)	µg/L	13	0.1	100	31.2	38.2	46.8	49.0	65.0	700	2,000
Beryllium, dissolved (as Be)	µg/L	13	0.006	23	<0.006	<0.006	<0.006	<0.006	0.01	na	4
Bismuth, dissolved (as Bi)	µg/L	13	0.1	8	<0.1	<0.1	<0.1	<0.1	0.83	na	na
Boron, dissolved (as B)	µg/L	13	3	100	45	66	128	183	292	2,400	[a]6,000
Cadmium, dissolved (as Cd)	µg/L	13	0.016	62	<0.016	<0.016	0.019	0.027	0.059	3	5
Cerium, dissolved (as Ce)	µg/L	13	0.1	8	<0.1	<0.1	<0.1	<0.1	0.13	na	na
Cesium, dissolved (as Cs)	µg/L	13	0.1	15	<0.1	<0.1	<0.1	<0.1	0.70	na	na
Chromium, dissolved (as Cr)	µg/L	13	0.07	92	<0.07	0.73	1.2	1.4	2.2	50	100
Cobalt, dissolved (as Co)	µg/L	13	0.023	100	0.047	0.067	0.105	0.195	1.94	na	na
Copper, dissolved (as Cu)	µg/L	13	0.8	100	1.0	11	17	29	77	2,000	[a]1,000
Gallium, dissolved (as Ga)	µg/L	13	0.1	100	2.31	2.79	3.38	3.73	4.74	na	na
Iodine, dissolved (as I)	µg/L	13	0.1	100	3.4	7	14	17	32	na	na
Iron (total), dissolved (as Fe)	µg/L	13	4	77	<4	5	9	22	111	na	[a]300
Lead, dissolved (as Pb)	µg/L	13	0.025	69	<0.025	<0.025	0.06	0.15	0.69	na	15
Lithium, dissolved (as Li)	µg/L	13	0.22	100	4.47	6.30	8.86	10.3	16.2	na	na
Manganese, dissolved (as Mn)	µg/L	13	0.15	100	0.15	1.2	2.73	4.75	31.2	na	[a]50
Molybdenum, dissolved (as Mo)	µg/L	13	0.014	100	1.12	1.99	3.09	4.15	5.27	na	[a]200
Nickel, dissolved (as Ni)	µg/L	13	0.09	100	0.24	0.29	0.41	0.62	9.1	na	[a]100
Neodymium, dissolved (as Nd)	µg/L	13	0.1	8	<0.1	<0.1	<0.1	<0.1	0.1	na	na

Table 4. Summary statistics for selected physical properties, inorganic water-quality constituents, and raw and modeled isotopes in groundwater samples collected by the Afghanistan Geological Survey from eight wells, four springs, and one kareze in Chakari Basin, Afghanistan, 2012–2013.—Continued

[MRL, minimum reporting limit; Min, minimum; Max, maximum; WHO, World Health Organization; EPA, U.S. Environmental Protection Agency; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; na, no value or not applicable; °C, degrees Celsius; mg/L, milligrams per liter; <, less than; e, estimated; µg/L, micrograms per liter; per mil, parts per thousand; TU, tritium units]

Water-quality properties and constituents	Units	Number of samples	Common MRL	Percentage of samples above MRL	Concentration					WHO drinking-water standard	EPA drinking-water standard
					Min	Quartile 25th	Quartile 50th	Quartile 75th	Max		
Trace elements—Continued											
Rubidium, dissolved (as Rb)	µg/L	13	0.1	100	0.18	0.28	0.72	1.9	6.5	na	na
Selenium, dissolved (as Se)	µg/L	13	0.03	100	0.12	1.3	1.8	2.0	2.9	40	50
Silver, dissolved (as Ag)	µg/L	13	0.005	15	<0.005	<0.005	<0.005	<0.005	0.007	na	[a]100
Strontium, dissolved (as Sr)	µg/L	13	0.2	100	364	790	951	1,100	1,440	na	na
Tellurium, dissolved (as Te)	µg/L	13	0.1	100	0.45	0.54	0.63	0.67	0.85	na	na
Thorium, dissolved (asTh)	µg/L	13	0.1	31	<0.1	<0.1	<0.1	0.37	1.7	na	na
Tin, dissolved (as Sn)	µg/L	13	0.1	38	<0.1	<0.1	<0.1	0.25	1.0	na	na
Titanium, dissolved (as Ti)	µg/L	13	0.1	100	0.44	0.55	0.66	0.77	1.5	na	na
Uranium, natural, dissolved (as U)	µg/L	13	0.04	100	0.47	3.7	5.3	8.9	14	30	30
Vanadium, dissolved (as V)	µg/L	13	0.08	100	0.39	1.1	3.1	4.5	14.2	na	na
Zinc, dissolved (as Zn)	µg/L	13	1.4	69	<1.4	<1.4	22.3	66.3	189	na	[a]5,000
Isotopes											
CFC–11 modeled years	Years	13	na	100	13.75	27.7	28.5	29.5	49.9	na	na
CFC–12 modeled years	Years	13	na	100	9.9	10.65	21.2	23.3	41.9	na	na
CFC–113 modeled years	Years	13	na	100	23.2	24.2	25	25.3	39.4	na	na
Deuterium (^{2}H) in water × 1,000	Ratio of $^{2}H/^{1}H$, per mil	13	na	100	-66	-56.4	-55.3	-53.8	-52.8	na	na
Deuterium excess × 1,000	Unitless	13	na	100	11.44	13.02	13.92	15.34	16.2	na	na
delta ^{18}O in water × 1,000	Ratio of $^{18}O/^{16}O$, per mil	13	na	100	-10.06	-8.8	-8.63	-8.53	-8.18	na	na
delta ^{18}O in nitrate × 1,000	Ratio of $^{18}O/^{16}O$, per mil	13	na	100	1.32	2.14	2.75	3.29	3.98	na	na
delta ^{15}N in nitrate × 1,000	Ratio of $^{15}N/^{14}N$, per mil	13	na	100	4.03	6.27	6.96	7.31	10.24	na	na
SF–6 modeled years	Years	13	na	100	3.74	6.5	7.5	19.5	31.3	na	na
^{14}C, percent modern	Percent	13	na	100	31.9	73.6	83.4	86.8	94.8	na	na
Tritium (^{3}H)	TU	13	na	100	-0.01	2.2	6.7	8.6	9.7	na	na

[a]Nonenforceable lifetime health advisory or secondary drinking-water standard.

[b]Nonenforceable taste threshold.

[c]The WHO defines the maximum permissible concentration of nitrate in drinking water as 50 mg/L, which is equivalent to 10 mg/L as nitrogen.

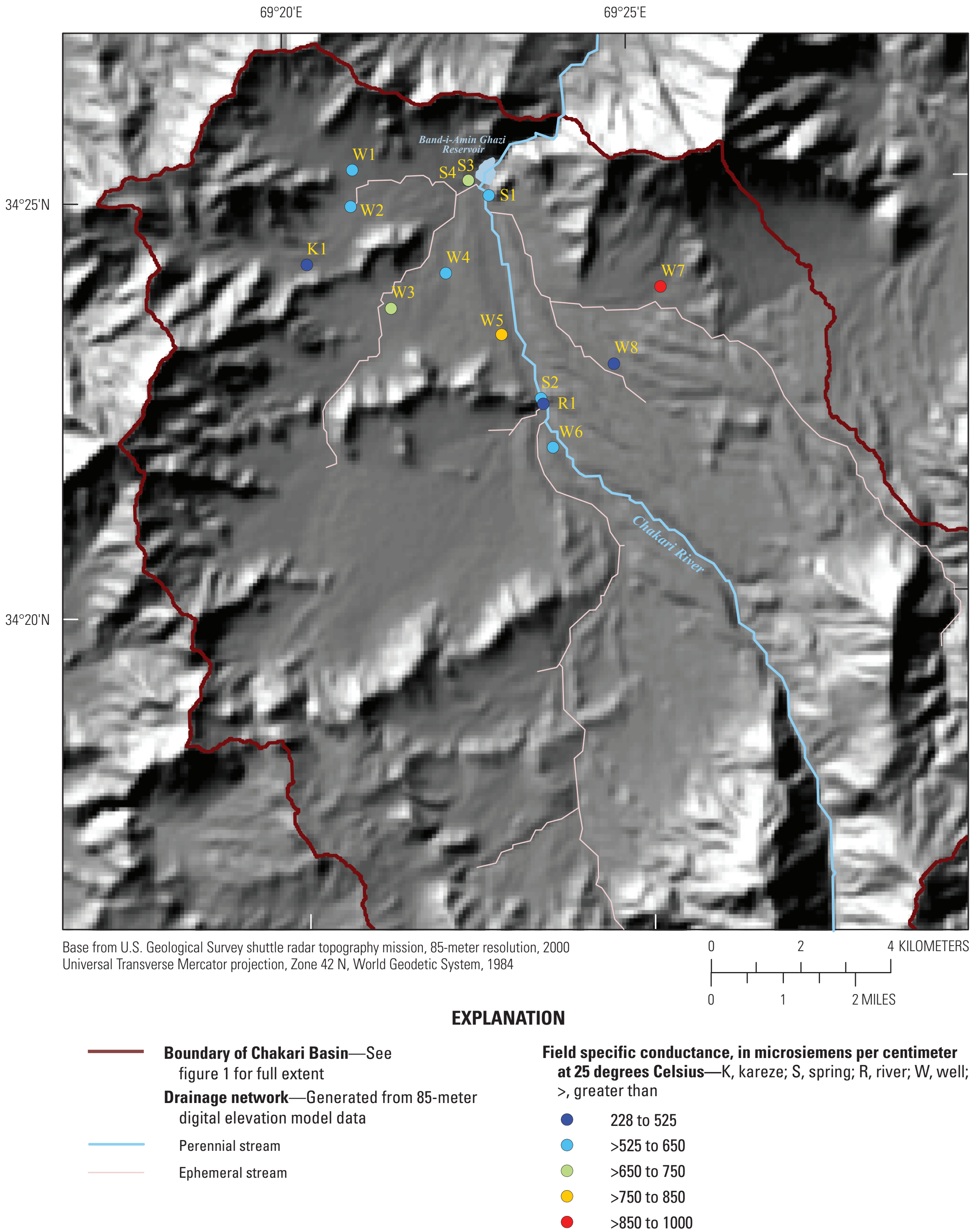


Figure 10. Specific conductance of water in the Chakari Basin, Afghanistan, 2012–2013.

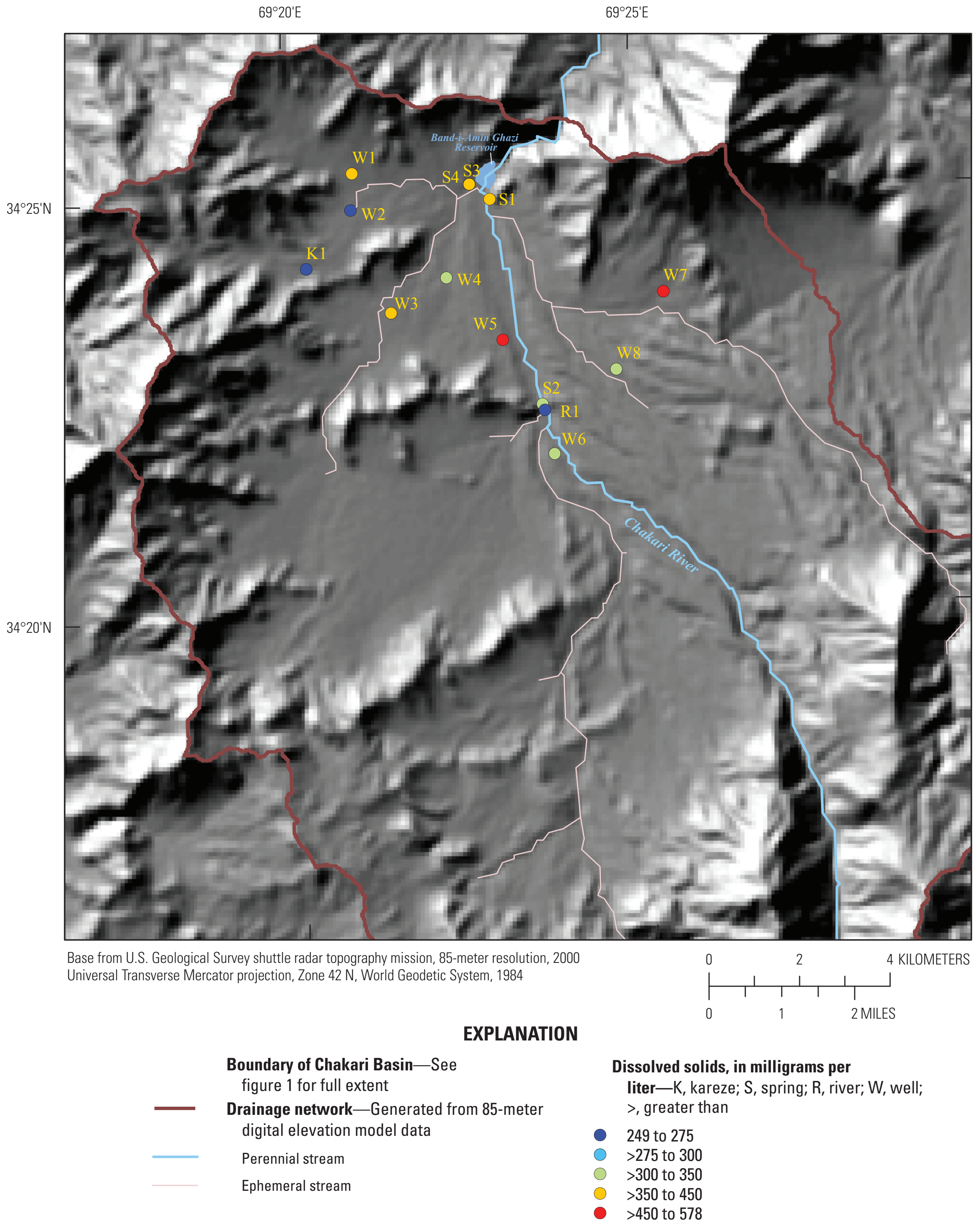


Figure 11. Dissolved solids concentrations in water in the Chakari Basin, Afghanistan, 2012–2013.

water and rock, including calcite and gypsum precipitation and cation exchange, may be occurring in shallow groundwater. Arsenic, if available for mobilization, may be partially removed from groundwater, possibly through adsorption on iron-manganese oxyhydroxides. Solute concentrations in the Chakari Basin groundwater samples were generally about one order of magnitude greater than the concentration in the surface-water sample from the Chakari River. The low solute concentration of surface water indicates that the Chakari River probably loses water rather than gains discharged groundwater (which would have a relatively high solute concentration) as it traverses unconsolidated aquifer sediments. The enrichment of dissolved ions in groundwater compared to surface water in the Chakari Basin is relatively low compared with the enrichment of as much as two orders of magnitude that is found in other subbasins of the Kabul Basin (Mack and others, 2010).

Nutrients

Concentrations of nitrogen and phosphorous species were highest in two springs (S3, S4) near the mouth of the watershed and in one well (W5) along the Chakari River in an area of relatively high population (figs. 3 and 4; appendix 1). Estimated concentrations of nitrate plus nitrite—collectively referred to as nitrate in this report—ranged from 0.21 to 12.9 mg/L as nitrogen (N) in 13 groundwater samples. The estimated median nitrate concentration of 3.1 mg/L as N was similar or slightly higher than the median nitrate concentration in other subbasins (1.2 to 3.8 mg/L as N) of the Kabul Basin (Mack and others, 2010). Nitrate concentrations in groundwater samples from the Chakari Basin also were similar to background concentrations observed in the arid southwestern United States (Anning and others, 2012). The concentration of one sample from well W5 (12.9 mg/L as nitrate; fig. 12; appendix 1) exceeded the World Health Organization's (WHO; 2011) maximum permissible limit of 10 mg/L for nitrate as N (table 4). The low nitrate concentration (0.21 mg/L as N) in the groundwater sample from well W8 most likely is due to the fact that the sample contains a large fraction of old water (see "Hydrogen and Oxygen Isotopes of Water" section).

Bacteria

Coliform bacteria are found in soil, surface water, plants and in the intestines of animals and humans. The presence of coliform bacteria in groundwater indicates poorly constructed, cracked or unsealed wells. *E. coli* is a type of fecal coliform bacteria commonly found in intestines of animals and humans. *E. coli* bacteria were not detected in any samples, reflecting the relatively sparse population in the Chakari Basin. Total coliform bacteria were detected in three out of the four spring samples and in one water sample from well W5 (appendix 1). Livestock graze in the lowland areas near the springs. As reported earlier, well W5, a dug well, also had a nitrate concentration of 12.9 mg/L as N, indicating contamination from anthropogenic sources and possibly a poor well seal (fig. 12).

Oxidation-Reduction Conditions

Oxic conditions (where dissolved oxygen concentrations exceed 1 mg/L) are often found in shallow groundwater in areas with dry climates (Ayotte and others, 2011; Anning and others, 2012). Water-quality constituents that are sensitive to reduction and oxidation (redox) conditions, such as nitrogen species, iron, and manganese, provided evidence of oxic conditions in groundwater in the Chakari Basin (appendixes 1 and 2). Most of the nitrogen (estimated to be 89 to 100 percent) was present as nitrate, the most oxidized form of nitrogen. Low concentrations of iron (median of 8.9 µg/L) and manganese (median of 2.7 µg/L) in groundwater further indicated oxic conditions because these elements are less soluble under oxidizing conditions than under reducing conditions. The highest concentrations of iron (111 µg/L) and manganese (31.2 µg/L) and the lowest concentrations of nitrate (0.21 mg/L as N) were found at well W8. The large fraction of old water at well W8 indicates a longer and (or) a slower flow path compared with other sites in the basin. A longer flow path would allow for more time for interaction between water and rock, which in turn promotes the consumption of dissolved oxygen, leading to less oxidized groundwater conditions.

Trace Elements

Concentrations of many trace elements in groundwater of the Chakari Basin reflect the mineralized geology and the dry climate of the area (appendix 2). However, none of the trace element concentrations exceeded a WHO or EPA human-health benchmark or nonhealth guideline (table 4). High concentrations of boron (greater than 50 µg/L), selenium (greater than 1 µg/L), strontium (greater than 500 µg/L), and uranium (greater than 3 µg/L) in most samples from the Chakari Basin are typical of groundwater in unconsolidated sand aquifers under dry, oxic conditions and slightly alkaline pH (Ayotte and others, 2011). Concentrations of boron, selenium, strontium, and uranium in the groundwater samples from the Chakari Basin were similar to concentrations in other subbasins around the Kabul Basin (Mack and others, 2010) and were about twice as high as concentrations in groundwater samples in unconsolidated sand and gravel aquifers in arid regions of the United States (Ayotte and others, 2011). Zinc and copper concentrations in the groundwater samples from the Chakari Basin were 5 to 10 times higher than concentrations in groundwater samples from subbasins in the Kabul Basin (Mack and others, 2010) or in similar western regions of the United States (Ayotte and others, 2011). High concentrations of zinc and copper in groundwater samples from the Chakari Basin likely reflect the presence of dolomitic

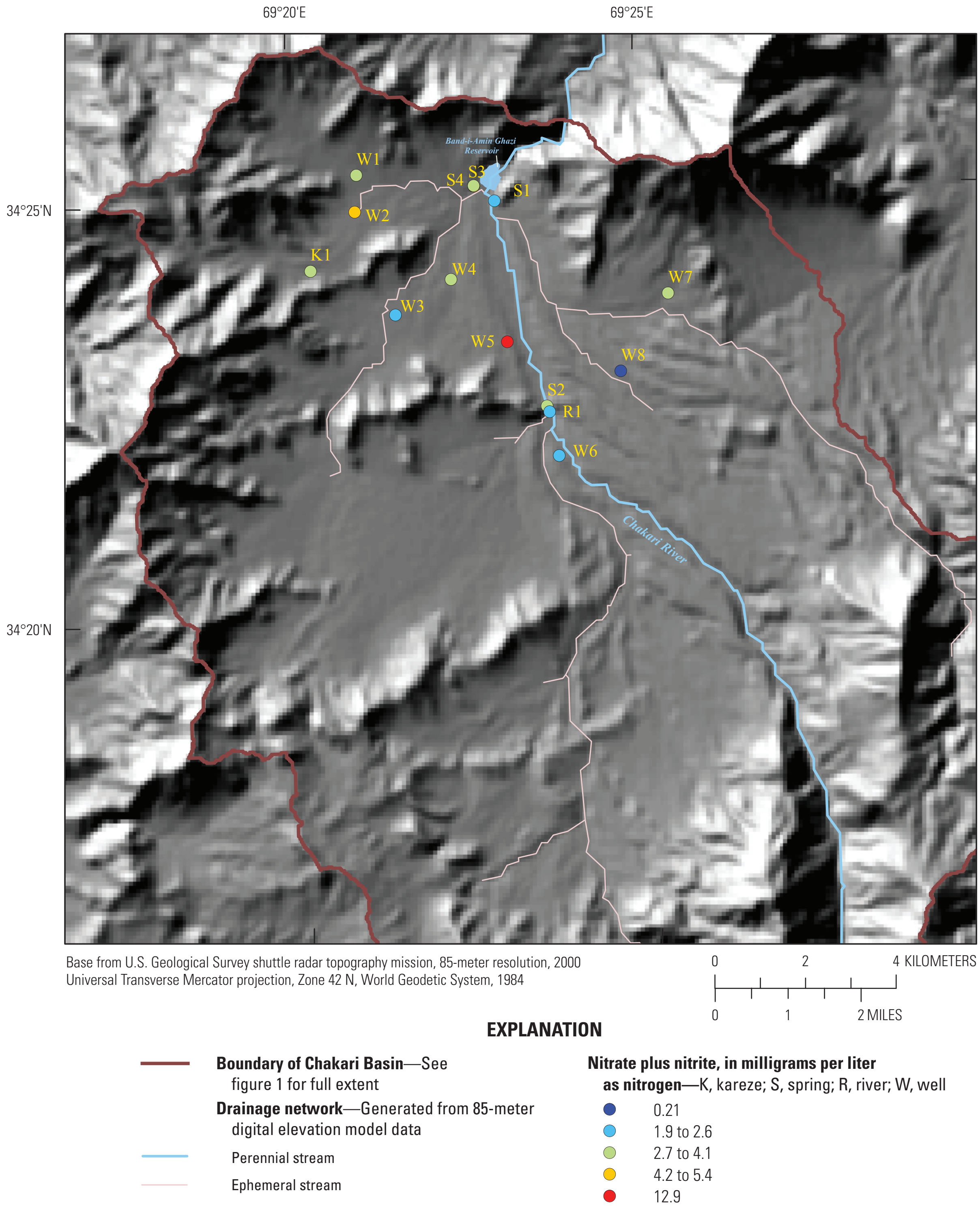


Figure 12. Nitrate plus nitrite concentrations in water in the Chakari Basin, Afghanistan, 2012–2013.

marble (a metasedimentary rock) in the mineral-rich area (fig. 5; Peters and others, 2011; K.M. Renaud, W.R. Stettner, and S.G. Peters, written commun., 2014).

The trace-element concentrations in samples from the four springs and one kareze in the Chakari Basin were similar to concentrations in groundwater except for the concentrations of zinc. Concentrations of zinc in the springs (less than 1.4 to 4.5 µg/L), the kareze (less than 1.4 µg/L), and surface water (1.6 µg/L) were relatively low compared with concentrations in well water (20 to 189 µg/L; appendix 2). Many of the highest trace element concentrations in the water samples from the Chakari Basin were from well W1 and springs S1, S3, and S4 along the northern edge of the valley floor (fig. 4). Well W1 had the highest concentrations of aluminum, boron, cobalt, iodine, antimony, titanium, and uranium. Spring S1 had the highest concentrations of copper, cadmium, and molybdenum, whereas springs S3 and S4 had the highest concentrations of arsenic, bismuth, and lithium. Farther from the northern ridge but near limestone and dolostone hills (fig. 5), well W4 had the highest concentrations of nickel and zinc. The proximity of wells W1 and W4 and springs S1, S3, and S4 to the mineral-rich surrounding hills and ridges probably explains the relatively high concentrations of some of these trace elements compared with concentrations in samples from other wells and springs at greater distances from the mineral deposits.

Inorganic and Anthropogenic Tracer Constituents

Inorganic and anthropogenic tracers provide information on the apparent source and age of groundwater and processes affecting groundwater composition. However, these tracer-derived ages are considered "apparent" ages because a single water sample from a well or spring can be a mixture of groundwaters with different ages (appendix 3).

Nitrogen and Oxygen Isotopes of Nitrate

The isotopic compositions of nitrogen ($\delta^{15}N$) and oxygen ($\delta^{18}O$) in nitrate often are useful for determining sources of nitrate in groundwater and surface water (Kendall and Aravena, 2000). Different sources of nitrate have characteristic isotopic signatures (^{15}N relative to ^{14}N, expressed as $\delta^{15}N$). Isotope ratios are expressed as the ratio of the heavier isotope to the lighter isotope relative to the standard (nitrogen in air for $\delta^{15}N$) and are in parts per thousand (per mil). Sources from atmospheric nitrogen have $\delta^{15}N$ ratios that are near zero as defined by their reference to atmospheric N_2. The $\delta^{18}O$ ratios of soil nitrate formed from in situ nitrification of ammonium typically range from –10 to +10 per mil. Commercial fertilizers and vascular plants have $\delta^{15}N$ ratios in the range of –4 to +4 per mil because they have an atmospheric source of nitrogen. Commercial fertilizers and desert areas with high-nitrate sediments may have $\delta^{18}O$ ratios of nitrate in the range of +18 to +26 per mil. Natural soil organic matter has $\delta^{15}N$ values that range from +3 to +9 per mil. $\delta^{15}N$ ratios from human and animal wastes range widely, typically around +8 to +22 per mil (Böhlke, 2002).

$\delta^{18}O$ ratios of nitrate in the 13 groundwater samples ranged from +1.32 to +3.98 per mil, and $\delta^{15}N$ ratios of nitrate in 12 of the 13 groundwater samples ranged from +4.0 to +9.3 per mil, indicating organic soil matter as the predominant nitrogen source (fig. 13; table 4). The one exception

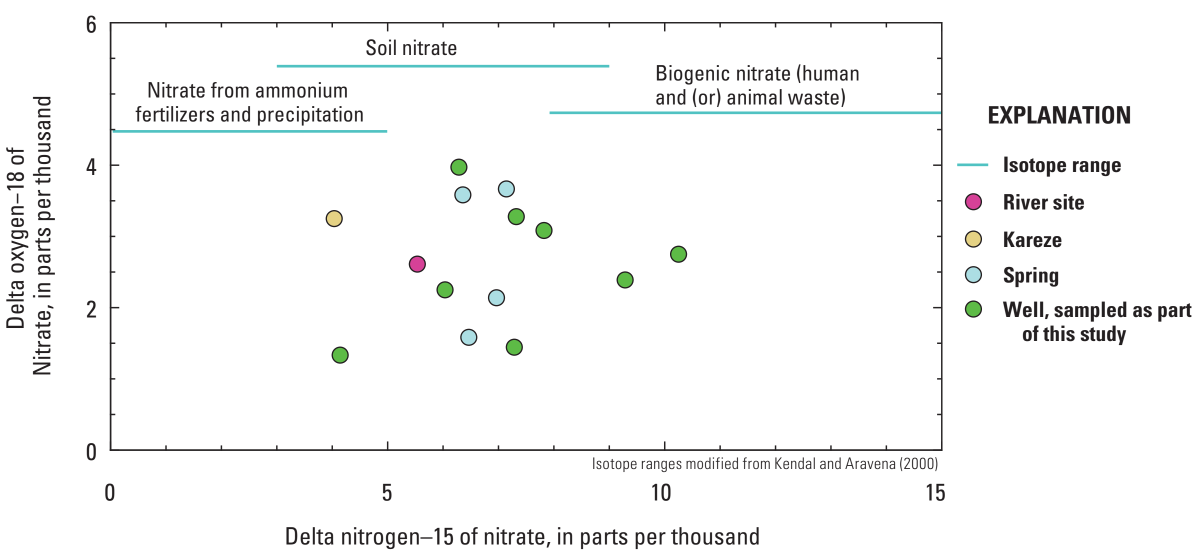


Figure 13. The isotopic composition of the nitrate in water samples from the Chakari Basin, 2012–2013.

was the water sample from well W5, which had a $\delta^{15}N$ ratio of +10.24 per mil. The higher $\delta^{15}N$ value at this site suggests some of the nitrogen is from human or animal waste. Well W5 is in an area of undifferentiated sands with the highest population density found in the basin (150–336 people per square kilometer), making it vulnerable to anthropogenic influences. A high nitrate concentration (12.9 mg/L as N), detections of coliform bacteria, and a $\delta^{15}N$ value greater than +10 per mil all indicate possible anthropogenic contamination in groundwater at this site. Groundwater from well W5 also was likely recharged in the past 11 years, based on apparent ages from anthropogenic tracers (see "Chlorofluorocarbons and Sulfur Hexafluoride" section). Well W5 is a large-diameter hand-dug well lined with stones that allow for natural seepage into the well and is likely more vulnerable to surface contamination than modern wells that are constructed with more rigorous, sanitary methods.

Hydrogen and Oxygen Isotopes of Water

The isotopic ratios of hydrogen (δ^2H) and oxygen ($\delta^{18}O$) in water are used to differentiate between higher and lower elevation sources of the water in streams and aquifers (Clark and Fritz, 1997). Low isotopic ratios of hydrogen and oxygen in water reflect water from high-elevation source areas where a large part of the water draining to streams and recharging groundwater originates as snowmelt. In the Chakari Basin, well W8 had the lowest δ^2H (–66 per mil) and $\delta^{18}O$ (–10 per mil) ratios, suggesting that a greater part of the groundwater at this well originated as high-elevation source water from snowmelt. Well W8 is not immediately adjacent to mountains; therefore, snowmelt-derived recharge to this well must have followed a relatively long flow path. All samples from the Chakari Basin plotted to the left of the global meteoric water line (fig. 13; Rozanski and others, 1993), indicating that no substantial evaporation has occurred. Chloride concentrations in most groundwater samples in the Chakari Basin were about 10 times higher than the chloride concentration in the surface water sample (see "Mass-Concentration Ratios" section). Because δ^2H and $\delta^{18}O$ ratios indicated no substantial evaporation, the elevated chloride concentrations in groundwater most likely were the result of water uptake by vegetation because transpiration removes water without altering $\delta^{18}O$ and δ^2H compositions (Mack and others, 2010) but does concentrate dissolved solutes, such as chloride, in the water that is left behind.

Groundwater in the Chakari Basin had $\delta^{18}O$ and δ^2H isotopic ratios most similar to groundwater from the Paghman and upper Kabul subbasins (fig. 14). Deuterium excess, defined as δ^2H minus eight times $\delta^{18}O$ (Dansgaard, 1964), ranged from 11.4 to 16.2 for groundwater in the Chakari Basin (appendix 3), compared with 12 to 19 in the Paghman and upper Kabul subbasins. The deuterium excess is a function of the relative humidity; a value of +20 indicates 70 percent relative humidity, and a value of +10 indicates 85 percent relative humidity (global mean relative humidity). $\delta^{18}O$ and δ^2H isotopic compositions indicate that the Chakari, Paghman, and upper Kabul subbasins have source-water origins from similar altitudes (approximately 2,000 to 4,000 m) and semiarid climates (Mack and others, 2010). The surface-water sample from the Chakari River had $\delta^{18}O$ and δ^2H isotopic ratios and a deuterium excess value (+16) similar to the values from the upper Kabul River (fig. 14; Mack and others, 2010). The Chakari and upper Kabul River $\delta^{18}O$ and δ^2H isotopic ratios similarly indicate no substantial evaporation, which is unusual for a semiarid climate.

Chlorofluorocarbons and Sulfur Hexafluoride

CFCs are stable, synthetic, halogenated alkanes that were developed in the early 1930s and have been used in a wide range of industrial and refrigerant applications. CFCs are a useful tool for determining the apparent residence times ("ages") of water on time scales of 50 to 70 years in age (International Atomic Energy Agency, 2006). SF_6 is a trace atmospheric gas that is primarily of anthropogenic origin but also occurs naturally in fluid inclusions of some minerals and igneous rocks. SF_6 is a useful tool in dating groundwater that originated as recharge since 1970 (Busenberg and Plummer, 2000).

All 13 groundwater samples contained CFC–11, CFC–12, CFC–113, and SF_6 (appendix 3), indicating that young water or water mixtures containing a part of young water were present in all wells, springs, and the kareze. Apparent ages for the young part of water calculated from CFC concentrations using a piston-flow model ranged from 10 to 50 years (appendix 3). SF_6-derived ages calculated using piston-flow modeling of SF_6 concentrations were slightly younger (4 to 31 years) but comparable to the CFC-derived ages.

Tritium, Helium, and Carbon-14 Isotopes

Tritium, helium, and ^{14}C also can provide information on the age distribution of groundwater. Tritium is a heavy isotope of hydrogen that radioactively decays to helium with a half-life of 12.3 years (Drever, 1988). Tritium is part of the water molecule and is not affected by water-rock reactions; its activities change only through changes in activities in precipitation and through radioactive decay. Tritium activities can be used to differentiate between water that has been recharged since 1953 and water recharged prior to the 1950s. Aboveground testing of hydrogen bombs from 1952 to 1969 added a large amount of tritium to the atmosphere, with a peak of nearly 3,500 tritium units (TU) in 1963 in Afghanistan (International Atomic Energy Agency, undated). Low levels of tritium (5 to 10 TU) are produced continuously by cosmic ray bombardment of the atmosphere (Clark and Fritz, 1997). Even with the variability in tritium content of precipitation over time, groundwater that has been recharged since 1953 (postbomb) likely contains more than 0.5 TU, whereas groundwater that was recharged before 1953 (prebomb) likely contains less than 0.5 TU.

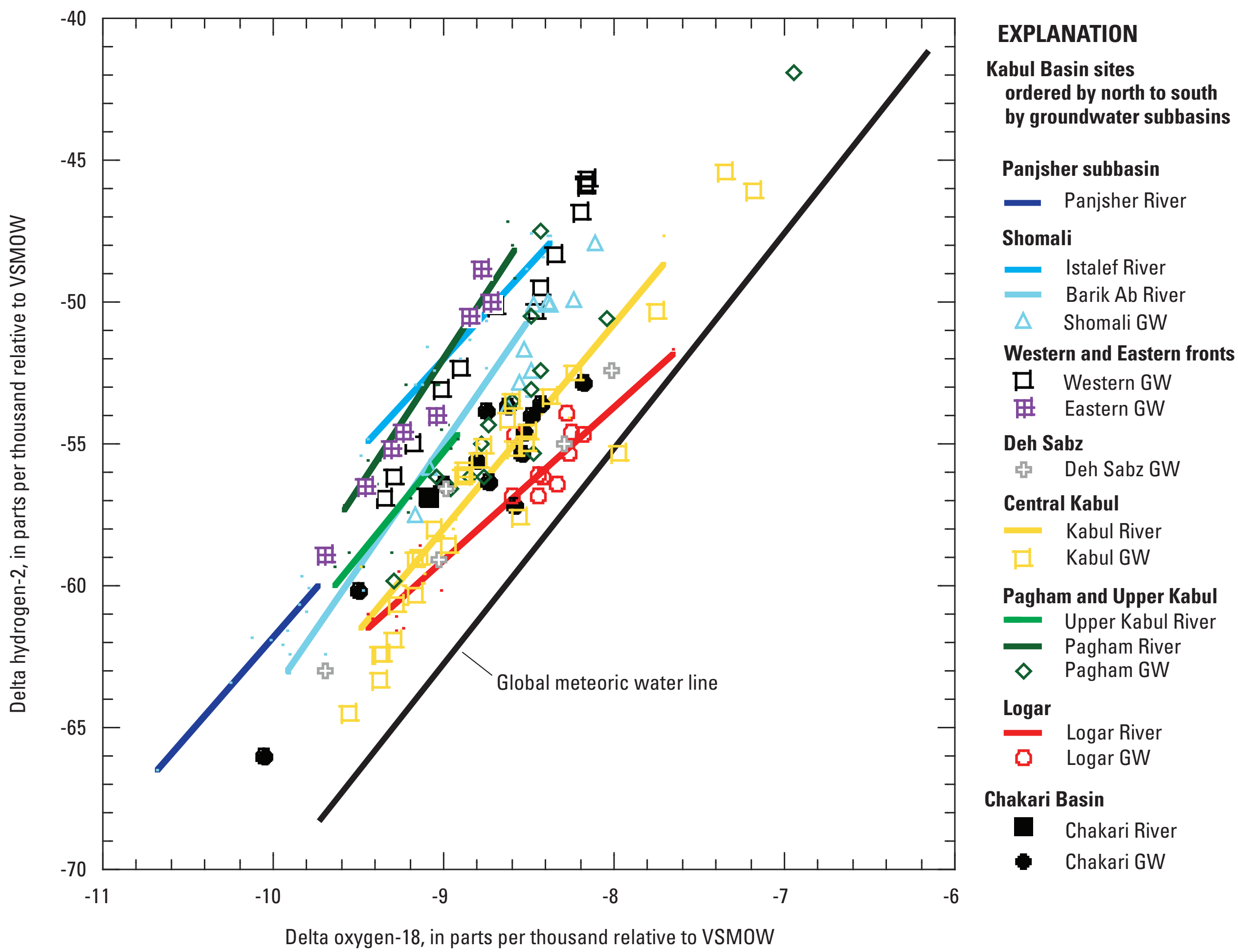


Figure 14. The hydrogen-2 (^{2}H) versus oxygen-18 (^{18}O) isotopic composition, relative to Vienna Standard Mean Ocean Water (VSMOW; Rozanski and others, 1993), of rivers and groundwater (GW; including springs and karezes) in the Chakari and Kabul Basins, Afghanistan. All data except for those for the Chakari Basin are from Mack and others (2010).

The tritium activity for well W8 (0.05 TU; appendix 3) indicates that most of the groundwater from this well was recharged before 1953. Samples from six of the remaining wells, four springs, and the kareze had tritium concentrations in the range of 2.0 to 9.7 TU, indicating that much of the groundwater from these sites was recharged after 1953 (appendix 3). Tritium activities agree with other inorganic and anthropogenic tracers for all wells and springs and the kareze with the exception of well W5. Well W5 is a hand-dug well with signs of surface contamination, including high nitrate concentration (12.9 mg/L as N) and detections of coliform bacteria. The tritium activity reported for well W5 (–0.01 TU; appendix 3) is very likely an erroneous value because it indicates groundwater recharged before 1953. This conclusion conflicts with all other indicators for well W5. Apparent ages for the water at well W5 based on piston-flow modeling of CFC and SF6 data are between 7 to 24 years.

Helium has two stable isotopes, helium-3 and helium-4. Helium-3 is added to groundwater by the decay of tritium, and the ^{3}H:^{3}He ratio can be used to determine the apparent age of groundwater. However, helium in groundwater originates from several sources, and these sources must be accounted for in order to determine the apparent age of groundwater from the ^{3}H:^{3}He ratio. Helium can become dissolved in groundwater from the atmosphere, from excess air (Busenberg and Plummer, 2000; Stute and Schlosser, 2000) in the unsaturated zone of an aquifer in contact with the water table, and from terrigenic helium derived from uranium and thorium radioactive decay reactions in the Earth's crust (Mamyrin and Tolstikhin, 1984).

Determination of the ^{3}H:^{3}He-derived groundwater age is done by measuring the time needed for the original tritium concentration to decay to the measured tritium concentration, once all other helium sources have been accounted for. The

^{3}H:^{3}He age cannot be determined if any of the following four conditions occur: (1) tritium concentration is too low (less than 1 TU), (2) excessive amounts of terrigenic helium are dissolved in the water sample, (3) degassing of the sample occurred, or (4) negative values are calculated for the helium-3 derived from decay of tritium that was in the sample at the time of recharge (L.N. Plummer, U.S. Geological Survey, written commun.). Degassing of a sample is indicated when excess helium-4 is less than excess neon; excess refers to the difference between the concentration of a gas in the groundwater sample and the expected concentration in the groundwater at equilibrium with atmospheric concentrations under the conditions at recharge (L.N. Plummer, U.S. Geological Survey, written commun.).

^{3}H:^{3}He results were valid for only 5 of the 13 groundwater samples owing to low tritium content in wells W5 and W8; large excesses of terrigenic helium in wells W1 and W4; degassing in kareze K1, spring S1, and wells W1, W2, W5, and W6; and negative calculated values of helium-3 in spring S1 and wells W2, W5, W6, and W8 (L.N. Plummer, U.S. Geological Survey, written commun.). The apparent ^{3}H:^{3}He age for springs S2, S3, and S4 and wells W3 and W4 ranged from 1.3 to 20.3 years (appendix 3).

The best way of evaluating the accuracy of results from the ^{3}H:^{3}He method is to compare them with the results of other age-dating techniques. ^{3}H:^{3}He ages were similar or slightly younger than ages derived from CFC and SF_6 data. The sum of tritium plus helium-3 provides the tritium concentration at the time of recharge if the sample has not been diluted with old water (L.N. Plummer, U.S. Geological Survey, written commun.); comparison of the apparent age derived from the ^{3}H:^{3}He method with the initial tritium activity thus calculated is another way to evaluate the accuracy of the ^{3}H:^{3}He ages. The three springs are all young water (0–9 years), based on ^{3}H:^{3}He ages and initial tritium activities. The ^{3}H:^{3}He age of the water sample from well W4 is 17 years; the initial tritium activity of 25 TU in the sample suggests little or no dilution with old water. The initial tritium activity of 6.8 TU for the water sample from well W3 is relatively low for the ^{3}H:^{3}He age of 20 years. Assuming that the part of old water is free of tritium, well W3 appeared to contain about 27 percent of 20-year-old water diluted with old, tritium-free water (L.N. Plummer, U.S. Geological Survey, written commun.).

The radioactive isotope of carbon ^{14}C is incorporated into dissolved carbonate species in water. Activities of ^{14}C in dissolved carbon in groundwater are determined by the activities in equilibrium with atmospheric ^{14}C at when the groundwater was recharged. Because ^{14}C decays with a half-life of 5,730 years, low activities of ^{14}C, relative to modern values in groundwater, generally indicate the presence of groundwater that is several thousands of years old. Thus, ^{14}C is a useful tool for age-dating older groundwater sources ranging in age from approximately 2,000 to 40,000 years from the date of recharge. However, some reactions between rock and water, such as the dissolution of limestone, can dilute the ^{14}C in dissolved inorganic carbon by adding dissolved carbon to the groundwater from old rock sources that contain little or no ^{14}C. Left uncorrected, this would result in modern ^{14}C water samples appearing to be old.

Using the revised Fontes and Garnier model (Han and Plummer, 2013) and assuming the samples were all old water (greater than 60 years old), the uncorrected ^{14}C modeled ages for wells W7 and W8 were 2,200 and 4,100 years, respectively (appendix 3; L.N. Plummer, U.S. Geological Survey, written commun.). These are minimum age estimates before accounting for the possibility that the old water was mixed with younger water containing “artificial” ^{14}C. These uncorrected ^{14}C modeled ages suggest that a large part of water from these wells is old groundwater.

Comparisons of apparent ages based on ^{14}C data with CFC–11, CFC–12, CFC–113, and SF_6 concentrations data indicate that wells W3, W7, and W8 were most likely mixtures of young and old water, whereas the rest of the wells and springs and the kareze contain primarily young water (fig. 15; L.N. Plummer, U.S. Geological Survey, written commun.). The parts of young and old water in wells W3, W7, and W8 were calculated assuming binary dilution. Binary dilution equations were solved using assumptions that old water (greater than 60 years old) would be free of the four tracers and young water would have concentrations similar to the concentrations in northern hemisphere air in January 2013. We thus determined that wells W3 and W7 contain approximately 60 percent old water, and well W8 contains 80 percent old water (appendix 3; L.N. Plummer, U.S. Geological Survey, written commun.).

Following the linear relation between ^{14}C activity and concentrations of the CFC tracers, the old part of water (identified by the *y* intercept (fig. 15), where the concentration of the CFC tracer is equal to zero) contains approximately 20 percent modern ^{14}C (L.N. Plummer, U.S. Geological Survey, written commun.). Radiocarbon modeling of this corrected 20 percent modern ^{14}C using a revised Fontes and Garnier model (Han and Plummer, 2013) indicates that the actual age of the old part of water in wells W3, W7, and W8 is 7,200 to 7,900 years (L.N. Plummer, U.S. Geological Survey, written commun.).

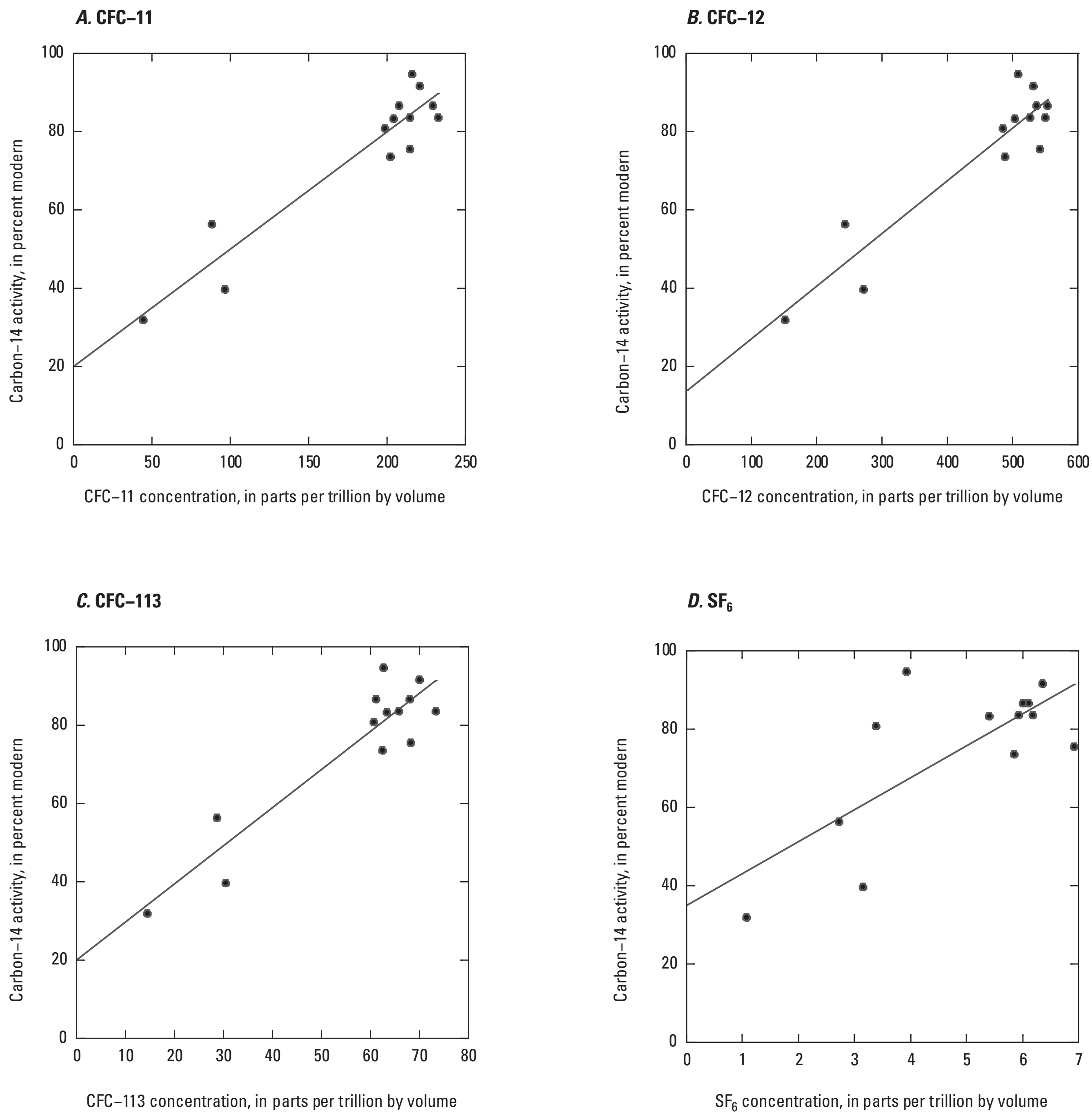


Figure 15. Carbon-14 activities in relation to concentrations of chlorofluorocarbons (CFCs) *A*, trichlorofluoromethane (CFC–11), *B*, dichlorodifluoromethane (CFC–12), *C*, trichlorotrifluoroethane (CFC–113), and *D*, sulfur hexafluoride (SF_6) in groundwater samples from the Chakari Basin, Afghanistan, 2012–2013.

Summary and Conclusions

The U.S. Geological Survey and the Afghanistan Geological Survey assessed the hydrogeology and water quality of the Chakari Basin, a 391-square-kilometer (km^2) watershed near Kabul, Afghanistan. This assessment forms the basis of an understanding of the water resources in an area of Afghanistan with considerable copper and other mineral resources. Water quality, chemical, and isotopic samples were collected at eight wells, four springs, one kareze, and the Chakari River in a basin-fill aquifer in the Chakari Basin by the Afghanistan Geological Survey.

The water quality in the sparsely populated Chakari Basin is influenced by the geology and climate of the area. Concentrations of many trace elements in groundwater of the Chakari Basin are elevated, reflecting the mineralized geology and dry climate of the area. However, none of the trace element concentrations exceeded a World Health Organization human-health benchmark or a U.S. Environmental Protection Agency drinking-water standard or guideline.

A combination of interactions between water and rock and evapotranspiration were the major factors affecting groundwater chemistry in the Chakari Basin. The major ion chemistry of groundwater was calcium-magnesium-bicarbonate-type water. Solute concentrations in groundwater were about one order of magnitude higher than concentrations in the surface water from the Chakari River. Stable hydrogen and oxygen isotope results from groundwater samples indicated no substantial evaporation (all samples plotted above the global meteoric water line). High concentrations of zinc and copper in groundwater samples from the Chakari Basin likely reflect the metasedimentary rocks, particularly dolomitic marble, of the North Aynak-Taghar mineral area. Higher ratios of calcium, magnesium, and sulfate relative to chloride in surface water compared with those in groundwater indicated interactions between water and rock, including calcite and gypsum precipitation and cation exchange in shallow groundwater.

The nitrate values of 2 to 5 milligrams per liter as nitrogen (mg/L as N) for most of the groundwater samples from the Chakari Basin may be the result of agricultural contamination, but the isotope composition of nitrate values suggest that natural soil nitrate may be the predominant source. Detection of coliform bacteria, high concentrations of nitrate (12.9 mg/L as N), and a nitrate isotope value greater than 10 per mil indicate the vulnerability of hand-dug wells (such as well W5; fig. 4) to surface contamination sources. Concentrations of chlorofluorocarbon concentrations and sulfur hexafluoride and carbon-14 activities indicated that groundwater from wells W3, W7, and W8 consists of a mixture of old and young groundwater, with the old part being 7,200 to 7,900 years. All other wells and springs and the kareze likely have groundwater that was recharged less than 50 years ago.

Isotopic analysis of the water samples indicates that some of the groundwater travels thousands of years to reach a point of discharge (that is, a well, spring, or kareze), whereas another component of the groundwater travels only a few years to decades to reach a point of discharge. It is likely that the older water represents flow through the fractured bedrock of the surrounding valley walls and underlying bedrock to the basin-fill sediments. For example, although the surficial sediments at well W7 are about 40 meters (m) thick, the surficial basin-fill sediments extend only about a 1 kilometer upgradient from the well. The source of groundwater at well W7 is likely groundwater that has flowed or drained slowly through fractured bedrock. It is likely that groundwater in the shallow upper sediments (fig. 7) originates from the small amount of recharge from modern (less than 40 years) precipitation that infiltrates at drainage channels, and groundwater deep in the basin-fill sediments is thousands of years old. Analysis of water-level fluctuations and chemical analysis of water indicates that considerable recharge may occur in the basin-fill aquifer through infiltration of surface water, originating primarily as snowmelt from upland areas of the Chakari Basin, at the Chakari River and other stream channels in the basin. Recharge was estimated to be 2×10^{-4} meters per day (m/d) at one point adjacent to the Chakari River. Recharge at this point reflects primarily inflow from upland areas and secondarily direct precipitation. Seepage losses and infiltration from perennial and, to a lesser degree, ephemeral streams traversing areas underlain by unconsolidated sediments likely represent sources of concentrated recharge to the underlying aquifers. Areal basinwide recharge estimated from historical streamflows leaving the basin indicates an average annual recharge rate of only about 7×10^{-5} m/d. The source of this recharge is most likely derived from snow on upland mountains and subsequent meltwater-fed streams.

The average saturated thickness indicated by wells drilled in the basin is approximately 20 m. In the center of the Chakari Basin, saturated basin-fill sediments are as much as 100 m thick, but the saturated thickness in most areas near the center of the basin is likely to be 30 to 60 m. Groundwater in the basin-fill aquifers consists of a near-surface young component, years to decades in age, and a deep component hundreds to thousands of years old that likely has traveled from upland bedrock areas. These groundwater resources meet the drinking-water needs of the existing villages, which rely on low-capacity hand pumps for drinking-water supply and rely on surface water for irrigation. There may be sufficient groundwater storage in the center of the basin for additional groundwater withdrawals. However, the installation and use of wells with high-capacity pumps would need careful evaluation, particularly with respect to the existing water supplies of the surrounding communities. Sustainable use of water in the Chakari Basin for industrial purposes would likely require an integrated surface water and groundwater assessment, using a groundwater flow model, and regional management strategies that consider groundwater and surface-water storage and strategies for enhancing the infiltration of surface water during periods of high streamflow for groundwater recharge.

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Appendixes 1–3

These appendixes are available at *http://pubs.usgs.gov/sir/2014/5113/*.

Appendix 1. Physical Properties, Nutrient, Bacteria, and Major Ion Water-Quality Data for the Chakari Basin, Afghanistan

Appendix 2. Trace-Element Water-Quality Data for the Chakari Basin, Afghanistan

Appendix 3. Inorganic and Anthropogenic Tracer and Dissolved Gas Data for the Chakari Basin, Afghanistan

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