

# Chapter 3C. Geohydrologic Summary of the Badakhshan Gold Area of Interest

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## 3C.1 Introduction

This chapter describes the geohydrology of the Badakhshan gold area of interest (AOI) in northern Afghanistan identified by Peters and others (2007). The AOI is located in Baharak, Fayzabad, Ragh, and Shighnan Districts in Badakhshan Province (fig. 3C–1*a,b*). Fayzabad (Faizabad), the province center, is located in the southwestern part of the AOI. The entire AOI is mountainous, with deeply incised stream channels. The northwestern edge of the AOI is adjacent to the Amu Darya River (Daryai Panj) and the Afghanistan-Tajikistan border.

Water is needed not only to process mineral resources in Afghanistan, but also to supply existing communities and the associated community growth that may accompany a developing mining economy. Information on the climate, vegetation, topography, and demographics of the AOI is summarized to provide information on the seasonal availability of, and seasonal demands for, water. The geohydrology of the AOI is described through the use of maps of streams and irrigated areas, generalized geohydrology and topography, and well locations. Where these data are available, the depth to water and height of static water in wells are documented. The results of lineament analyses are presented to identify areas where the rock may be more fractured than in other areas, which may be an indicator of high relative water yield and storage in bedrock aquifers.

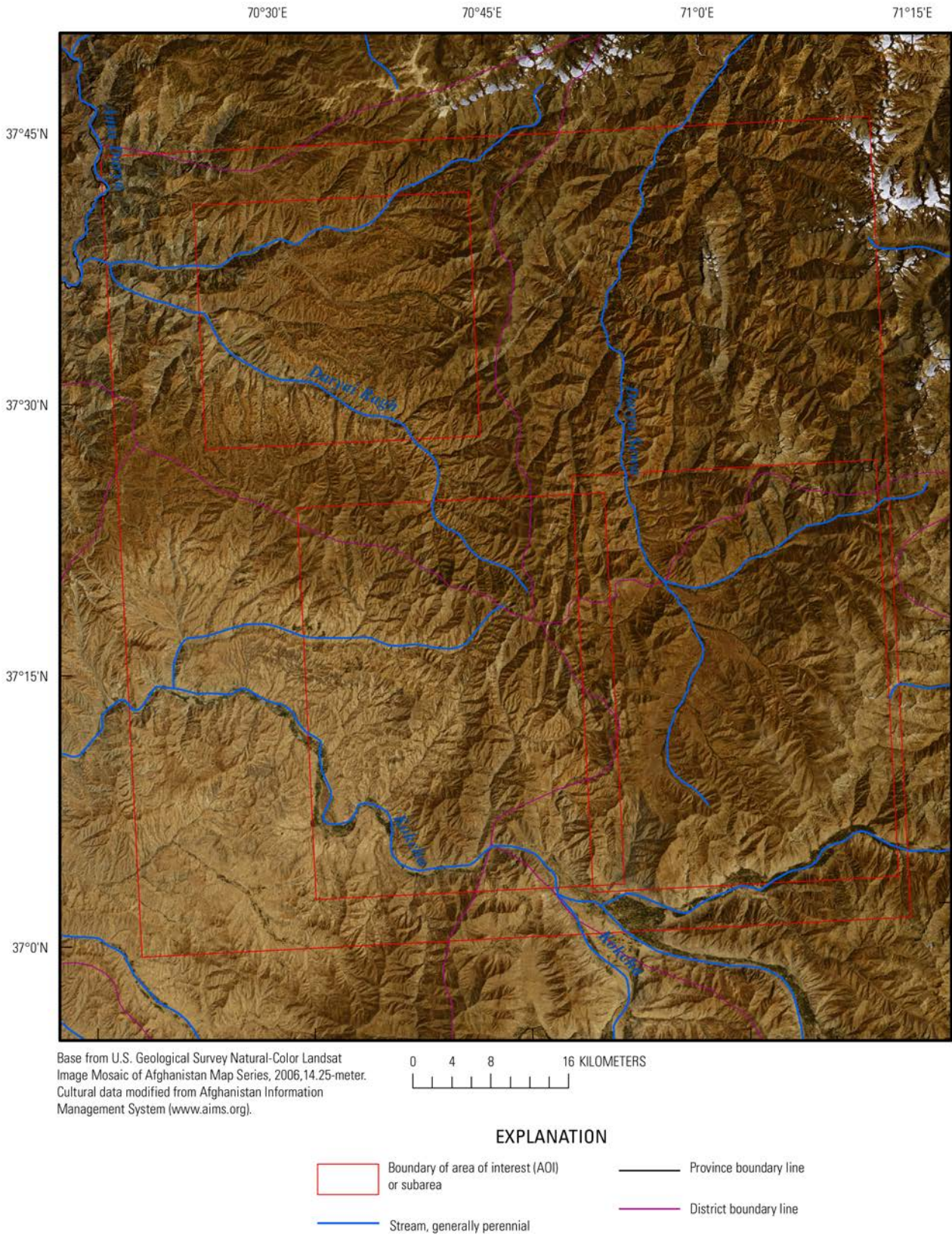
Afghanistan's recent turbulent history has left many of the traditional archival institutions in ruins, and most water-resource and meteorological data-collection activities had stopped by 1980. Recently (2011), nongovernmental organizations (NGOs), foreign government agencies, and the Afghan government have begun water-resource investigations; however, these activities and the amount of data collected are limited. This report summarizes the satellite imagery and climatic, topographic, geologic, surface-water, and groundwater data available. Geohydrologic inferences are made on the basis of an integrated analysis of these data and an understanding of conditions in other areas of Afghanistan.

## 3C.2 Climate and Vegetation

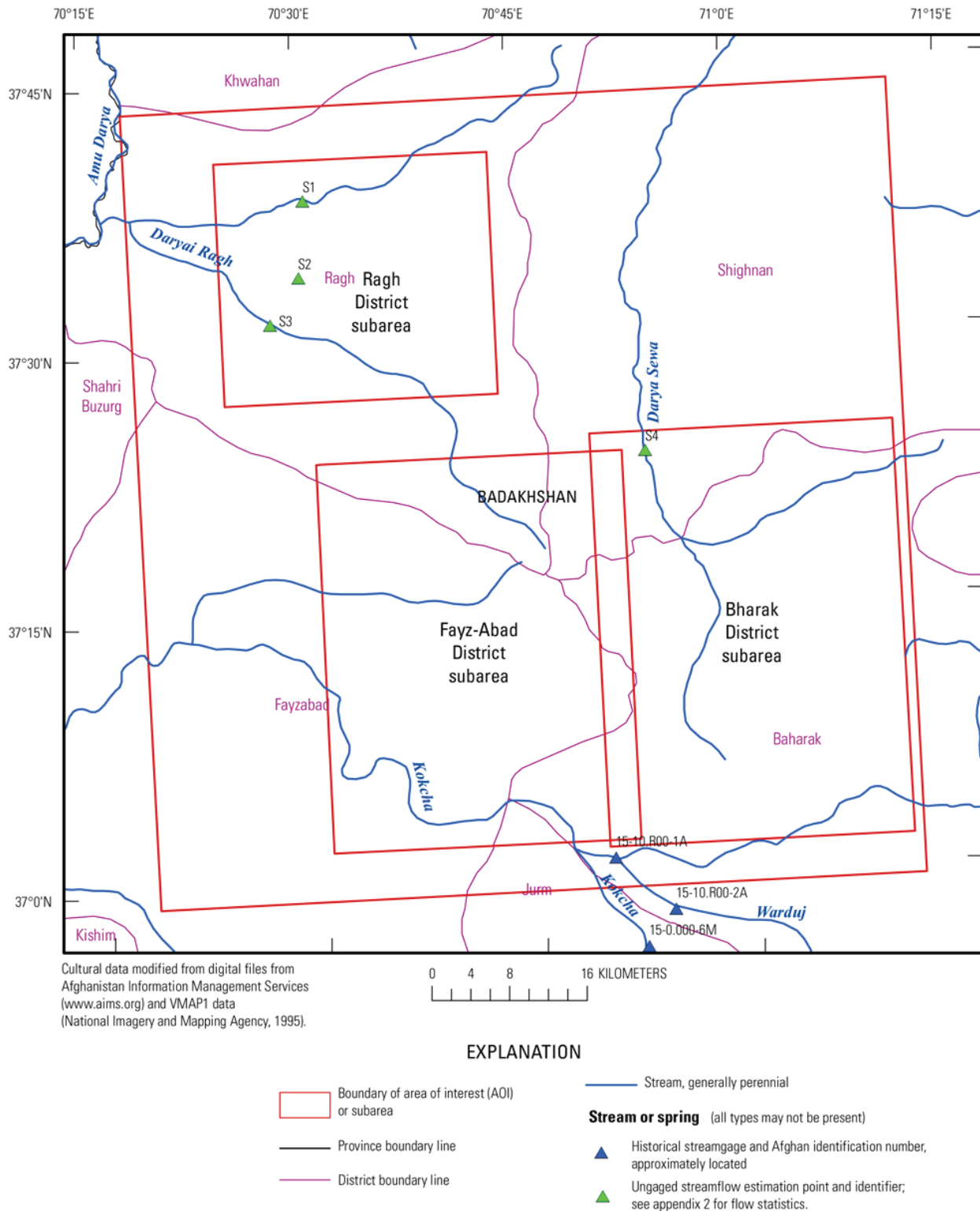
Climate information for the Badakhshan gold AOI is based on data generated for the Afghanistan agricultural-meteorological (Agromet) project. Agromet was initiated by the U.S. Agency for International Development and the United Nations Food and Agriculture Organization in 2003 to establish data-collection stations and develop country-wide agrometeorological services. Scientists with the Agromet project are assisting the Afghan Government to collect and analyze agricultural and meteorological data as they relate to crop production, irrigation, water supply, energy, and aviation. The U.S. Geological Survey (USGS) assumed responsibility for the operation of the project in 2005; by the end of August 2010, 87 Agromet stations were recording precipitation data and other parameters. Additionally, the Agromet project receives data from 18 Afghanistan Meteorological Authority (AMA) weather stations. The Agromet project has developed a database that includes data collected at the Agromet stations over the past 6 years (2005–2011), data collected at the AMA weather stations, and historical data collected at weather stations from 1942 to 1993. Data collected as part of the Agromet project are compiled annually by water year (September through August) and are reported in the Afghanistan Agrometeorological Seasonal Bulletin (Seasonal Bulletin) published by the Ministry of

Agriculture, Irrigation, and Livestock. Unless otherwise specified, the Agromet data cited in this report are from the agricultural season that extends from 1 September, 2009, to 31 August, 2010.

a



**b**



**Figure 3C–1.** (a) Landsat image showing the location of, and (b) place names, stream names, and streamgage station numbers in, the Badakhshan gold area of interest in northern Afghanistan.

The climate of the AOI is typical of a continental interior mountainous region. The winters are characterized by cold temperatures (less than 0°C (degrees Celsius)) (Ministry of Agriculture, Irrigation, and Livestock, 2010) and substantial amounts of precipitation (81–255 mm (millimeters)) (Ministry

of Agriculture, Irrigation, and Livestock, 2010, map 2). The summers are warm (28–37.5°C) (Ministry of Agriculture, Irrigation, and Livestock, 2010, map 12) and dry (precipitation 24–100 mm) (Ministry of Agriculture, Irrigation, and Livestock, 2010, map 4). Spring is a transition period, with increasing temperatures and some rain. The Fayz-Abad Agromet station is located in the district of Fayzabad in the Fayz-Abad District subarea near the Kokcha River (Ministry of Agriculture, Irrigation, and Livestock, 2010). Precipitation and temperature data for the Fayz-Abad Agromet station are shown in table 3C–1. Precipitation recorded at this station for the 2009–2010 water year was 601.2 mm, much greater than the long-term average (LTA) of 492.6 mm (Ministry of Agriculture, Irrigation, and Livestock, 2010). Snow fell at the Fayz-Abad Agromet station on 7 days during the 2009–2010 water year—1 in January, 5 in February, and 1 in March. Snow-cover maps are provided by Agromet and the USGS Famine Early Warning Systems Network (U.S. Geological Survey and U.S. Agency for International Development, 2010). Snow accumulation was reported as 46 cm (centimeters) during the 2009–2010 water year and 21 cm during the 2008–2009 water year. No precipitation was recorded during September and October 2009 or July and August 2010. The Afghanistan snow-depth map for 17 January, 2009, shows 10 to 30 cm of snow cover in the Fayz-Abad District subarea. The same map shows that the snow depth ranged from 10 to 100 cm across the AOI and increased to the east, where elevations are higher. The Afghanistan snow-depth map for 30 September, 2010, shows less than 2 cm of snow over the AOI (Ministry of Agriculture, Irrigation, and Livestock, 2010). The minimum average monthly temperature at the Fayz-Abad Agromet station during the 2009–2010 water year was 1.7°C (in February) and the maximum average monthly temperature was 26.1°C (in July) (Ministry of Agriculture, Irrigation, and Livestock, 2010). The LTA minimum and maximum average monthly temperatures were -0.6°C for January and 26.9°C for July, respectively.

**Table 3C–1.** Annual, long-term annual average, and long-term minimum and maximum average monthly precipitation and temperature at the Fayz-Abad Agrometeorological (Agromet) station, Afghanistan.

Agromet station	Distance from AOI center (km)	Elevation (m asl)	2009–10 annual (mm)	Precipitation			Temperature		
				Long-term average <sup>1</sup>			Long-term average <sup>1</sup>		
				Annual (mm)	Monthly minimum (mm) and month	Monthly maximum (mm) and month	Minimum (°C) and month	Monthly mean (°C)	Maximum (°C) and month
Fayz-Abad	30	1,200	601.2	492.6	1.1 August	99.2 April	–0.6 January	11.3	26.9 July

<sup>1</sup>Long-term averages are based on data from 1942 to 1993 and 2005 to 2010 as reported in the Afghanistan Agrometeorological Seasonal Bulletin (Ministry of Agriculture, Irrigation, and Livestock, 2010).

The “Potential Natural Vegetation” described in Breckle (2007) is the vegetation cover that would be present if not modified by human activity. Today, as a result of continued exploitation such as grazing, farming, and deforestation, much of the original natural vegetation is found only in a few remote areas of Afghanistan. The destruction of the natural vegetation has resulted in the degradation and erosion of the soil cover in some areas. Many areas exhibit signs of long-lasting desertification caused by human activity.

Precipitation, elevation, and soil cover control the types of vegetation in the AOI. The natural vegetation in the AOI is of three distinct types. The upper elevations are dominated by alpine vegetation and are classified by Breckle (2007) as “thorny cushions, subalpine and alpine deserts and meadows,” and the lower slopes are classified as “juniperous-woodlands.” Aerial imagery and irrigation information (fig. 3C–2) indicate that some agricultural development is present adjacent to the larger streams in the AOI but is limited by the width of the valley bottoms and is confined to the terraces along the streams. Aerial images of the AOI show that approximately 2 percent of the side channels and low-gradient side slopes are occupied by cultivated fields or pastures.

### 3C.3 Demographics

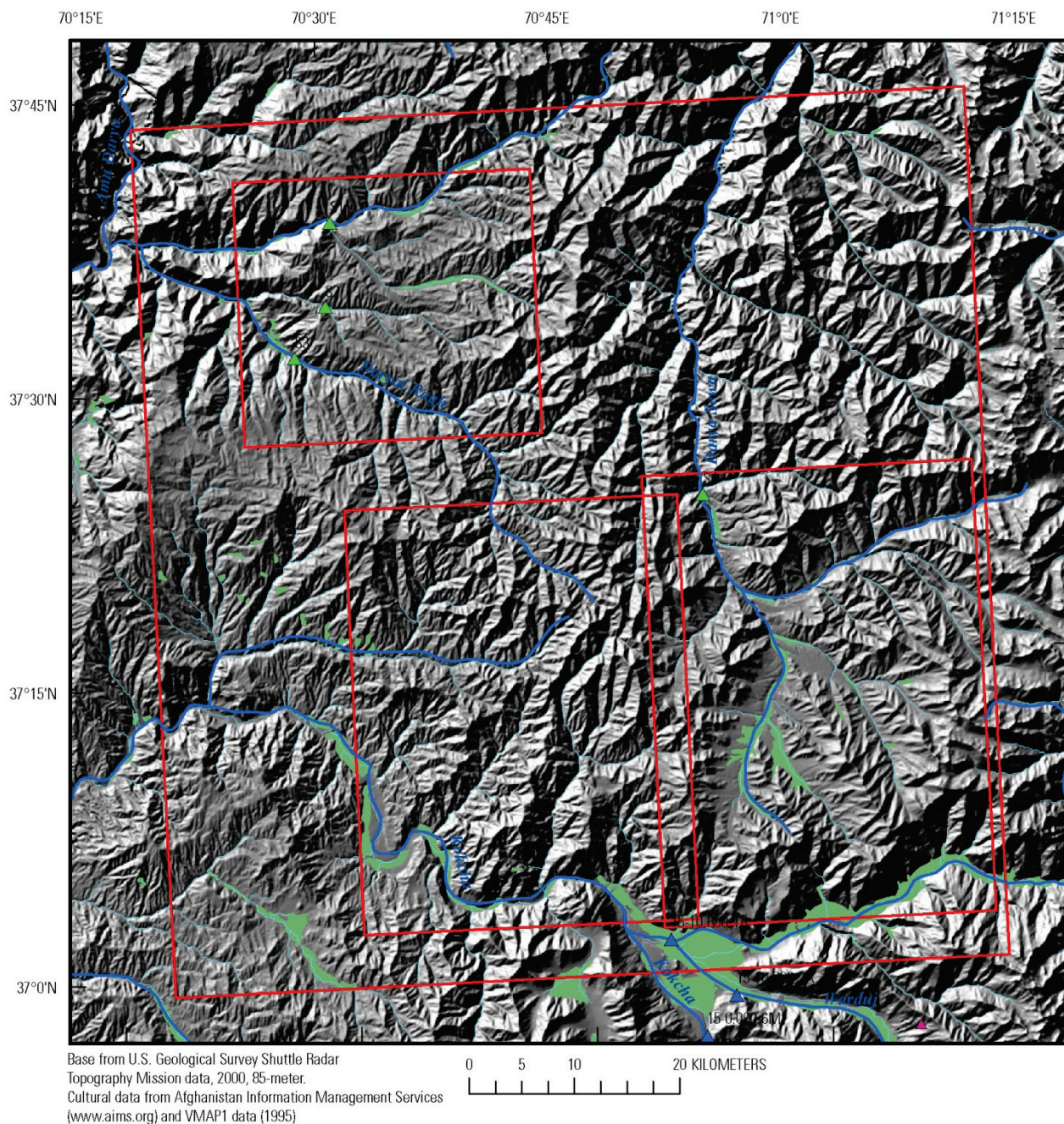
The largest community in Badakhshan is the province center, Faizabad, located in the southwestern part of the Badakhshan gold AOI (fig. 3C–1*b*). Most of the people living in Faizabad are merchants or farmers. The city is located along the Kokcha River, a perennial stream that ultimately discharges into the Amu Darya River. The only roads in the AOI are mapped as “tracks” on the Fayzabad and Ragh District maps (Afghanistan Information Management Services, 2004). A few of the “tracks” connect the AOI to the Amu Darya River.

Land type within the AOI varies from barren on the upper mountain and ridge tops to cultivated fields and small villages in the valleys of the larger perennial and ephemeral streams (figs. 3C–1*a* and 3C–2). Small villages and farm areas are located in some upland basins (between the stream bottoms and the ridge tops). The size, in both area and population, of the settlements is limited by the amount of land suitable for building and by the availability of water. These settlements are located near local water sources that can be used for domestic consumption and for irrigation of crops. Some upland areas have been developed into summer pastures for livestock grazing. Aerial images of the AOI show that almost all areas suitable for settlement and agriculture are populated. The population density of the AOI as mapped by LandScan (Oak Ridge National Laboratory, 2010) indicates that the population is more dispersed (fig. 3C–3) than is indicated by the Afghanistan Information Management Services (2004). Population density in a few cells of figure 3C–3 is 2,500 to 5,000 per km<sup>2</sup> (square kilometer); in most areas of the AOI, however, it is fewer than 100 people per km<sup>2</sup>. The 2009–2010 settled population statistics for Badakhshan Province indicate 32,800 in urban and 827,500 in rural areas (Afghanistan Central Statistics Organization, 2010). The population density shown in figure 3C–3 has a pixel resolution of about 1 km<sup>2</sup> (Oak Ridge National Laboratory, 2010).









### 3C.4 Topography and Geomorphology

The Badakhshan gold AOI is in the Hindu Kush Mountains. Several mountain peaks in and immediately adjacent to the AOI reach elevations in excess of 2,900 m (meters) above sea level (asl) (Bohannon, 2005). Farther east (at approximately longitude 70° 45') are three peaks that range in elevation from 3,802 to 4,152 m asl. North of the AOI, the elevation of the peaks is consistently greater than 3,500 m. The AOI is cut by deeply incised perennial and ephemeral streams. The major streams flow west into the Amu Darya River. The elevation of the Amu Darya River where it is closest to the AOI is about 700 m asl. The stream channels form a series of roughly east-west-trending ridges and valleys. The major streams in the AOI on average are at or above the 2,000-m contour line, and stream-valley bottoms and ridge tops are separated by about 600 m of relief (Bohannon, 2005).

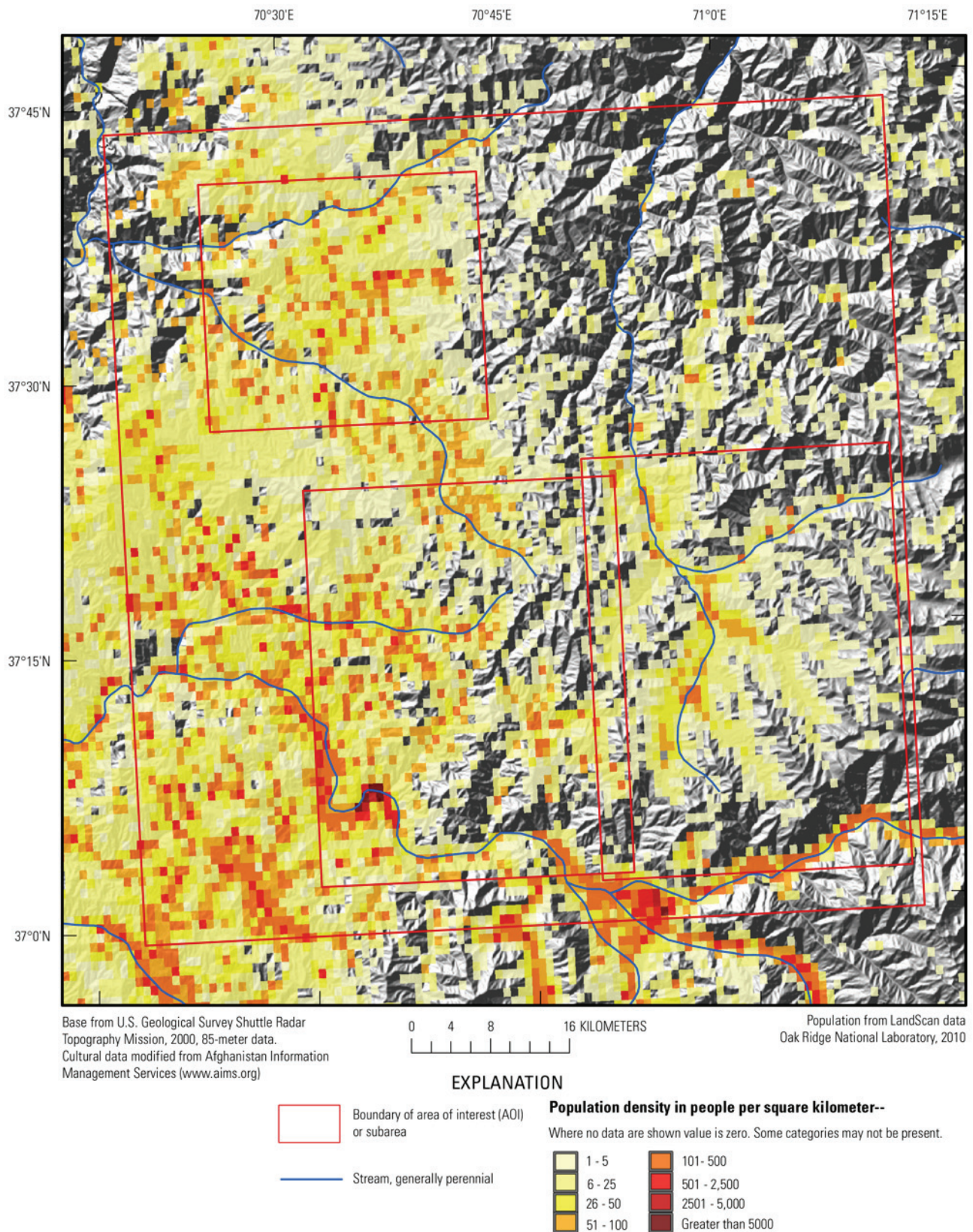
The geomorphology of the AOI is dominated by glacial and fluvial processes that have been enhanced by the ongoing tectonic uplift of the Hindu Kush Mountains, which, at the higher elevations and especially on the north-facing slopes, are permanently covered with snow and ice. Although no glaciers are currently (2011) located in the AOI, the landforms, including arêtes and cirques, preserve alpine glacial processes. The major stream channels are V-shaped and incised. Varying thicknesses of alluvial material are present in the stream channels (Bohannon and Stoeser, 2005). The smaller streams display dendritic drainage patterns and are identified as bedrock outcrop on the geologic map, indicating that little alluvial material is present in the smaller stream valleys (Bohannon, 2005; Davis, 2006).



#### EXPLANATION

- |   |  |   |
|---|--|---|
|  | Boundary of area of interest (AOI) or subarea  | <b>Stream or spring</b> {all types may not be present}  |
|  | Irrigated areas  |  Historical streamgauge and Afghan identification number, approximately located            |
|  | Stream, generally perennial  |  Ungaged streamflow estimation point and identifier; see appendix for flow statistics.     |
|  | Drainage network generated from 85-m digital elevation model (DEM) data, (primarily ephemeral, some perennial) |  Spring or watering hole, VMAP1 data (National Imagery and Mapping Agency, 1995)           |
|   |  |  Spring or watering hole, alkaline, VMAP1 data (National Imagery and Mapping Agency, 1995) |

**Figure 3C–2.** Historical streamgauge station locations, digitally generated drainage network, and irrigated areas in the Badakhshan gold area of interest in northern Afghanistan.



**Figure 3C–3.** Population density of Badakhshan gold area of interest in northern Afghanistan.

### 3C.5 Geohydrology

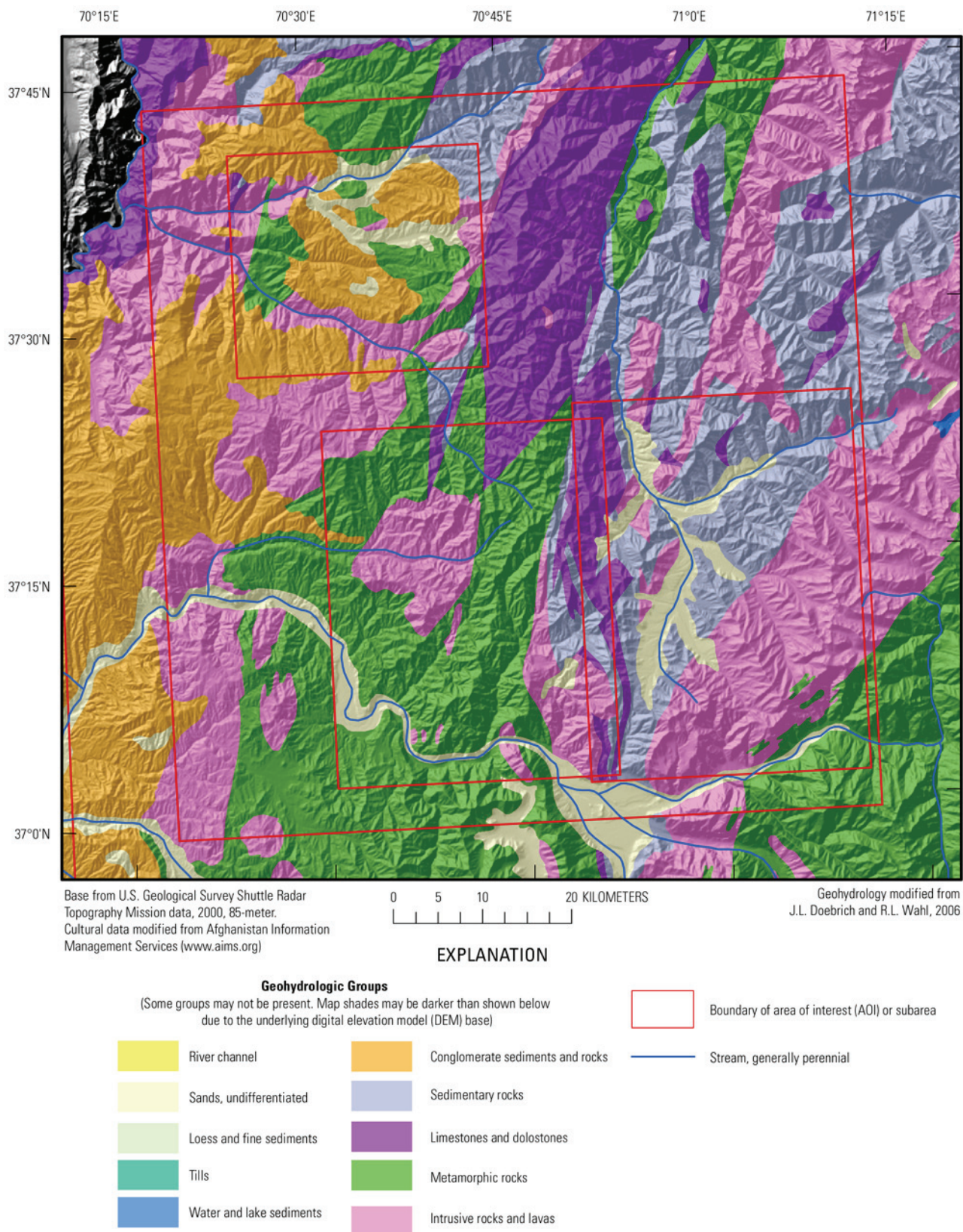
The geohydrology of Afghanistan has been described in general terms by Abdullah and Chmyriov (1977, book 2). As defined in their “Geology and mineral resources of Afghanistan,” the Badakhshan gold AOI is in the Central Afghanistan Hydrogeological Folded Region. Abdullah and Chmyriov (1977) describe the geology of this region as “variably metamorphosed Precambrian, Paleozoic, and Mesozoic stratified rocks and intrusions of different ages.” The outcrops and near-surface rocks in the AOI can be grouped according to their physical and hydraulic properties. The generalized geohydrology of the AOI is shown in figure 3C–4 with the underlying topography to allow examination of the geohydrology in the context of relief. Figure 3C–5 shows the generalized geohydrology without topography for a clearer depiction of the geohydrologic units. Generalized geohydrologic groups were created from a country-wide geologic coverage (Doebrich and Wahl, 2006) by combining sediments and rocks into major sediment- or rock-type groups of similar hydrologic characteristics. The geohydrologic groups in the AOI, ranked from high to low relative hydraulic conductivity (Freeze and Cherry, 1979, table 2.3), are “sands, undifferentiated; conglomerate sediments and rocks; limestones and dolostones; sedimentary rocks; metamorphic rocks; and intrusive rocks and lavas” (figs. 3C–4 and 3C–5). Doebrich and Wahl (2006) used geologic maps at a scale of 1:250,000, modified from Russian and Afghan Geological Survey (AGS) mapping, to generate the country-wide geologic coverage. The 1:250,000-scale geologic map that covers this AOI is provided by Bohannon and Stoesser (2005).

The infiltration and movement of water in the metamorphic and igneous rocks is probably controlled by the fractures in those rocks. Many north-south-trending to northeast-southwest-trending, and northwest-southeast-trending, faults have been mapped in the AOI (Ruleman and others, 2007). The fracture densities and orientations in the metamorphic and igneous rocks are probably influenced by the presence and trends of the faults. Where flow paths in fractures intersect the land surface, such as in valleys, spring discharge may occur. Abdullah and Chmyriov (1977) state, “The Precambrian aquifer system is within the Hendukush Badakhshan, Hari Rod, Upper Helmand and Argandab hydrogeological massifs. Water bearing rocks are gneisses, shales, migmatites, and quartzites.”

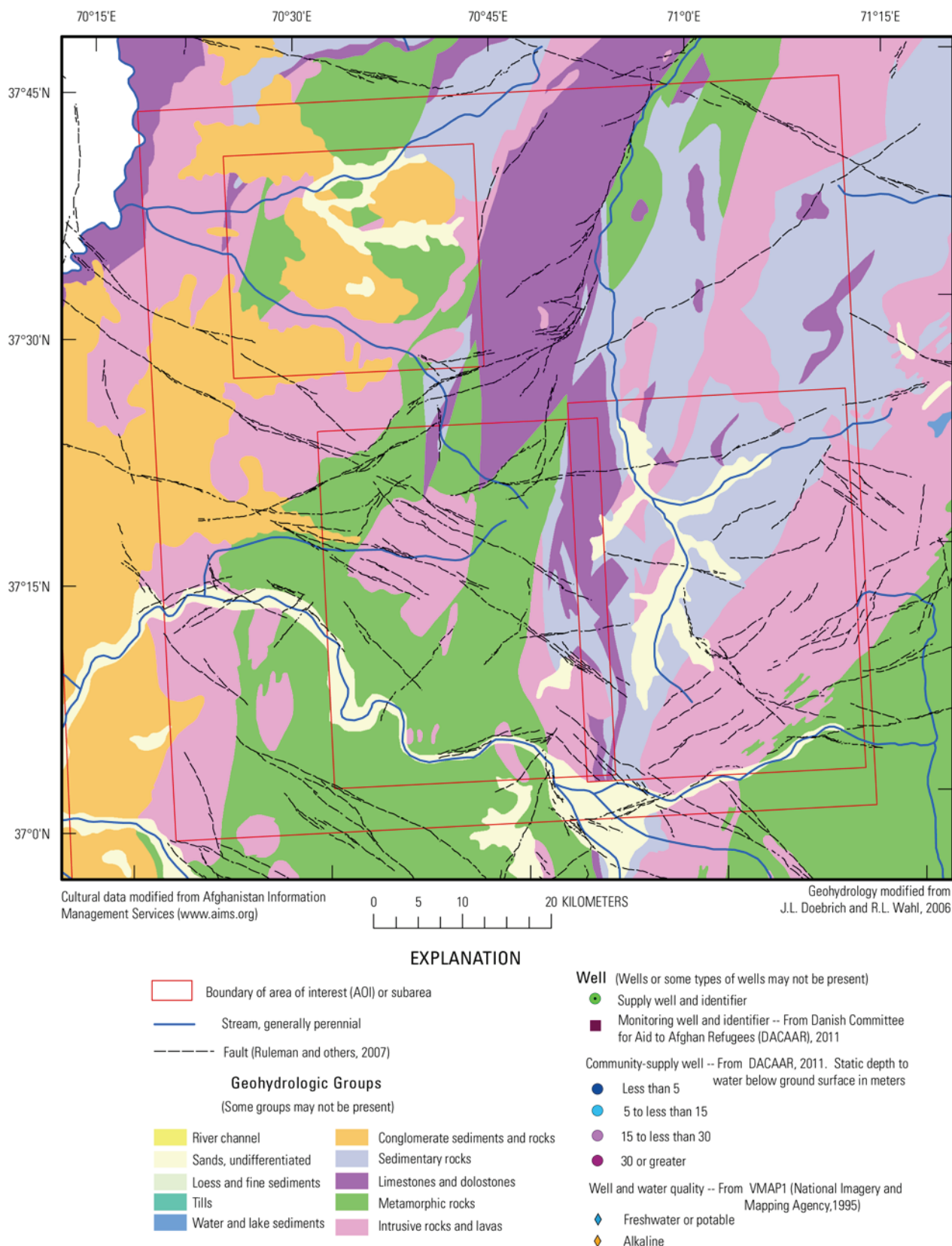
A geologic map of the area (Bohannon and Stoesser, 2005) shows alluvium (grouped as sands, undifferentiated) in the Kokcha, Darya Ragh, and Darya Sewu River valleys (fig. 3C–4). Deposits of alluvium and colluvium are present on the more gently sloping hillsides and in the upland basins (figs. 3C–4 and 3C–5). The thickness of these deposits is unknown, but is sufficient to support the growth of trees in some areas. Aerial images show no evidence of any karezes (traditional hand-dug tunnels for water supply) in the AOI. The absence of karezes could be attributable to the predominance of bedrock outcrop with only a thin covering of sediments in the area.

The bedrock outcrops in the northwest Badakhshan-Ragh District subarea are composed of gneiss, granite and granodiorite, conglomerate, and sandstone (3C–5). One prospect site in the Ragh District subarea is located in an area of limestone outcrop (Peters and others, 2007). Abdullah and Chmyriov (1977) report that the “Water bearing rocks are limestones, dolomites, sandstones, and siltstones.” The lateral extent of the limestone in the AOI could be limited by faulting and the intrusion of igneous rocks. The extensive conglomerate sediments (semi-consolidated) and rocks present on the surface north of this site could be underlain by the limestone aquifer.

Sandstones and conglomerates in the AOI are potential aquifers of limited area and thickness. Two outcrops of these rock types in the Ragh District subarea (Bohannon and Stoesser, 2005) have a combined area of about 160 km<sup>2</sup>. The stream channels that cut through the sandstones and conglomerates expose a thickness of at least 250 m of section, so the volume of this unit could be as much as 40 km<sup>3</sup>. These groups are exposed on fairly flat upland surfaces; therefore, the potential for local infiltration and storage of groundwater is good. Sandstone and conglomerate are also present along the western border of the AOI.



**Figure 3C–4.** Topography and generalized geohydrology in the Badakhshan gold area of interest in northern Afghanistan.



**Figure 3C–5.** Generalized geohydrology and mapped faults in the Badakhshan gold area of interest in northern Afghanistan.

Metamorphic rocks and intrusive rocks and lavas comprise much of the outcrop in the southeast Badakhshan-Baharak and the southwest Badakhshan-Fayz Abad District subareas (figs. 3C–4 and

3C–5). The metamorphic rocks are generally gneiss and the intrusive rocks and lavas are granites, granodiorites, and rhyolitic lavas. These rocks are cut by north- to northeast-trending faults (Bohannon and Stoesser, 2005; Ruleman and others, 2007). The presence of faults with associated fracture zones can enhance the water-transmitting and storage capacity of these rocks. It is possible that zones of secondary fracturing have been created by the intrusion of the igneous rocks into the sedimentary and metamorphic rocks. The large areal extent of these outcrops and the recharge potential of the winter snowpack increase the probability that some groundwater resources are available within this geohydrologic group in the AOI.

A distinct band of north- to northeast-trending sedimentary rocks, as well as limestones and dolostones, is present in the center of the AOI (figs. 3C–4 and 3C–5). The approximate mapped area of these groups in the AOI is 550 km<sup>2</sup>. The primary porosity of the limestone and dolostone makes these rocks potentially high-yielding aquifers. Both of these geohydrologic groups are cut by north- to northeast-trending faults and have been intruded by igneous rocks (Bohannon and Stoesser, 2005). Because the faults likely enhance fracturing and cause secondary porosity in these rocks, the total porosity of the limestone and dolostone could be very high. The presence of fractures could enhance the water-storage capacity of this group as well. Therefore, these rocks could be an important aquifer—one that has not been used extensively—in the AOI.

## 3C.6 Surface Water

A network of major streams, mostly perennial streams, modified from AIMS (Afghanistan Information Management Services, 1997) and VMAP1 (National Imagery and Mapping Agency, 1995), in the Badakhshan gold AOI is shown in figure 3C–2. A network representing likely ephemeral streams, generated with a digital elevation model (DEM), also is shown in figure 3C–2. Names of major streams and identification numbers for any streamgages and ungaged streamflow estimation sites in the AOI are shown in figure 3C–1*b*. The AOI lies within the Amu Darya River Basin (Olson and Williams-Sether, 2010, fig. 2). The Amu Darya River (also called the Oxus) originates in the Pamir region of Afghanistan and forms more than 1,100 km (kilometers) of Afghanistan's northern border with the countries of Tajikistan and Turkmenistan (Uhl and Tahiri, 2003). The flow of the Amu Darya River, one of the major sources of water for the Aral Sea, is regulated by international agreements (Favre and Kamal, 2004). The Amu Darya River touches the northwestern corner of the AOI (figs. 3C–1*a, b*). The largest river in the AOI, the Kokcha River, is a tributary to the Amu Darya River. This river originates in the northeastern part of the Hindu Kush Mountains, is perennial, and has substantial flow from snowmelt runoff in the spring months. The Kokcha River enters the AOI at the middle of the southern border and exits at the western border. The province center of Faizabad is located on the Kokcha River. The other named streams in the AOI are the Daryai Ragh and the Darya Sewu (fig. 3C–1*b*). There is no indication of any dams constructed on the main channel of the Kokcha River or any of the side channels. Historical streamflow data are available from three streamgages on the Kokcha River and one of its tributaries—one in, and two just outside, the AOI (fig. 3C–1*b*) (Olson and Williams-Sether, 2010). The period of record for these stations extends from 22 April, 1969, to 30 September, 1978. The Warduj River at Shashpul streamgage station (fig. 3C–1*b*, Afghan identification number 15–10.R00–1A) in the AOI has an elevation of 1,407 m asl. This station has a drainage area of 4,485 km<sup>2</sup> and is located about 40 km upstream from Faizabad and about 4 km upstream from the confluence of the Warduj and Kokcha Rivers (fig. 3C–2). The mean annual flow for the period of record was 52.5 m<sup>3</sup>/s (cubic meters per second) with a standard deviation of 8.14 m<sup>3</sup>/s (Olson and Williams-Sether, 2010). The annual mean streamflow per unit area for this station is 0.012 m<sup>3</sup>/s/km<sup>2</sup>. The maximum monthly mean streamflow was 203 m<sup>3</sup>/s (June 1973). The minimum monthly mean streamflow was 11.8 m<sup>3</sup>/s (February 1972 and March 1975). A statistical summary of monthly and annual mean streamflows for this station (Olson and Williams-Sether, 2010) is presented in table 3C–2. Statistical summaries of streamflow data for all available historical gages in Afghanistan can be accessed at <http://afghanistan.cr.usgs.gov/water.php>.

The Kokcha River near Jurm streamgage (fig. 3C–1*b*, Afghan identification number 15–0.000–6M) is just outside the southern border of the AOI. This station has a drainage area of 7,670 km<sup>2</sup> (Olson and Williams-Sether, 2010) and its elevation is 1,449 m asl. The period of record for this station is 1 October, 1969, to 30 September, 1978. The mean annual flow for that period was 74.1 m<sup>3</sup>/s with a standard deviation of 10.9 m<sup>3</sup>/s (Olson and Williams-Sether, 2010). The annual mean streamflow per unit area for this station is 0.0097 m<sup>3</sup>/s/km<sup>2</sup>. The maximum monthly mean streamflow was 302 m<sup>3</sup>/s for July 1973 and the minimum monthly mean streamflow was 17.2 m<sup>3</sup>/s for February 1971. A statistical summary of monthly and annual mean streamflows for this station (Olson and Williams-Sether, 2010) is presented in table 3C–3.

The Warduj River near Baharak streamgage (fig. 3C–1*b*, Afghan identification number 15–10.R00–2A) is about 8 km upstream from the Warduj River near Shashpul station and is just outside the southern border of the AOI. This station has a drainage area of 3,350 km<sup>2</sup> (Olson and Williams-Sether, 2010) and its elevation is 1,465 m asl. The period of record for this station is 22 April, 1969, to 30 September, 1978. The mean annual flow for that period was 34.8 m<sup>3</sup>/s, with a standard deviation of 4.94 m<sup>3</sup>/s (Olson and Williams-Sether, 2010). The annual mean streamflow per unit area for this station is 0.010 m<sup>3</sup>/s/km<sup>2</sup>. The maximum monthly mean streamflow was 128 m<sup>3</sup>/s for July 1978 and the minimum monthly mean streamflow was 7.35 m<sup>3</sup>/s for April 1977. A statistical summary of monthly and annual mean streamflows for this station (Olson and Williams-Sether, 2010) is presented in table 3C–4.

**Table 3C–2.** Statistical summary of monthly and annual mean streamflows for the Warduj River at Shashpul streamgage station, Afghanistan.  
[m<sup>3</sup>/s, cubic meters per second]

15–10.R00–1A Warduj River at Shashpul

Month	Maximum		Minimum		Mean			
	Streamflow (m <sup>3</sup> /s)	Water year of occurrence	Streamflow (m <sup>3</sup> /s)	Water year of occurrence	Streamflow (m <sup>3</sup> /s)	Standard deviation (m <sup>3</sup> /s)	Coefficient of variation	Percentage of annual streamflow
October	45.1	1970	25.8	1972	31.3	5.82	0.19	4.99
November	30.5	1970	19.5	1976	23.5	3.30	0.14	3.74
December	23.5	1970	16.2	1976	19.1	2.17	0.11	3.04
January	23.2	1970	13.5	1972	15.8	2.91	0.18	2.52
February	21.0	1970	11.8	1972	14.6	2.75	0.19	2.33
March	16.0	1970	11.8	1975	13.6	1.34	0.10	2.17
April	29.2	1978	13.8	1977	20.4	4.99	0.24	3.25
May	70.6	1973	23.4	1974	45.2	17.6	0.39	7.21
June	203	1973	84.2	1976	134	39.7	0.30	21.3
July	184	1973	115	1970	146	27.9	0.19	23.3
August	126	1978	77.3	1974	105	15.4	0.15	16.7
September	74.1	1970	44.3	1974	59.5	11.3	0.19	9.48
<b>Annual</b>	<b>66.4</b>	<b>1973</b>	<b>41.4</b>	<b>1974</b>	<b>52.5</b>	<b>8.14</b>	<b>0.15</b>	<b>100</b>

**Table 3C–3.** Statistics of monthly and annual mean streamflows for the Kikcha River at Jurm streamgauge station.  
[m<sup>3</sup>/s, cubic meters per second]

15–0.000–6M Kokcha River near Jurm

Month	Maximum		Minimum		Mean			
	Streamflow w (m <sup>3</sup> /s)	Water year of occurrence	Streamflow w (m <sup>3</sup> /s)	Water year of occurrence	Streamflow w (m <sup>3</sup> /s)	Standard deviation (m <sup>3</sup> /s)	Coefficient of variation	Percentage of annual streamflow
October	54.4	1970	35.3	1975	46.3	6.78	0.15	5.23
November	41.4	1974	29.4	1975	34.6	4.10	0.12	3.91
December	32.8	1977	24.0	1975	28.2	3.05	0.11	3.19
January	30.0	1970	19.1	1972	24.2	3.40	0.14	2.73
February	27.9	1974	17.2	1971	22.0	3.56	0.16	2.48
March	23.6	1971	17.9	1978	20.5	1.76	0.09	2.31
April	39.2	1971	18.2	1977	26.6	6.94	0.26	3.01
May	112	1971	38.0	1972	63.3	25.4	0.40	7.15
June	282	1973	107	1976	175	52.5	0.30	19.7
July	302	1973	150	1970	207	53.9	0.26	23.3
August	186	1973	112	1972	151	23.5	0.16	17.0
September	112	1970	69.5	1972	88.0	12.5	0.14	9.94
<b>Annual</b>	<b>96.8</b>	<b>1973</b>	<b>58.2</b>	<b>1972</b>	<b>74.1</b>	<b>10.9</b>	<b>0.15</b>	<b>100</b>

**Table 3C–4.** Statistics of monthly and annual mean streamflows for the Warduj River near Baharak streamgauge station.  
[m<sup>3</sup>/s, cubic meters per second]

15–10.R00–2A Warduj River near Baharak

Month	Maximum		Minimum		Mean			
	Streamflow (m <sup>3</sup> /s)	Water year of occurrence	Streamflow (m <sup>3</sup> /s)	Water year of occurrence	Streamflow (m <sup>3</sup> /s)	Standard deviation (m <sup>3</sup> /s)	Coefficient of variation	Percentage of annual streamflow
October	25.4	1970	18.8	1973	21.5	2.19	0.10	5.14
November	16.1	1973	14.3	1977	15.4	0.58	0.04	3.67
December	13.7	1973	11.4	1977	12.8	0.69	0.05	3.05
January	12.4	1970	9.86	1977	11.2	0.98	0.09	2.68
February	11.4	1973	8.44	1971	10.5	1.12	0.11	2.51
March	11.2	1972	7.38	1971	9.55	1.14	0.12	2.28
April	12.1	1978	7.35	1977	10.5	1.57	0.15	2.52
May	28.5	1971	10.3	1977	19.3	7.57	0.39	4.62
June	119	1973	43.9	1976	74.8	26.0	0.35	17.9
July	128	1978	73.3	1972	103	22.1	0.21	24.7
August	113	1969	61.0	1974	84.6	15.8	0.19	20.2
September	56.3	1973	36.2	1972	45.2	7.61	0.17	10.8
<b>Annual</b>	<b>43.3</b>	<b>1978</b>	<b>28.4</b>	<b>1972</b>	<b>34.8</b>	<b>4.94</b>	<b>0.14</b>	<b>100</b>

Streamflows were estimated for ungaged streams in the AOI. Estimates of streamflow statistics were calculated for points S1, S2, S3, and S4 (fig. 3C–2) using a drainage-area-ratio method (Olson and Mack, 2011) based on historical flows at the Warduj River near Baharak (fig. 3C–1b, Afghan identification number 15–10.R00–2A). The Warduj River near Baharak streamgauge station was selected

as the most representative historical gage, based on drainage-basin size and location in Afghanistan, for use with this method at this location. The estimated mean annual streamflow for point S1 (app. 2), with a drainage area of  $508 \text{ km}^2$ , based on historical data is about  $4.87 \text{ m}^3/\text{s}$ . By applying the same method, the estimated mean annual streamflow at points S2, S3, and S4 is 0.85, 5.4, and  $10.64 \text{ m}^3/\text{s}$ , respectively. The seasonal timing of minimum and maximum monthly streamflow, with high flows in summer and low flows in winter and early spring (app. 2), probably is similar to that of the Warduj River near Baharak station (fig. 3C–2).

There are two large streams in the Ragh District subarea (fig. 3C–1) in the northwestern section of the AOI that may have sustained flow throughout the year, although the flow would vary seasonally. Both streams have headwaters in the eastern part of the AOI and drain to the west, ultimately discharging into the Amu Darya River. There are no streamgages on either of these streams, but streamflow estimates were calculated for points S1 and S3 on these tributaries (fig. 3C–2). The two streams have roughly parallel main drainage channels, and the southern stream joins the northern stream just outside the western border of the AOI. The northern stream has a main channel about 61 km long and a tributary channel. The headwaters are in an area where glacial cirques are common at an elevation of about 3,500 m asl. Many snow fields are present on the north-facing slope of the arête formed by the cirques, but there do not appear to be any permanent snow fields on the south-facing slopes during the warmer months of the year. Flow in this stream (S1, fig. 3C–2) probably is high in the late spring and early summer. The estimated midsummer flows are the highest monthly flows (app. 2) and may be sustained by snowmelt, groundwater discharge at springs, and occasional summer rains throughout this time of the year. The estimated flows are lowest in the winter months when the contribution to flow from snowmelt is smallest. The tributary stream has an east-west channel about 27 km long and flows through the middle of the Ragh District subarea. The headwaters are located in deeply incised valleys at about 2,800 m asl. The north-facing slopes have some perennial snow cover. The drainage area of this stream network is about  $550 \text{ km}^2$ . There is no indication of any dams constructed on the main channel of this stream or any of the side channels.

The southern stream located in the northwestern part of the AOI, the Daryai Ragh (S3, fig. 3C–2), is about 36 km long with a tributary channel in the center of the Ragh District subarea (S2, fig. 3C–2). The headwaters of this stream consist of several dendritic streams that branch off from the main stream channel. These streams are in upland valleys at about 2,600 m asl. This headwaters area is on the eastern edge of the Ragh District subarea. The headwaters area is bordered by north- and south-facing slopes. The north-facing slopes appear to have some year-round snow fields. Snowmelt probably supplies water to the Daryai Ragh drainage basin throughout the summer and fall. Spring streamflow and rainfall events also could supply water for sustained flow. The drainage area of this stream network is about  $660 \text{ km}^2$ . A major stream on the east side of the AOI, the Darya Sewa, flows through the Baharak District subarea (fig. 3C–1a,b, and S4 in fig. 3C–2).

## 3C.7 Groundwater

No published information on groundwater in the Badakhshan gold AOI was available for this study (fig. 3C–5), and the nearest groundwater-monitoring well was about 170 km from the AOI. However, inferences can be made regarding the availability of groundwater based on analysis of recent precipitation data, historical streamflow records, and the geohydrologic characteristics of the AOI. The average precipitation in the AOI is about 490 mm/yr (table 3C–1). Geohydrologic conditions probably are similar to those in the nearby Warduj River basin ( $3,350 \text{ km}^2$ ). The Warduj River basin is unregulated and has about 1.6 percent irrigated area (Olson and Mack, 2011), whereas the AOI has less than 1 percent irrigated area (app. 2). The monthly mean flows during the low-flow period of the year, December through April, are slightly more than  $10 \text{ m}^3/\text{s}$  (table 3C–2). This value is equivalent to a monthly mean low flow of about  $0.003 \text{ m}^3/\text{s}/\text{km}^2$ , indicating that recharge rates may be relatively high. Recharge is likely to be greater in this area than in other areas of Afghanistan, particularly areas south of Kabul, where streamflow per square kilometer is greater (Mack and others, 2010), and a large

component of the streamflow out of the basin during low-flow periods is likely to be groundwater discharging from alluvial and bedrock aquifers. Groundwater discharge and, therefore, recharge may be considerably different if snowpacks in the region are not similar to those present during the historical streamflow-measurement period. Historically, high streamflows occurred during the summer months, when water needs for agriculture typically are greatest. Additional streamflow measurement and analysis would be needed to assess whether flows during the summer months exceed those needed for agriculture and could also support other activities such as mining.

The recharge rates discussed above are generalized and are not specific to any particular area. The amount of recharge in a specific area depends on the type of rock exposed at the surface, the presence and depth of alluvial cover with associated vegetation, and the gradient of the land surface. Steep slopes have a greater potential for producing runoff, whereas gentle slopes enhance the potential for spatially distributed infiltration. Where rocks with high matrix permeability are exposed on gentle slopes, the potential for infiltration and recharge of groundwater is good.

The mapped alluvial deposits in the AOI are limited to the major stream valleys (figs. 3C–4 and 3C–5). The area and the thickness of these deposits are constrained by the width, length, and gradient of the valley. The presence of farms (fig. 3C–3) with irrigated fields and pastures (fig. 3C–2) in these valleys indicates the alluvial deposits are aquifers of at least limited extent. Infiltration of surface water, especially during the spring and summer runoff, likely provides sufficient recharge to the aquifer to support local water-use needs. No construction information, hydraulic data, or water-chemistry data from wells constructed in these deposits are available. Using information from other shallow wells located in similar geohydrologic settings in Afghanistan, water levels probably fluctuate seasonally along with the flow in the adjacent stream channels (Akbari and others, 2007). Water levels most likely are high in the spring and summer in response to the melting of snow and the resulting increase in streamflow. As streamflow decreases in the late summer through fall and winter, the water levels in the wells probably decline. The extraction of water from the wells also affects the water levels. Because the alluvial aquifers in the AOI are limited in area and thickness, they probably will not support a large increase in the withdrawal of groundwater above current levels. The gently sloping areas where the conglomerate and sandstone crop out have favorable potential for groundwater recharge (figs. 3C–4 and 3C–5). The presence of farming communities with fields and pastures in these areas indicates that some groundwater is available for domestic use and irrigation (fig. 3C–2). Some vegetation, including thick stands of trees, is growing in the ephemeral stream channels located in these outcrops. The examination of aerial images indicates that springs and seeps are present on the side slopes of the ephemeral streams in this unit and in some areas are used for irrigation. Wells constructed in the conglomerate and sandstone could be a source of groundwater. The thickness and extent of these aquifers would need to be mapped to determine the quantity of water that may be available.

Rocks having fracture-dominated permeability, such as granite, granodiorite, and metamorphic rocks (figs. 3C–4 and 3C–5), are potential aquifers in the AOI. The three subareas have extensive outcrops composed of these rock types. Aerial images show that vegetation appears to be growing along well-defined lineaments, which would indicate that the vegetation is growing preferentially in fractures, where water is more readily available. The linear shape of some of the main stream channels indicates they are controlled by fracture location and orientation (figs. 3C–4 and 3C–5). The density of ephemeral stream channels in these areas provides a mechanism for concentrating runoff and enhancing infiltration into fractures. Thin alluvial cover over bedrock outcrops probably drains quickly to the bedrock contact, where water can infiltrate into fractures.

The production of groundwater from wells completed in fractured-rock aquifers is dependent, in part, on the density of fractures (number of fractures per volume of rock), the hydraulic properties of the fractures, and the interconnectivity of the fractures. Wells constructed to intersect faults, fault zones, and fracture zones in the metamorphic rocks and intrusive rocks and lavas geohydrologic groups most likely will have more sustainable production than wells constructed in areas where faults and fractures are not

present. Detailed fracture mapping is needed to assess potential water yields and to site new wells in locations with greater and more sustainable yields. .

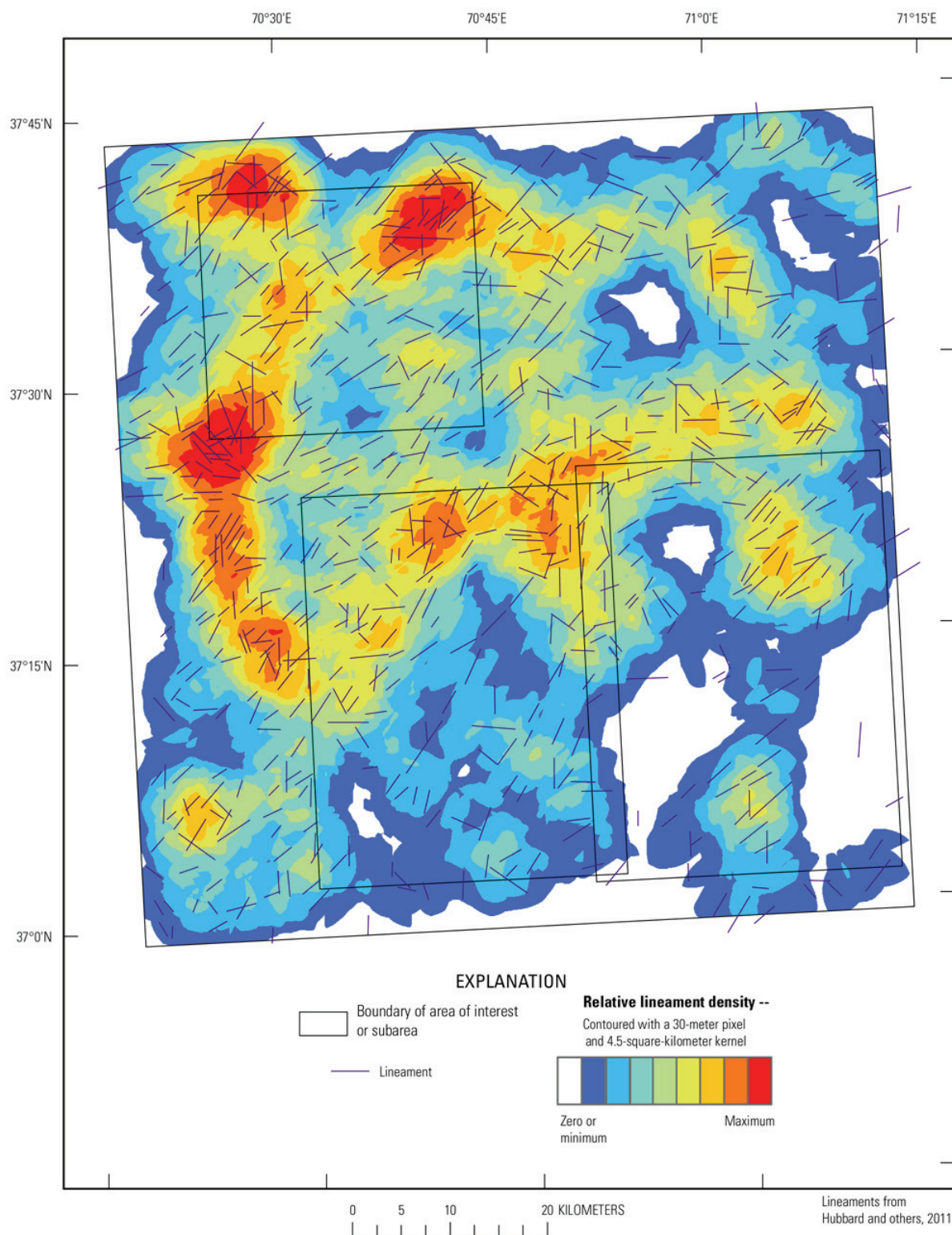
### 3C.8 Lineament Analyses

Lineaments are photolinear features that could be the result of underlying zones of high-angle bedrock fractures, fracture zones, faults, or bedding-plane weaknesses. Lineament analyses of the Badakhshan gold AOI were conducted using DEM and natural-color satellite imagery (fig. 3C–6) and Advanced Spaceborne Thermal Emission and Reflection Radiometry (ASTER) satellite imagery (fig. 3C–7*a,b*). Lineament identification and analysis have long been used as a reconnaissance tool for identifying areas in carbonate bedrock environments where groundwater resources are likely to be found (Lattman and Parizek, 1964; Siddiqui and Parizek, 1971). Lineament analysis is increasingly used to identify areas of high relative well yields in other bedrock settings, including crystalline bedrock (Mabee, 1999; Moore and others, 2002). The lineaments shown in figure 3C–6 were delineated visually, whereas those in figure 3C–7 were delineated using an automated process and on the basis of the multispectral characteristics of the land surface (B.E. Hubbard, T.J. Mack, and A.L. Thompson, U.S. Geological Survey August 24, 2011, written commun.). Water wells in bedrock aquifers generally are most productive where boreholes are located in areas of highly fractured bedrock. Areas where lineament density is high (figs. 3C–6 and 3C–7*a,b*) potentially are areas where bedrock fractures are more prevalent than in other areas of the AOI. Lineaments provide an indication of areas that warrant further investigation for optimal bedrock water-well placement. Lineaments may also indicate areas of preferential flow and storage of groundwater, and areas with a high density of lineaments may indicate high secondary porosity. Any lineament analyses, including those presented in this investigation, need to be corroborated by field investigations and additional data to confirm the nature of the lineaments and their relation to water-filled bedrock fracture zones.

The lineament analysis of the AOI shows several patterns of prominent lineaments. The DEM lineaments identified many features in the Ragh District subarea (fig. 3C–6) and an area of denser northeast-southwest-trending lineaments in the center of the AOI. The lineaments in the center of the AOI, the northern area of the Fayz-Abad District subarea, coincide with an area of faults mapped by Ruleman and others (2007) (fig. 3C–5). The ASTER lineaments also identify these features but with a greater density (figs. 3C–7*a,b*). The northeast-southwest-trending zone of increased lineament density is likely an area where the rock is more highly fractured than in other areas of the AOI and may be an area of increased bedrock-aquifer yield and storage.

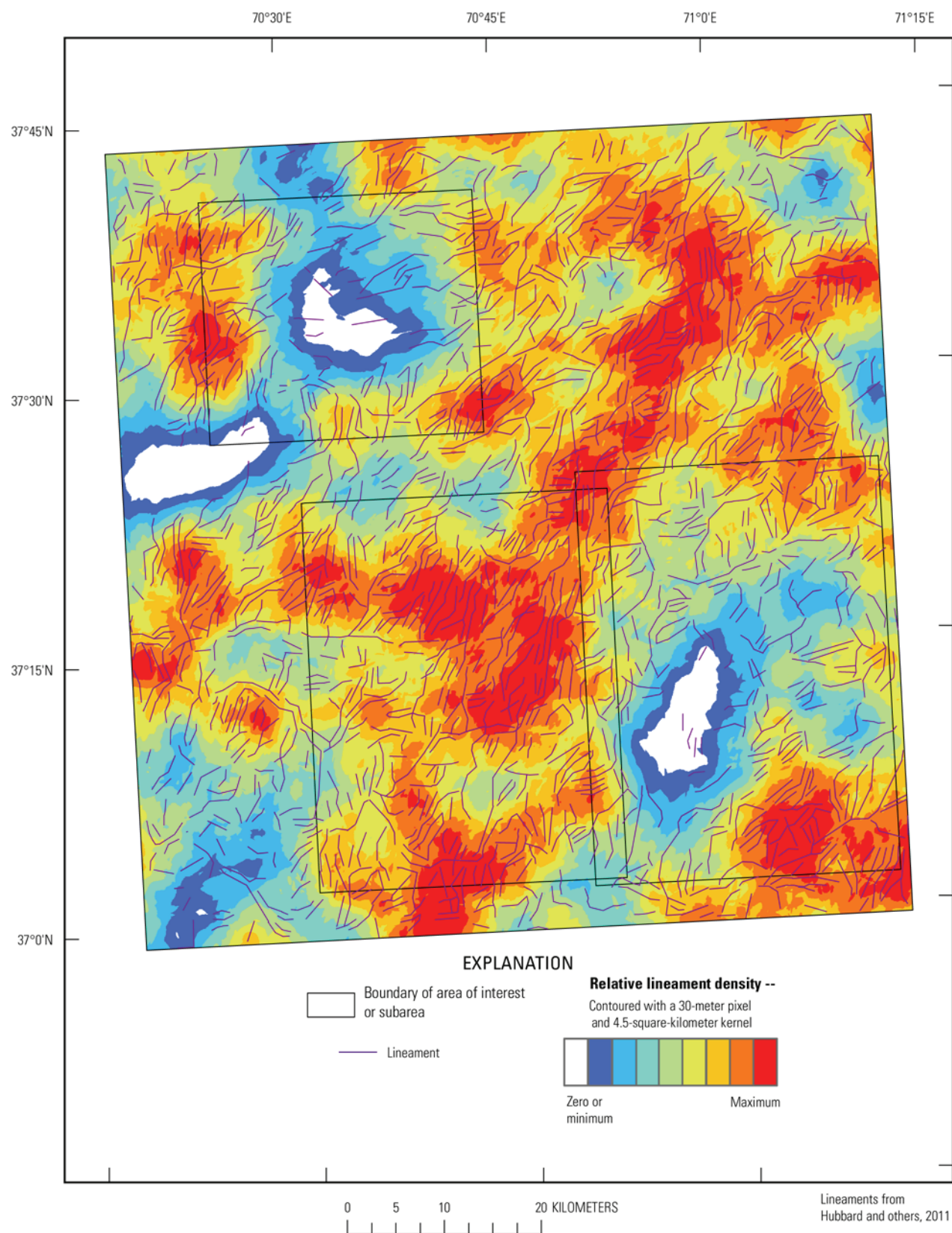
### 3C.9 Summary and Conclusions

The quantity of water available in the Badakhshan gold area of interest (AOI) is greater than that in many other areas of Afghanistan. The Amu Darya River is the largest source of surface water in the area and is adjacent to the northwest corner of the AOI. The Amu Darya River forms the border between Afghanistan and Tajikistan and its use is regulated by international agreements. The elevation of the Amu Darya River is about 700 m asl at the location closest to the AOI. The average elevation of the subareas in the AOI is more than 2,500 m asl. Currently, the only roads in the AOI are unimproved dirt roads (tracks), and few connect to the Amu Darya River. The two perennial streams in the AOI may supply water for additional municipal, or potentially mining-related, activities. The AOI receives more precipitation, about 490 mm/yr, and likely more recharge, than southern areas of Afghanistan. Additionally, the seasonal high streamflows resulting from snowmelt occur during the summer months (June, July, and August), and the surface-water resources of this region may exceed those needed to supply local agriculture. However, current streamflow data and additional analysis are needed to quantify river flows to meet local needs and ensure that precautions are taken to preserve the quantity and quality of water resources for local users.

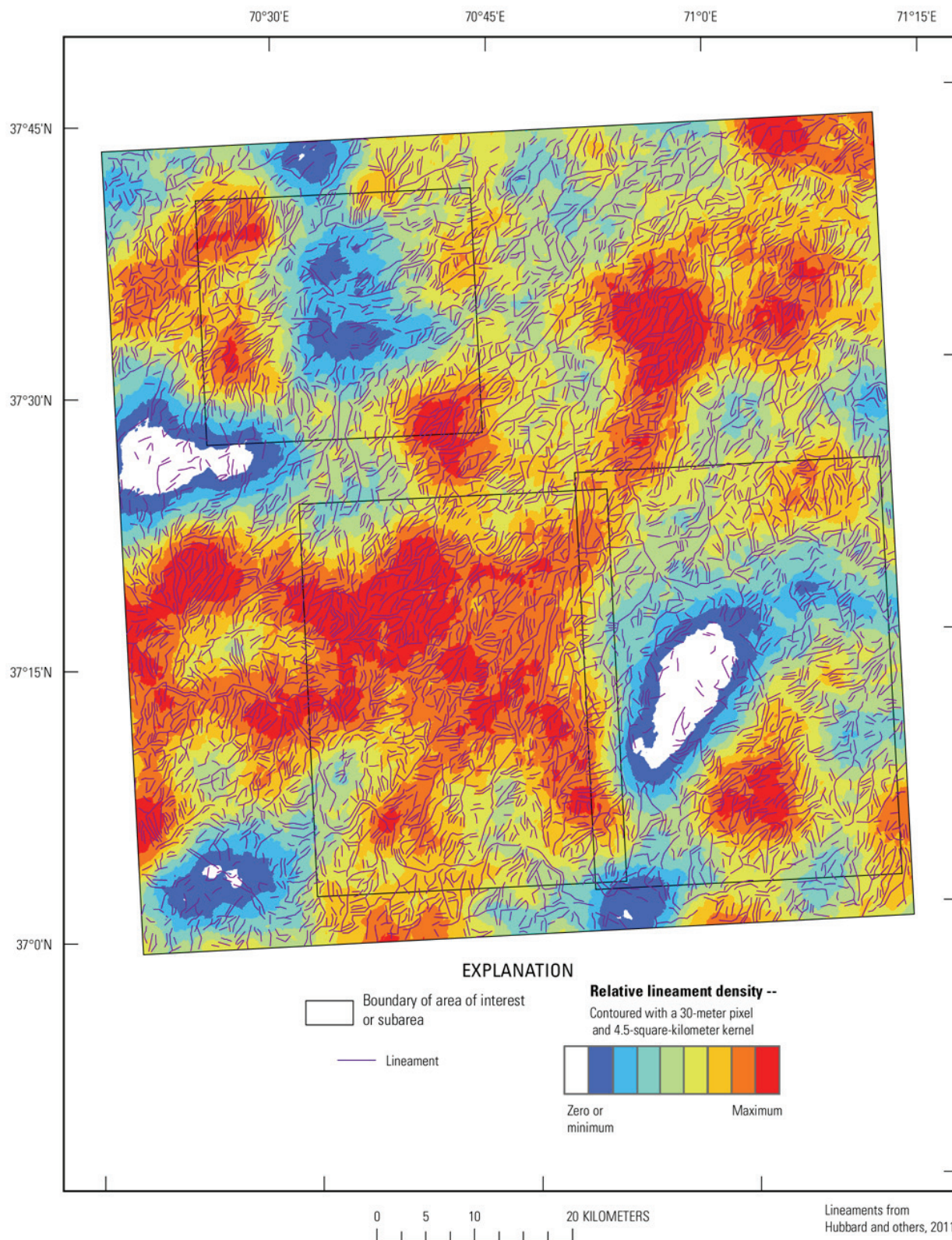


**Figure 3C–6.** Lineaments and lineament density based on 30-meter digital-elevation-model data and natural-color Landsat imagery in the Badakhshan gold area of interest in northern Afghanistan.

a



b



**Figure 3C–7.** (a) Lineaments and lineament density based on 30-meter multispectral Landsat imagery in the Badakhshan gold area of interest and (b) lineaments and lineament density based on 15-meter multispectral Landsat imagery in the Badakhshan gold area of interest in northern Afghanistan.

The characteristics of groundwater resources in the AOI are unknown because well data are limited. The existence of settlements in the stream valleys and in some of the upland valleys indicate that dug wells likely are present and that groundwater resources in alluvial aquifers likely are sufficient to supply local demands for water. Examination of historical streamflows near the AOI indicates that seasonal recharge to the shallow alluvial aquifers is probably sufficient to replenish water withdrawals for local consumption. However, without information on the thickness of the surficial aquifer, it is uncertain whether the alluvial aquifers can supply more water than currently is being used for domestic consumption and irrigation. The potential for the availability of additional groundwater resources in bedrock aquifers in the AOI is good. The fracture and fault zones and corresponding areas of high lineament density in the AOI could provide storage in, and pathways for surface water to infiltrate into, the bedrock aquifer. The infiltration of water into the matrix of sedimentary rocks can produce spatially distributed recharge, especially on low-gradient surfaces. The presence of vegetation, particularly trees, in upland areas indicates that seeps and springs are discharging groundwater from upland bedrock areas. Additionally, relatively high streamflow during low-flow periods indicates that groundwater storage in bedrock may be considerable.

Some areas of the AOI, as indicated by generalized geohydrologic maps and lineament analyses, are likely areas for further exploration for groundwater resources. The quality and sustainability of water resources in the AOI remain to be determined, however. Careful evaluation and management of potential new surface-water or groundwater withdrawals would help to protect the quantity and quality of the existing supply for current local water uses. Field investigations including geologic mapping, geophysical surveys, and hydraulic well testing are needed to adequately characterize the extent and availability of groundwater resources in the AOI.

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