Table 4. Summary statistics for physical properties and concentrations of major ions and bacteria by subbasin and region in the Kabul Basin, Afghanistan between May 2006 and July 2007.—Continued

[m, meters; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligrams per liter; Alk, titration alkalinity; <, less than; > greater than or equal to; –, not applicable]

Region	Statistic	Mg mg/L	Na mg/L	K mg/L	Alk mg/L as $CaCO_3$	Cl mg/L	SO_4 mg/L	F mg/L	Br mg/L	SiO_2 mg/L
Groundwater - Subbasin										
Central Kabul	Number of samples	13	13	13	13	13	13	12	13	13
	min	8.1	14.6	2.8	126.0	7.3	25.2	<0.05	<0.05	10.8
	max	269.0	1,230.0	17.4	532.0	1,650.0	1,323.0	1.61	2.43	41.1
	mean	84.8	190.5	9.6	307.4	261.4	270.8	0.40	0.49	26.3
	median	62.3	72.6	8.5	307.4	98.7	90.3	0.29	0.16	25.7
Deh Sabz	Number of samples	3	3	3	3	3	3	3	3	3
	min	14.7	35.1	4.4	137.9	29.2	86.3	0.38	0.08	30.4
	max	42.6	139.0	5.0	220.0	67.9	292.0	0.62	0.29	41.1
	mean	26.8	75.9	4.6	175.4	46.1	174.1	0.51	0.18	34.0
	med	23.0	53.6	4.5	168.0	41.2	144.0	0.54	0.17	30.6
Eastern Front Source Area	Number of samples	6	6	6	6	6	6	6	6	6
	min	12.6	1.4	0.7	144.0	1.7	14.5	0.16	<.05	6.3
	max	37.2	65.1	2.9	311.0	29.0	140.0	0.36	0.16	19.0
	mean	28.6	27.2	1.6	231.4	13.7	62.5	0.25	0.06	15.9
	med	28.8	18.1	1.3	208.6	8.3	50.5	0.20	<.05	17.3
Logar	Number of samples	4	4	4	5	4	4	4	4	4
	min	30.4	61.3	4.5	319.0	58.6	40.6	0.25	0.08	19.0
	max	87.9	96.5	6.9	467.0	92.0	138.0	0.49	0.23	26.3
	mean	64.9	74.6	5.3	386.4	74.3	91.2	0.36	0.15	22.7
	median	61.8	70.4	4.7	385.0	63.2	80.2	0.27	0.13	22.7
Paghman and Upper Kabul	Number of samples	6	6	6	7	6	6	6	6	6
	min	12.5	10.2	1.6	148.0	3.6	10.8	0.20	<.05	18.5
	max	74.7	87.9	6.7	398.0	103.0	122.0	0.57	0.19	31.2
	mean	37.1	39.5	4.4	286.2	39.4	62.3	0.31	0.08	24.2
	median	23.0	29.9	3.7	259.0	23.4	28.4	0.24	0.06	21.1
Shomali	Number of samples	7	7	7	7	7	7	7	7	7
	min	14.2	9.4	2.7	201.0	3.6	7	0.11	<.05	15.9
	max	70.5	108.0	13.0	401.0	139.0	174	0.28	0.22	28.0
	mean	31.8	38.4	5.7	287.5	43.4	47.8	0.22	0.06	23.9
	median	28.1	18.6	4.0	270.6	11.2	19.9	0.24	<0.5	24.7
Western Front Source Area	Number of samples	4	4	4	6	4	4	4	4	4
	min	7.4	6.6	1.2	148.0	2.7	4.3	0.11	<.05	17.6
	max	32.1	23.4	4.2	303.0	64.8	23.8	0.59	0.07	27.3
	mean	16.7	12.7	2.8	211.7	19.4	11.2	0.28	0.02	22.0
	median	8.2	9.0	2.5	210.0	4.5	7.8	0.19	<0.05	19.2
Kabul Basin - all groundwater	Number of samples	43	43	43	47	43	43	42	47	43
	min	7.4	1.4	0.7	126.9	1.7	4.3	<.05	<.05	6.3
	max	269.0	1,230.0	17.4	532.0	1,650.0	1,323.0	1.61	2.43	41.1
	mean	49.4	86.6	5.7	279.3	105.4	128.7	0.33	0.19	24.0
	median	31.4	47.8	4.5	262.4	29.2	80.2	0.25	0.11	28.0

Table 4. Summary statistics for physical properties and concentrations of major ions and bacteria by subbasin and region in the Kabul Basin, Afghanistan between May 2006 and July 2007.—Continued

[m, meters; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligrams per liter; Alk, titration alkalinity; <, less than; > greater than or equal to; –, not applicable]

Region	Statistic	Well depth (m)	Sample water level (m)	Water temperature (° C)	Specific conduc - tance (µS/cm)	pH field	O^2 mgL	Total coli counts/ 100 mL	*E. coli* counts/ 100 mL	NO_3 N mg/L	Ca mg/L
Surface water - Subbasin and River(s)											
Central Kabul	Number of samples	–	–	11	11	11	–	1	1	8	8
	min	–	–	0.8	366	8.6	–	>2,420	>2,420	2.3	39.1
Kabul River at Tangi-Gharu	max	–	–	22.9	929	9.0	–	>2,420	>2,420	3.9	60.6
	mean	–	–	11.2	662	–	–	–	–	3.0	52.0
	median	–	–	10.0	742	8.8	–	–	–	2.9	55.8
Logar	Number of samples	–	–	11	11	11	–	1	1	7	7
	min	–	–	0.5	412	8.6	–	1,120	162	1.4	48.3
Logar River	max	–	–	22.2	1,215	8.8	–	1,120	162	3.4	55.6
	mean	–	–	8.4	661	–	–	–	–	2.1	51.7
	median	–	–	7.8	623	8.8	–	–	–	1.9	50.2
Paghman and Upper Kabul	Number of samples	–	–	12	12	12	–	1	1	8	8
	min	–	–	3.7	67	8.4	–	116	42	0.4	8.1
Paghman River	max	–	–	18.0	143	9.0	–	116	42	1.3	16.3
	mean	–	–	10.0	110	–	–	–	–	0.9	12.6
	median	–	–	8.5	111	8.9	–	–	–	1.0	13.8
	Number of samples	–	–	10	10	10	–	1	1	6	6
	min	–	–	2.7	277	8.3	–	1,414	387	2.1	35.5
Kabul River at Tangi Saidan	max	–	–	14.7	786	8.6	–	1,414	387	3.3	72.4
	mean	–	–	8.0	515	–	–	–	–	2.6	51.5
	median	–	–	6.4	508	8.5	–	–	–	2.5	41.9
Shomali	Number of samples	–	–	13	13	13	–	–	1	7	7
	min	–	–	4.2	78	8.4	–	–	>2,420	0.5	10.6
Istalef River	max	–	–	17.8	196	8.8	–	–	>2,420	1.9	21.3
	mean	–	–	8.6	140	–	–	–	–	1.3	16.7
	median	–	–	11.0	140	8.5	–	–	–	1.3	16.9
	Number of samples	–	–	8	8	8	–	1	1	5	5
	min	–	–	0.6	114	8.3	–	>2,420	>2,420	1.4	20.5
Barik Ab River	max	–	–	14.8	1,497	8.6	–	>2,420	>2,420	5.9	88.6
	mean	–	–	7.0	568	–	–	–	–	2.7	46.7
	median	–	–	7.5	496	8.5	–	–	–	2.0	43.4
Panjsher	Number of samples	–	–	11	11	11	–	2	2	7	7
	min	–	–	9	232	8	–	435	70	0.7	29.3
Panjsher River at Sayad	max	–	–	15	474	9	–	649	99	1.4	53.2
	mean	–	–	11.1	363	–	–	–	–	1.1	39.9
	median	–	–	11.2	401	8.4	–	–	–	1.1	33.0
	Number of samples	–	–	–	–	–	–	–	–	1	1
	min	–	–	–	–	–	–	–	–	0.8	26.7
Panjsher River at Shukhi[1]	max	–	–	–	–	–	–	–	–	0.8	26.7
	mean	–	–	–	–	–	–	–	–	–	–
	median	–	–	–	–	–	–	–	–	–	–

Table 4. Summary statistics for physical properties and concentrations of major ions and bacteria by subbasin and region in the Kabul Basin, Afghanistan between May 2006 and July 2007.—Continued

[m, meters; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligrams per liter; Alk, titration alkalinity; <, less than; > greater than or equal to; –, not applicable]

Region	Statistic	Mg mg/L	Na mg/L	K mg/L	Alk mg/L as $CaCO_3$	Cl mg/L	SO_4 mg/L	F mg/L	Br mg/L	SiO_2 mg/L
Surface water - Subbasin and River(s)										
Central Kabul	Number of samples	8	8	8	8	8	8	8	8	8
	min	12.6	11.8	2.3	140.0	10.5	19.2	0.13	<.05	9.1
Kabul River at Tangi-Gharu	max	43.5	59.7	6.7	294.0	70.0	89.9	0.31	0.15	19.2
	mean	29.1	34.5	4.2	228.5	35.0	49.4	0.22	0.06	14.3
	median	32.2	37.8	4.0	229.3	36.8	51.0	0.20	0.06	14.4
Logar	Number of samples	7	7	7	7	7	7	7	7	7
	min	21.7	22.6	2.8	199.2	18.5	31.8	0.2	0.05	12.6
Logar River	max	71.8	97.2	6.5	386.0	108.0	113.0	0.4	0.19	21.6
	mean	37.5	42.3	3.9	266.1	40.5	53.9	0.28	0.07	15.4
	median	38.8	42.1	3.8	268.8	37.8	51.0	0.29	0.07	15.7
Paghman and Upper Kabul	Number of samples	8	8	8	8	8	8	8	8	8
	min	1.4	2.1	0.8	22.8	0.9	4.3	<.05	<.05	6.7
Paghman River	max	2.1	3.3	1.4	48.6	2.3	6.8	0.06	<.05	9.5
	mean	1.8	2.8	1.0	36.1	1.6	5.5	0.01	–	7.6
	median	1.9	3.0	0.9	39.6	1.4	5.4	<.05	<.05	7.0
	Number of samples	6	6	6	6	6	6	6	6	6
	min	6.9	5.2	1.5	110.9	4.2	9.2	0.08	<.05	9.4
Kabul River at Tangi Saidan	max	22.2	19.9	3.4	259.8	21.9	17.3	0.12	<.05	14.8
	mean	12.8	10.5	2.1	173.2	10.6	13.1	0.11	–	11.8
	median	8.8	6.6	1.7	130.2	5.8	11.4	0.12	–	11.0
Shomali	Number of samples	7	7	7	7	7	7	7	7	7
	min	1.4	2.0	1.6	32.0	0.8	2.7	<.05	<.05	9.3
Istalef River	max	2.8	4.2	2.3	65.0	2.5	5.0	0.07	<.05	12.3
	mean	2.2	3.3	2.0	51.1	1.6	4.0	0.03	–	11.0
	median	2.3	3.5	2.1	49.7	1.8	4.4	<.05	<.05	11.0
	Number of samples	5	5	5	5	5	5	5	5	5
	min	5.6	8.7	2.5	64.0	8.5	15.5	0.07	<.05	8.2
Barik Ab River	max	70.8	132.0	8.0	360.6	149.0	192.0	0.30	0.18	26.7
	mean	26.6	48.9	4.6	198.6	58.5	82.5	0.16	–	13.5
	median	18.7	32.6	4.4	173.4	35.9	65.1	0.15	<.05	11.7
Panjsher	Number of samples	7	7	7	7	7	7	7	7	7
	min	5.5	6.6	3.3	82.0	11	17	0.05	<.05	6
Panjsher River at Sayad	max	14.1	22.8	5.7	162.0	38	33	0.10	<.05	8
	mean	9.7	14.3	4.4	118.7	22.7	24.4	0.07	–	7.7
	median	8.1	10.4	3.6	102.3	15.2	22.1	0.08	<.05	8.0
	Number of samples	1	1	1	1	1	1	1	1	1
	min	5.3	7.7	2.9	79.7	9.9	14.8	0.07	<.05	14.8
Panjsher River at Shukhi[1]	max	5.3	7.7	2.9	79.7	9.9	14.8	0.07	<.05	14.8
	mean	–	–	–	–	–	–	–	–	–
	median	–	–	–	–	–	–	–	–	–

1 - one value

Table 5. Summary statistics for trace-element concentrations by subbasin and region in the Kabul Basin, Afghanistan between May 2006 and July 2007 (Values in bold indicate maximum values that exceed World Health Organization guidelines).

[<, less than; ug/L, micrograms per liter; WHO, World Health Organization, 2006; --, not applicable]

Region	Statistic	As µg/L	Ba µg/L	Br µg/L	B µg/L	Cr µg/L	Co µg/L	Cu µg/L	Fe µg/L	Li µg/L
WHO guideline or proposed guideline		10	700	--		50	--	2,000	--	--
Groundwater Subbasin										
Central Kabul	Number of samples	13	13	13	13	13	13	13	13	13
	min	0.3	18	0.05	90	<1	<0.1	0.6	<20	<4
	max	8.9	223	2.43	**6,660**	24	2.33	9.6	90	518
	mean	2.4	71	0.49	1,172	6	0.52	2.3	8.5	128
	median	1.6	52	0.16	760	3	0.27	1.2	<20	104
Deh Sabz	Number of samples	3	3	3	3	3	3	3	3	3
	min	0.9	16	0.08	130	<1	0.25	0.7	<20	15
	max	4.4	34	0.29	420	9	0.35	2.5	<20	21
	mean	2.1	24	0.18	240	4	0.30	1.6	--	17
	median	1.1	22	0.17	170	2	0.31	1.6	<20	15
Eastern Front Souce Area	Number of samples	6	6	6	6	6	6	6	6	6
	min	0.4	8	<0.05	20	<1	0.06	0.3	<20	<1
	max	2.5	69	0.16	150	9	0.50	1.4	720	15
	mean	1.2	44	0.06	92	3	0.20	1.0	175	7
	median	0.9	44	<0.05	100	2	0.13	1.1	<20	6
Logar	Number of samples	4	4	4	4	4	4	4	4	4
	min	0.9	50	0.08	910	<1	0.12	0.7	<20	129
	max	1.9	104	0.23	**1,210**	7	0.30	1.8	<20	287
	mean	1.3	77	0.15	1,048	3	0.22	1.4	--	186
	median	1.1	67	0.13	980	1	0.19	1.3	<20	154
Paghman and Upper Kabul	Number of samples	6	6	6	6	6	6	6	6	6
	min	0.8	14	>.05	60	<1	0.14	0.6	<20	6
	max	3.8	103	0.19	**880**	7	0.37	5.7	<20	157
	mean	2.1	58	0.08	445	2	0.24	2.5	--	67
	median	2.2	49	0.06	190	<1	0.22	1.9	<20	33
Shomali	Number of samples	7	7	7	7	7	7	7	7	7
	min	0.3	28	<0.05	40	<1	0.11	0.3	<20	7
	max	1.9	123	0.22	**1,420**	8	0.42	1.7	40	329
	mean	0.9	72	0.06	386	4	0.26	0.8	8.6	77
	median	0.8	74	<0.05	70	3	0.27	0.7	<20	25
Western Front Source Area	Number of samples	6	4	4	4	4	4	6	4	4
	min	0.2	21	<.05	20	<1	0.07	0.3	<20	4
	max	1.1	46	0.1	50	4	0.49	1.4	<20	16
	mean	0.5	34	0.02	30	1	0.31	1.0	--	8
	median	0.4	29	<.05	20	<1	0.30	1.1	<20	5
Kabul Basin - all groundwater	Number of samples	47	43	47	43	43	43	43	43	43
	min	0.2	8	<.05	20	<1	0.06	0.3	<20	<1
	max	8.9	223	2.43	**6,660**	24	2.33	9.6	720	518
	mean	1.6	59	0.19	609	4	0.33	1.7	28	81
	median	1.1	49	0.11	170	2	0.27	1.2	<20	24

Table 5. Summary statistics for trace-element concentrations by subbasin and region in the Kabul Basin, Afghanistan between May 2006 and July 2007. Values in bold indicate maximum values that exceed World Health Organization guidelines.—Continued

[<, less than; ug/L, micrograms per liter; WHO, World Health Organization, 2006; --, not applicable]

Region	Statistic	Mn µg/L	Mo µg/L	Ni µg/L	Pb µg/L	Se µg/L	Sr µg/L	U µg/L	V µg/L	Zn µg/L
WHO guideline or proposed guideline		400	70	70	10	10	--	15	--	--
Groundwater Subbasin										
Central Kabul	Number of samples	13	13	13	13	13	13	13	13	13
	min	<1	0.8	<0.3	0.07	<1	516	2.60	0.7	4
	max	108	55.3	33.1	3.10	**38**	12,530	**31.80**	21.9	2030
	mean	11	8.0	11.5	0.48	6	2,276	10.36	8.0	297
	median	1	4.3	7.8	0.37	2	988	5.84	6.7	42
Deh Sabz	Number of samples	3	3	3	3	3	3	3	3	3
	min	<1	2.9	0.3	0.09	2	659	2.90	4.3	7
	max	4	8.5	4.5	1.90	7	1,310	11.60	14.2	48
	mean	2	5.4	1.7	0.74	4	925	6.97	9.9	21
	median	2	2.0	0.4	0.22	3	805	6.40	11.3	8
Eastern Front Souce Area	Number of samples	6	6	6	6	6	6	6	6	6
	min	<1	1.8	<0.1	0.38	<1	293	2.70	0.5	3
	max	21	3.7	1.9	**29.50**	3	978	9.20	6.7	134
	mean	5	2.6	0.8	11.51	1	701	6.05	3.1	41
	median	<1	2.3	0.6	2.95	1	659	5.30	1.7	9
Logar	Number of samples	4	4	4	4	4	4	4	4	4
	min	<1	1.7	0.3	0.16	1	865	5.10	1.1	5
	max	2	3.6	5.3	1.50	4	1,470	8.90	15.3	130
	mean	1	2.4	2.3	0.92	3	1,070	6.29	5.8	39
	median	<1	1.9	0.8	0.61	4	866	5.20	3.4	5
Paghman and Upper Kabul	Number of samples	6	6	6	6	6	6	6	6	6
	min	<1	1.2	0.1	0.10	<1	457	2.20	0.5	3
	max	3	4.4	13.1	4.00	3	1,120	14.90	9.5	511
	mean	2	2.5	6.0	1.09	1	693	7.40	3.2	92
	median	2	2.0	1.3	0.32	1	617	5.40	1.9	9
Shomali	Number of samples	7	7	7	7	7	7	7	7	7
	min	<1	0.6	0.1	0.08	<1	339	2.60	1.6	7
	max	17	4.0	0.9	7.12	2	2,120	**17.80**	16.1	165
	mean	4	2.2	0.5	1.21	0.5	882	6.96	7.3	34
	median	<1	2.4	0.5	0.19	<1	831	4.51	6.6	12
Western Front Source Area	Number of samples	4	4	4	4	4	4	4	4	4
	min	<1	0.5	0.2	0.14	<1	219	1.30	2.4	2
	max	4	2.1	1.5	2.00	1	1,600	5.30	9.7	540
	mean	1	1.3	0.8	0.90	--	655	3.18	5.9	188
	median	<1	1.2	0.2	0.44	<1	284	2.02	4.9	4
Kabul Basin - all groundwater	Number of samples	43	43	43	43	43	43	43	43	43
	min	<1	0.1	<.1	0.07	<1	219	1.30	0.5	2
	max	108	55.3	33.1	**29.50**	**38**	12,530	**31.80**	21.9	2030
	mean	5	4.2	4.9	2.32	3	1,251	7.51	6.3	136
	median	3	2.4	0.8	0.40	1	831	5.40	4.8	13

Table 5. Summary statistics for trace-element concentrations by subbasin and region in the Kabul Basin, Afghanistan between May 2006 and July 2007. Values in bold indicate maximum values that exceed World Health Organization guidelines.—Continued

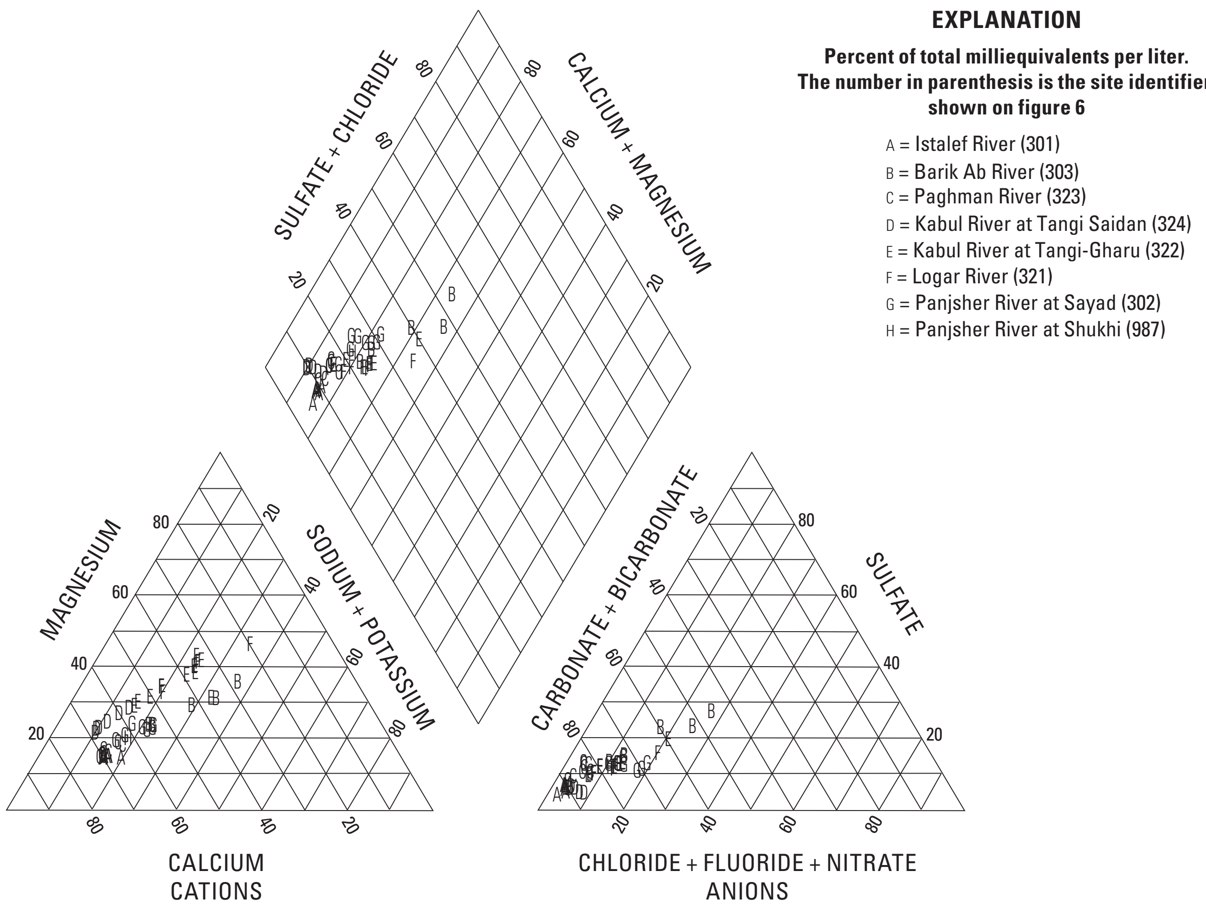
[<, less than; ug/L, micrograms per liter; WHO, World Health Organization, 2006; --, not applicable]

Region	Statistic	As µg/L	Ba µg/L	Br µg/L	B µg/L	Cr µg/L	Co µg/L	Cu µg/L	Fe µg/L	Li µg/L
Surface Water Subbasin and River(s)										
Central Kabul	Number of samples	8	8	8	8	8	8	8	8	8
	min	2.2	14	0.05	180	<1	0.13	0	<20	29
Kabul River at Tangi-Gharu	max	8.3	57	0.15	730	3	1.74	4.3	1,690	124
	mean	3.9	39	0.06	494	2	1.04	1.6	211	86
	median	3.1	47	0.06	570	2	0.81	1.0	<20	79
Logar	Number of samples	7	7	7	7	7	7	7	7	7
	min	2.4	32	<0.05	380	<1	0.19	0.5	<20	69
Logar River	max	4.4	58	0.19	1,290	4	2.38	2.2	440	224
	mean	3.0	47	0.07	674	2	1.24	1.2	93	128
	median	2.7	51	0.07	640	2	1.11	1.0	<20	134
Paghman and Upper Kabul	Number of samples	8	8	8	8	8	8	8	8	7
	min	0.4	3	<.05	<20	<1	<.05	<.1	<20	<1
Paghman River	max	0.8	6	<.05	40	<1	2.07	1.0	154	4
	mean	0.6	5	--	15	--	0.62	0.5	32	2
	median	0.7	5	<.05	<20	<1	0.18	0.5	<20	1
	Number of samples	6	6	6	6	6	6	6	6	6
	min	1.8	8	<.05	<20	<1	0.11	<.1	<20	<20
Kabul River at Tangi Saidan	max	4.6	38	<.05	480	1	1.29	0.4	170	170
	mean	2.8	19	--	143	<1	0.64	0.3	32	30
	median	2.0	9	<.05	<20	<1	0.50	0.4	<20	<20
Shomali	Number of samples	7	7	7	7	7	7	7	7	7
	min	0.3	8	<.05	<20	<1	<.05	0.2	<20	6
Istalef River	max	0.6	20	<.05	20	<1	1.77	1.0	120	21
	mean	0.4	15	--	4	--	0.44	0.4	47	14
	median	0.4	14	<.05	<20	<1	0.26	0.3	20	12
	Number of samples	5	5	5	5	5	5	5	5	5
	min	1.2	19	<.05	80	<1	0.08	0.3	<20	21
Barik Ab River	max	2.8	110	0.18	1,110	6	1.72	4.6	2,280	109
	mean	1.9	50	0.05	418	1	0.70	1.4	462	51
	median	1.7	43	<.05	330	<1	0.41	0.6	<20	43
Panjsher	Number of samples	7	7	7	7	7	7	7	7	7
	min	0.9	20	<.05	40	<1	0.06	<.1	<20	30
Panjsher River at Sayad	max	1.8	44	<.05	400	<1	0.46	0.7	40	78
	mean	1.2	31	--	223	--	0.26	0.3	6	48
	median	1.1	25	<.05	200	<1	0.24	0.2	<20	47
	Number of samples	1	1	1	1	1	1	1	1	1
	min	0.8	79	<.05	120	<1	<.05	0.5	<20	21
Panjsher River at Shukhi	max	0.8	79	<.05	120	<1	<.05	0.5	<20	21
	mean	--	--	--	--	--	--	--	--	--
	median	--	--	--	--	--	--	--	--	--

Table 5. Summary statistics for trace-element concentrations by subbasin and region in the Kabul Basin, Afghanistan between May 2006 and July 2007. Values in bold indicate maximum values that exceed World Health Organization guidelines.—Continued

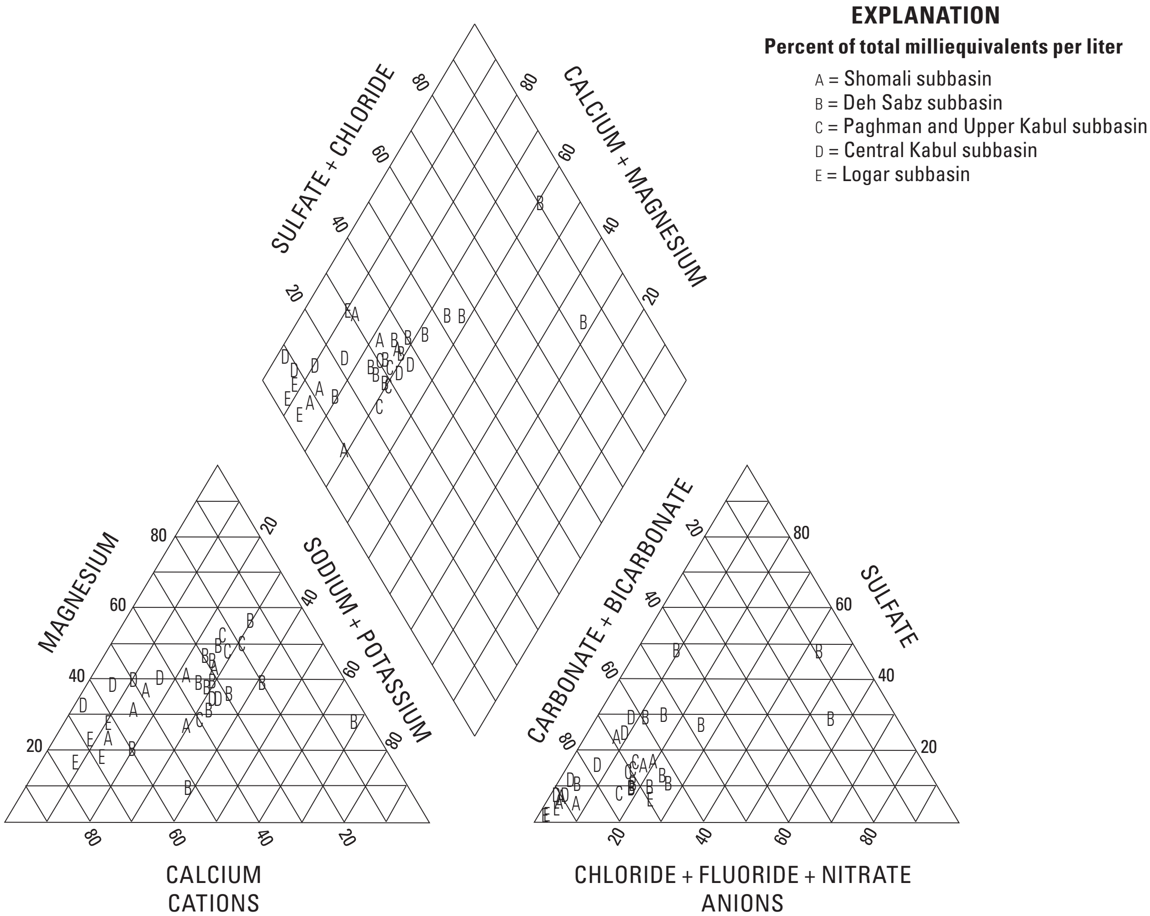
[<, less than; ug/L, micrograms per liter; WHO, World Health Organization, 2006; --, not applicable]

Region	Statistic	Mn µg/L	Mo µg/L	Ni µg/L	Pb µg/L	Se µg/L	Sr µg/L	U µg/L	V µg/L	Zn µg/L
Surface Water Subbasin and River(s)										
Central Kabul	Number of samples	8	8	8	8	8	8	8	8	8
	min	6	0.9	2.2	<.05	<1	202	1.34	1.6	<1
Kabul River at Tangi-Gharu	max	84	3.3	11.0	1.25	2	715	5.07	6.3	5
	mean	37	2.2	4.3	0.21	2	494	3.26	3.6	2
	median	25	2.6	3.3	<0.05	2	543	3.78	3.1	2
Logar	Number of samples	7	7	7	7	7	7	7	7	7
	min	3	2.2	2.8	<.05	<1	345	2.41	2.3	1
Logar River	max	44	3.7	7.6	0.57	3	1,460	8.78	4.9	9
	mean	18	3.0	4.1	0.15	2	643	4.55	3.2	3
	median	13	2.8	3.8	0.07	2	623	4.34	2.6	2
Paghman and Upper Kabul	Number of samples	8	8	8	8	8	8	8	8	8
	min	1	0.3	0.2	<.05	<1	32	0.06	1	<1
Paghman River	max	14	0.4	0.8	0.15	<1	59	0.20	2	12
	mean	5	0.4	0.5	0.06	--	47	0.11	0.9	3
	median	4	0.3	0.6	0.06	<1	49	0.09	0.6	2
	Number of samples	6	6	6	6	6	6	6	6	6
	min	5	0.6	1.5	0.03	<1	127	0.59	0.5	<1
Kabul River at Tangi Saidan	max	50	1.0	5.8	<.05	<1	397	1.93	2.1	2
	mean	24	0.7	3.2	0.03	--	235	1.12	1.2	1
	median	7	0.7	2.0	--	<1	161	0.66	0.6	<1
Shomali	Number of samples	7	7	7	7	7	7	7	7	7
	min	1	0.4	0.2	<.05	<1	38	0.24	2.5	<1
Istalef River	max	18	0.8	0.9	0.39	<1	480	0.66	3.9	9
	mean	8	0.6	0.6	0.10	--	131	0.47	3.4	3
	median	6	0.6	0.6	0.07	<1	82	0.50	3.5	3
	Number of samples	5	5	5	5	5	5	5	5	5
	min	8	0.9	0.7	<.05	<1	145	1.40	2.6	<1
Barik Ab River	max	64	3.0	6.2	1.67	3	1,920	**17.50**	10.9	8
	mean	24	2.0	2.4	0.39	1	721	6.47	5.7	2
	median	14	2.0	1.7	0.07	1	578	4.78	5.3	<1
Panjsher	Number of samples	7	7	7	7	7	7	7	7	7
	min	2	0.6	0.5	<.05	<1	126	0.83	0.4	<1
Panjsher River at Sayad	max	9	1.1	1.2	0.29	<1	328	2.37	1.3	4
	mean	5	0.8	1.0	0.08	--	214	1.62	0.7	2
	median	4	0.8	1.0	<.05	<1	153	1.59	0.6	1
	Number of samples	1	1	1	1	1	1	1	1	1
	min	<1	0.8	0.3	<.05	<1	128	0.91	0.5	21
Panjsher River at Shukhi	max	<1	0.8	0.3	<.05	<1	128	0.91	0.5	21
	mean	--	--	--	--	--	--	--	--	--
	median	--	--	--	--	--	--	--	--	--



A. Surface Water

Figure 18. Trilinear diagrams of (A) surface-water and (B) groundwater quality in the Kabul Basin, Afghanistan, 2006–07.



B. Groundwater

Figure 18. Continued.

Surface Water

In 2006 and 2007, samples were collected from eight rivers in the Kabul Basin and were analyzed for physical properties, bacteria, major ions, and trace elements (tables 4 and 5, fig. 18).

The specific conductance of surface water measured in the Kabul Basin ranged from a minimum of 67 µS/cm, at Paghman River to 1,497 µS/cm at Barik Ab River (table 4). The median specific conductances by subbasin ranged from 111 µS/cm in the Paghman River (Upper Kabul/Paghman subbasin) to 742 µS/cm in the Kabul River at Tang-i-Gharu (Central Kabul subbasin). Specific conductances (fig. 19) were low in streams flowing into the Kabul Basin from adjacent upland areas, such as the Istalef and Paghman Rivers (medians of 140 and 111 µS/cm respectively; table 4).

Nitrate concentrations (fig. 20) measured in the Kabul Basin ranged from 0.4 mg/L in the Paghman River to 5.9 mg/L at the Barik Ab River. Median concentrations by subbasin ranged from 1.0 mg/L at the Paghman River to 2.9 mg/L in the Kabul River at Tang-i-Gharu (table 4). Total coliform (fig. 21) was detected in all streams sampled and ranged from 116 in the Paghman River to at least 2,420 colonies per 100 mL in the Barak Ab River and Kabul River at Tang-i-Gharu. *E. coli* (fig. 22) was detected in water samples at the 7 surface-water sites tested (table 4). *E. coli* colonies in excess of 2,420 per 100 mL were detected in the Istalef River, the Kabul River at Tang-i-Gharu, and the Barik Ab River (fig. 22).

Surface-water quality was predominately of the calcium-bicarbonate type in the Kabul Basin, and sample compositions were generally tightly clustered in the trilinear plot with little variation (fig. 18A). More variation was observed in the Barik Ab River, Logar River, and the Kabul River at Tang-i-Gharu (fig. 18A) with samples containing more ions, particularly chloride and sulfate. At these sites, concentrations of chemical constituents were lower during spring-melt high-flow periods and higher during low-flow periods than at other times of the year.

Groundwater

As observed in data previously collected by the USGS and AGS (Broshears and others, 2005), groundwater quality in the Kabul Basin varied widely. The major-ion chemistry of Kabul Basin groundwater was generally of the calcium-magnesium bicarbonate type (fig. 18B). Some groundwater sampled in the Central Kabul and Deh Sabz subbasins and in the Paghman and Upper Kabul subbasin (one sample only) was of the sulfate-chloride type, and other samples collected in the same subbasins were of intermediate compositions (fig. 18B). Some chemical concentrations also were high in the Logar subbasin, probably because of proximity to urban areas, as was true for the Central Kabul subbasin. These differing chemistries indicated possible influences by anthropogenic or industrial contamination, poor well construction, possible dissolution of rocks containing gypsum, or increased concentrations of ions caused by evapotranspiration processes as suggested by Broshears and others (2005), especially in the Central Kabul subbasin. In the Deh Sabz subbasin, groundwater appears to have evolved from the calcium-magnesium bicarbonate type to a sulfate-chloride or sodium type (fig. 18B).

The median values of water-quality parameters in groundwater in the Central Kabul subbasin (fig. 1) were generally higher than in the other basins (tables 4 and 5). Parameters that appeared to have higher median values in the Central Kabul subbasin included specific conductance, and concentrations of hardness measured as alkalinity, nitrate plus nitrite, bromide, magnesium, sodium, potassium, chloride, arsenic, boron, nickel, and zinc. Additionally, concentrations of four elements—fluoride, boron, selenium and uranium—in the Central Kabul subbasin exceeded World Health Organization (WHO) guidelines. Uranium concentrations were higher than 5 µg/L in much of the Kabul Basin and higher than the WHO guideline of 15 µg/L in three samples.

Specific conductances and concentrations of dissolved oxygen and nitrate as N in the Kabul Basin (fig. 19) generally indicated the effects of urbanization. Median values of specific conductances in groundwater specific ranged from 51 in the Eastern Front Source Area (fig. 1) to 1,177 µS/cm in the Central Kabul subbasin (table 4). Overall, the conditions in the aquifer were slightly oxic with dissolved oxygen concentrations in the subbasins ranging from 0.1 to 1.9 mg/L as O_2 and a median value of 0.1 mg/L. The operation of some production pumps, however, may have increased the oxygen content of water samples. Median nitrate concentrations as N in the subbasins ranged from 1.2 mg/L in the Eastern Front Source Area to 6.7 mg/L in Central Kabul. Elevated nitrate concentrations in the Kabul Basin (fig. 20) also generally indicated the effects of urbanization. The median nitrate concentration for the entire Kabul Basin was 3.3 mg/L as N (table 4). The highest nitrate concentration (40.21 mg/L as N) was observed in water from one well in the Western Front Source Area. Concentrations of nitrate in groundwater from the Central Kabul and Paghman and Upper Kabul (median of 3.2 mg/L) subbasins were greater than concentrations measured in samples collected elsewhere in the Kabul Basin; most of the water samples with nitrate concentrations as N exceeding 10 mg/L were collected from the Central Kabul and Paghman and Upper Kabul subbasins (fig. 20).

Total coliform bacteria were detected in nearly all of the groundwater samples. The counts were more than 2,420 colonies per 100 mL in some wells (table 4). More than 100 colonies per 100 mL were detected in samples from all of the subbasins with the exception of the Eastern Front Source Area (4 colonies per 100 mL). *E. coli* was detected in 66 of 68 samples collected (table 4). Water from well 8 located in the Deh Sabz subbasin, with more than 2,420 colonies per 100 mL total coliform, had the highest reported concentration of colonies of *E. coli* (461 colonies per 100 mL); however, detections of *E. coli* appeared to be randomly distributed throughout the basin.

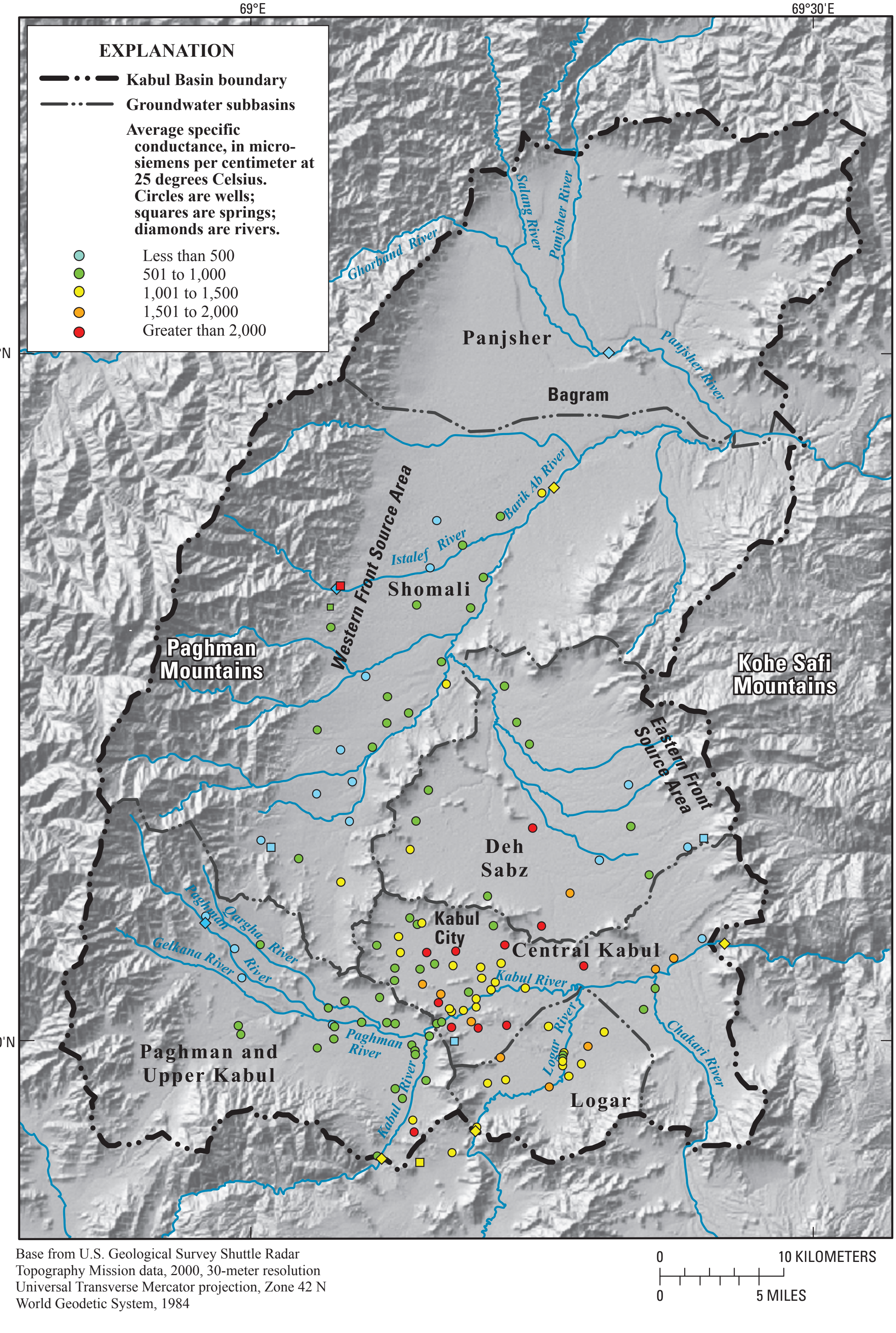


Figure 19. Specific conductance of water in the Kabul Basin, Afghanistan, 2006–07.

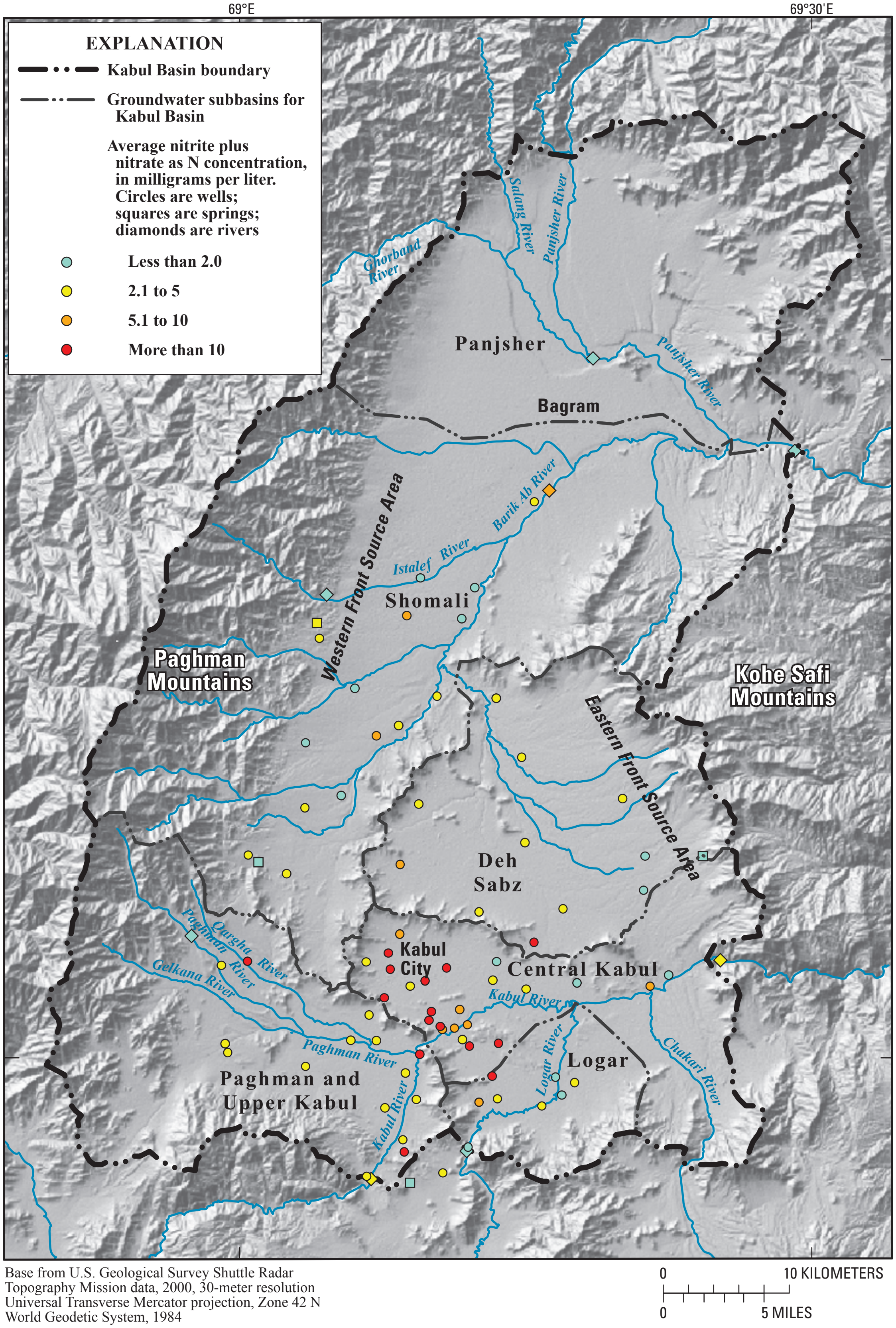


Figure 20. Nitrate concentrations in water in the Kabul Basin, Afghanistan, 2006–07.

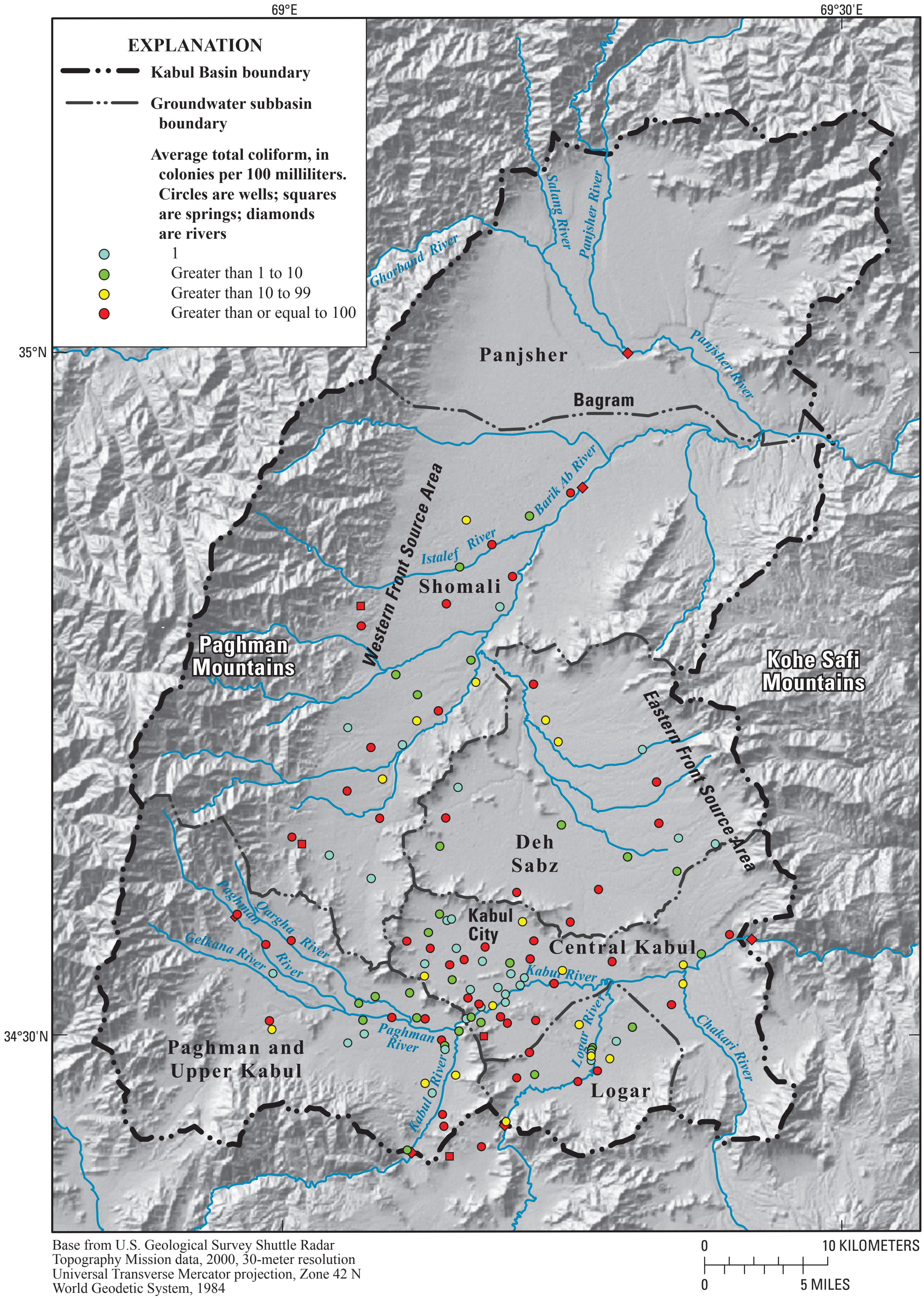


Figure 21. Concentrations of total coliform in water in the Kabul Basin, Afghanistan, 2006–07.

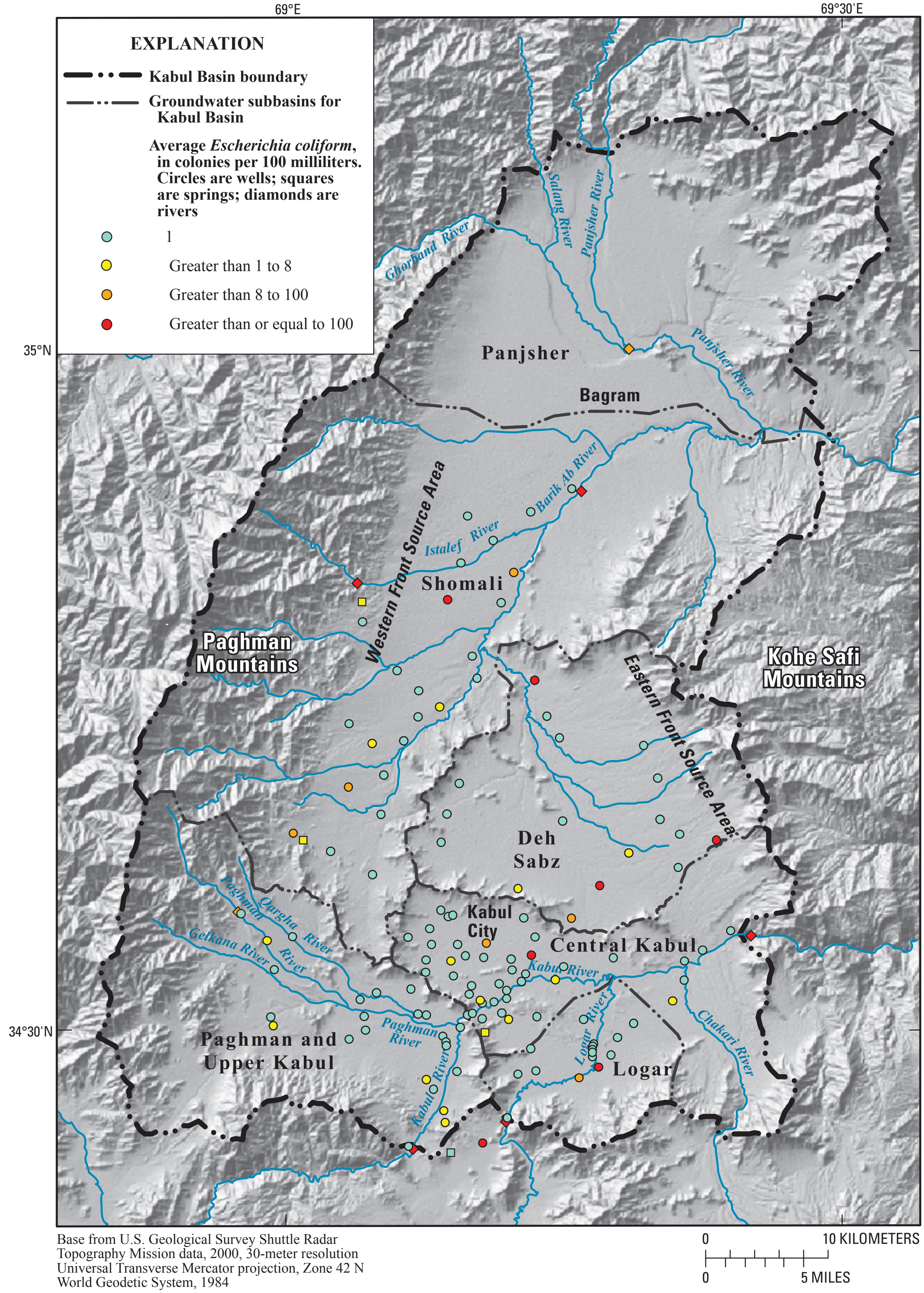


Figure 22. Concentrations of *Escherichia coli* in water in the Kabul Basin, Afghanistan, 2006–07.

Four groundwater exceedances with respect to WHO (2006) drinking-water guidelines were noted:

1. The guideline of less than 1 colony per 100 mL for *E. coli* was exceeded in 66 of 68 of the samples (97 percent).
2. The guideline of 50 mg/L as N for nitrate was not exceeded. Concentrations in 7 of 43 samples (16 percent), however, were greater than 10 mg/L.
3. The guideline of 10 µg/L for arsenic was not exceeded in any of the 47 samples and was greater than 5 mg/L only in 1 sample.
4. The guideline of 10 µg/L for lead was exceeded in 3 of 43 (7 percent) of the samples, all in the Eastern Front Source Area.
5. The guideline of 10 µg/L for selenium was exceeded in 1 of the 43 samples.
6. The guideline of 15 µg/L for uranium was exceeded in 3 of the 43 samples; concentrations in 26 of the 43 samples were greater than 5 µg/L.

As Broshears and others (2005) found, contamination of drinking-water sources by anthropogenic activities, such as the introduction of untreated wastewater and nitrate contamination from fertilizer applications, remains an important concern to the population of the Kabul Basin.

Chemical and Isotopic Analysis

Chemical and isotopic analyses of waters in the Kabul Basin focused on concentrations of stable hydrogen and oxygen isotopes, chlorofluorocarbons, and tritium in groundwater and surface water; mass concentration ratios; geochemical reactions; and solute origins.

Stable Hydrogen and Oxygen Isotopes in Groundwater and Surface Water

Previous stable isotope and tritium measurements in precipitation were made by the International Atomic Energy Agency (IAEA), which collected and analyzed integrated precipitation samples from the city of Kabul monthly between January 1962 and September 1989; although data for many months are missing (International Atomic Energy Agency, 2004), stable oxygen and hydrogen isotopic data for 86 monthly samples and 123 monthly composite values of tritium in precipitation are in the database composed by the IAEA and the World Meteorological Organization for Kabul.

The concentrations of the stable hydrogen isotopes (^{1}H and ^{2}H) and oxygen isotopes (^{16}O and ^{18}O) in precipitation commonly vary owing to differences in latitude, season, and other factors. The unique signatures of stable hydrogen and oxygen isotopes can be used to differentiate among surface waters and groundwaters recharged by these surface waters. In this study, 80 groundwater, 4 karez, 7 spring, and 76 surface-water samples were collected and analyzed for stable hydrogen and oxygen isotopic composition. Between early December 2006 and mid-July 2007, surface-water samples were collected at seven sites. The details of the analytical methods and the measurement results are discussed in detail in Appendix 11.

In the Kabul Basin, surface waters were assigned to four groups based on their stable hydrogen and oxygen isotopic composition (fig. 23). The samples lowest in ^{2}H and ^{18}O were those of the Panjsher River, this isotopic profile reflects meltwater from snow in the high-altitude source area extending to the Khyber Pass in Pakistan. The lowest ^{2}H and ^{18}O concentrations, which measured in late June, presumably reflect the highest fraction of snow meltwater. Samples from the Istalef River at Istalef and the Paghman River at Paghman surface-water sites were most enriched in ^{2}H and ^{18}O; this result is consistent with the relatively low-altitude source areas for these rivers in the foothills west of the Kabul Basin (fig. 23, fig. 1). None of the surface-water bodies studied are affected by significant evaporation.

Stable isotopic composition of surface waters in the Kabul Basin

Surface waters were assigned to four groups based on isotopic compositions:

1. The waters of the Istalef and the Paghman Rivers are isotopically indistinguishable from one another, reflect a precipitation source in an arid environment with the lowest relative humidity (approximately 70 percent), and are indistinguishable from precipitation collected by the IAEA at Kabul between 1962 and 1989.
2. The Kabul River at Tang-i-Saidan and the Barik Ab River near Bagram are hydrologically distinct (have different sources) but very similar isotopically.
3. The Kabul River at Tang-i-Gharu and the Logar River samples form a third isotopic grouping, but they are not the same water hydrologically. Because the Kabul River at Tang-i-Saidan, the Logar River, and the Paghman River supply water to the Kabul River at Tang-i-Gharu, the isotopic compositions of samples collected at this site are determined by the isotopic compositions and mass balances of the waters from the three sources.
4. Panjsher River samples by themselves form the fourth group.

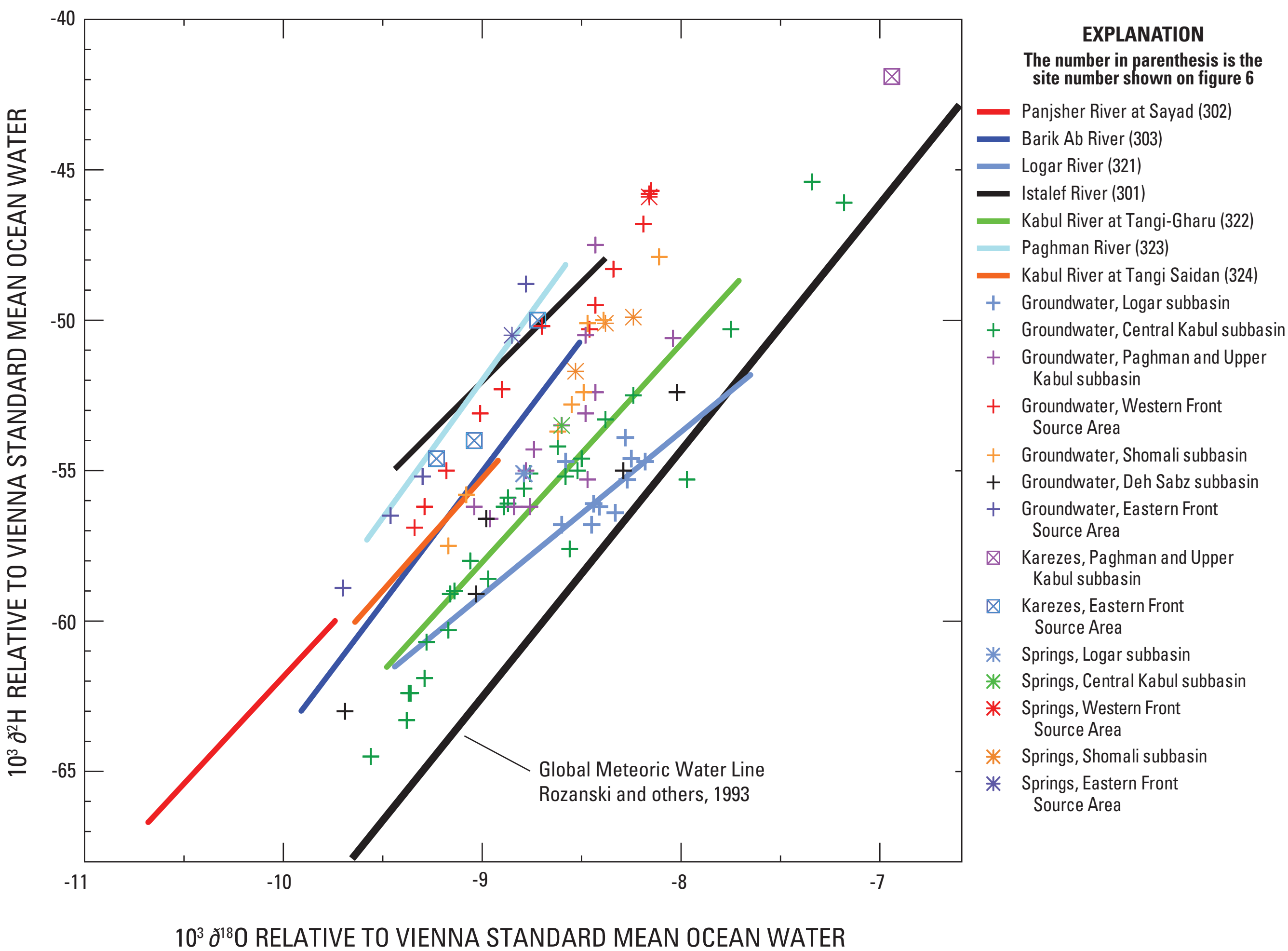


Figure 23. The hydrogen versus oxygen isotopic composition, relative to Vienna Standard Mean Ocean Water, of surface water, groundwater, and water from karezes and springs in the Kabul Basin, Afghanistan.

The isotopic compositions of water sampled from groundwater wells, karezes, and springs are plotted on figure 23, and with few exceptions, the points for each site plot near one of the four isotopically distinguishable surface-water sources discussed above. Water sampled from groundwater wells, karezes, and springs in the subbasins can be assigned to seven groundwater-source areas on the basis of isotopic and chemical analysis: Western Front Source Area, Shomali subbasin, Deh Sabz subbasin, Eastern Front Source Area, Paghman and Upper Kabul subbasin, Central Kabul subbasin, and Logar subbasin. Groundwaters in the Western Front Source Area area in the Shomali subbasin and the Eastern Front Source Area in the Deh Sabz subbasin differ from groundwater elsewhere in their respective subbasins on the basis of stable hydrogen and oxygen isotopes. Some of the groundwaters had chloride mass concentrations as high as 1,650 mg/L, a factor of 10 to 50 times higher than that in the presumed surface source waters. Had these chloride enrichments been caused by evaporative concentration, one would expect very substantial enrichments in ^{2}H and ^{18}O. No such enrichments were found; therefore, another mechanism must be responsible for the elevated chloride content. (See the subsection titled "Mass Concentration Ratios, Geochemical Reactions, and Solute Origins.")

Stable isotope evidence for groundwater regions of the Kabul Basin

In this arid environment, none of the isotopic compositions of the groundwater samples indicated substantial evaporation except for samples collected from a single karez. The groundwater, karez, and spring sites can be assigned on the basis of their stable isotopic composition to seven groundwater areas (fig. 1):

1. Western Front Source Area. This groundwater appeared to be runoff such as rain and snow meltwater from the Paghman Mountains. The relative humidity of the source area is among the lowest in the Kabul Basin (approximately 70 percent).

2. Shomali subbasin. The isotopic composition of this groundwater indicated that it was not recharged from modern Istalef River water, but from a source where the relative humidity was higher than 70 percent.

3. Deh Sabz subbasin. The stable hydrogen and oxygen isotopic compositions of these groundwater samples are similar to those of samples from the Kabul River at Tang-i-Gharu and Logar River.

4. Eastern Front Source Area. This water is similar in isotopic composition to that of the Western Front Source Area, possibly because the source of recharge in both areas is the adjacent mountains. The relative humidity of the source area is among the lowest in the region (approximately 70 percent).

5. Paghman and Upper Kabul subbasin. Except for samples collected from two wells, this groundwater had stable hydrogen and oxygen isotopic compositions that were similar, in geographic accord, to those of surface-water samples collected from the Kabul River at Tang-i-Gharu, the presumed source.

6. Central Kabul subbasin. This groundwater also had stable hydrogen and oxygen isotopic compositions that were very similar, in geographic accord, to those of surface-water samples collected from the Kabul River at Tang-i-Gharu.

7. Logar subbasin. This groundwater appeared to be derived from the Logar River on the basis of the similar stable hydrogen and oxygen isotopic compositions of samples collected from the two sources.

Mass Concentration Ratios, Geochemical Reactions, and Solute Origins

Chloride mass concentrations were nearly 4,200 mg/L in groundwater in the Central Kabul subbasin of the Kabul Basin. Several hypotheses for the origin of the high chloride concentrations were considered: evaporation of surface water (discussed in the preceding section on stable isotope data), geochemical water-rock reactions, dissolution of salts precipitated from evaporation of surface water, upward leakage of (presumed) deep saline water, and water uptake by vegetation (transpiration). These hypotheses are discussed in detail in Appendix 12. Table 6 summarizes average solute concentrations, stable isotope data, and tritium data for groundwater from the seven groundwater-source regions (fig. 1) and compares average solute concentrations in groundwater to average concentrations surface water in each region.

Mass concentration ratios of some of the dissolved solutes to dissolved chloride in groundwater were similar to the same ratios in surface-water samples from particular subbasins. This similarity is demonstrated most consistently in the data for dissolved sodium and sulfate, and to a lesser extent in the data for dissolved magnesium (fig. 24). Ratios in groundwater sampled in other subbasins were less similar to the surface-water ratios, and those differences can be attributed to common water-rock reactions, including calcite precipitation or removal or addition of Ca and HCO_3 by dissolution; cation exchange (Ca and Mg uptake and release of Na); gypsum dissolution (addition of Ca and SO_4); and sulfate reduction (removal of SO_4). The similarity of the mass ratios of the more conservative solutes (Na, SO_4, Mg) to chloride in groundwater to the same ratios for surface water, together with the isotope data, suggests a surface-water source for many of the groundwater samples. Plots that show solute

Table 6. Summary of average selected water-quality parameters measured in samples from groundwater and surface water from the Kabul Basin by groundwater region, 2004-2007.

[m, meters; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; Alk, titration alkalinity; $\delta^{2}H$, delta deuterium; $\delta^{18}O$, delta oxygen-18; TU, Tritium unit; na, not applicable; <, less than]

Region	No.	Well depth (m)	Sample water level (m)	Water temp. (°C)	Specific conduc-tance (µS/cm)	pH field	O_2, mgL	Total coli	*E. coli*	NO_3 N, mg/L	Ca, mg/L	Mg, mg/L	Na, mg/L	K, mg/L	Alk, mg/L as $CaCO_3$	Cl, mg/L
Ground water																
Central Kabul	66	52.8	14.5	16.9	2,210	7.6	5.9	391	9	10.3	91.6	112.0	265.0	10.3	309.5	409.6
Deh Sabz	19	54.4	17.9	17.1	1,152	7.5	7.2	469	43	4.1	63.8	42.9	81.5	3.3	213.4	81.5
Eastern Front Source Area	11	114.1	25.0	17.3	496	7.9	4.1	2	45	1.8	51.2	26.3	27.5	1.8	217.0	12.1
Logar	27	39.5	7.9	14.8	1,275	7.7	5.3	297	18	4.1	52.5	88.3	102.9	6.5	432.8	103.6
Paghman and Upper Kabul	36	50.7	14.6	15.0	734	7.6	9.1	128	9	4.9	98.1	36.3	60.0	4.3	248.3	38.6
Shomali	26	66.9	16.4	15.1	717	7.4	8.7	348	8	3.4	74.1	27.5	31.4	4.5	260.1	27.7
Western Front Source Area	21	38.3	12.0	14.5	498	7.4	6.7	604	11	7.1	65.8	15.9	11.0	3.0	200.2	11.8
Surface water																
Central Kabul	12	na	na	11.2	662	8.8	nd	2,420	2,420	3.0	52.0	29.1	34.5	4.2	228.5	35.0
Logar	11	na	na	8.4	661	8.7	nd	1,120	162	2.1	51.7	37.5	42.3	3.9	266.1	40.5
Paghman and Upper Kabul	22	na	na	9.0	294	8.6	nd	765	215	1.6	29.3	6.5	6.1	1.5	94.9	5.5
Shomali [1]	34	na	na	9.1	323	8.5	nd	1,168	1,252	1.6	32.8	11.1	18.8	3.5	104.1	23.6

Region	No.	SO_4, mg/L	F, mg/L	Br, mg/L	SiO_2, mg/L	As, µg/L	B, µg/L	Li, µg/L	Se, µg/L	Sr, µg/L	U, µg/L	V, µg/L	Zn, µg/L	$\delta^{2}H$ x 1,000	$\delta^{18}O$ x 1,000	Trit-ium, TU
Ground water																
Central Kabul	66	363.4	0.42	0.83	27.3	2.2	1,217	142	4.6	2,143	12.2	7.1	227	-56.5	-8.7	9.5
Deh Sabz	19	163.7	0.41	0.36	26.4	1.6	495	30	3.1	1,503	8.9	7.7	116	-57.2	-8.8	7.6
Eastern Front Source Area	11	54.9	0.25	0.11	15.8	1.3	75	9	1.4	794	5.2	3.3	39	-53.6	-9.1	9.0
Logar	27	128.2	0.47	0.30	26.5	3.1	1,444	219	4.4	1,452	9.8	4.5	169	-55.5	-8.4	10.8
Paghman and Upper Kabul	36	44.9	0.25	0.13	22.1	1.7	398	55	4.4	1,386	5.6	3.0	178	-53.3	-8.6	12.4
Shomali	26	44.9	0.25	0.12	24.2	0.8	217	40	1.0	834	6.8	6.6	283	-52.0	-8.5	13.4
Western Front Source Area	21	8.3	0.19	0.06	22.7	0.5	57	13	0.3	545	3.0	4.7	125	-50.5	-8.6	12.7
Surface water																
Central Kabul	12	49.4	0.22	0.10	14.3	3.9	494	86	2.0	494	3.3	3.6	2.7	-57.3	-8.9	8.2
Logar	11	53.9	0.28	0.10	15.4	3.0	674	128	1.8	643	4.6	3.2	3.1	-59.7	-9.1	7.1
Paghman and Upper Kabul	22	8.7	0.10	0.10	9.4	1.6	140	17	<1	128	0.5	1.0	3.0	-54.7	-9.1	9.4
Shomali [1]	34	31.3	0.10	0.11	10.3	1.1	271	35	2.0	307	2.4	2.9	5.3	-56.3	-9.3	10.1

[1] Panjsher River samples included with Shomali Basin samples for this analysis.

ratios for calcium and bicarbonate (appendix 12) indicate some departures from the ratios for surface water. The patterns of the Na, SO_4, and Mg solute ratios relative to chloride in groundwater (red symbols on fig. 24 for wells with a depth range of 5 to 185 m and a median depth of 48 m) and surface-water samples are similar to those for samples from relatively deep waters of the Kabul Basin (green cross symbols on fig. 24 for the former USSR PASSPORT wells with a depth range of 172 to 654 m and a median depth of 267 m) and for one sample from the recently drilled Japan International Cooperation Agency (JICA) Test Well 1 (purple point on fig. 24 for a well with total depth 640 m) (Japan International Cooperation Agency, 2007a, b). The similarity in solute ratios between waters from deep and shallow wells and surface waters suggests that infiltrated surface water has reached depths of at least 650 m in the Kabul Basin, presumably on a time scale of thousands of years. Departures in solute ratios in groundwater from those observed in surface water can be attributed to common water-rock reactions.

The chemical, stable isotope, and environmental-tracer data indicate that the infiltration of surface water is the most likely source of recharge for most of the groundwater in the Kabul Basin. In irrigated agricultural areas where pumps are used to deliver irrigation water, groundwater may be moved through multiple cycles of pumping, irrigation, and return flow to the water table; these cycles further elevate the dissolved solute concentration. The average solute mass concentrations in groundwater are increased during irrigation and infiltration cycles relative to those of local surface water by factors of 3.3, 1.9, 2.5, and 2.2 for the Central Kabul, Logar, Paghman and Upper Kabul, and Shomali subbasins, respectively.

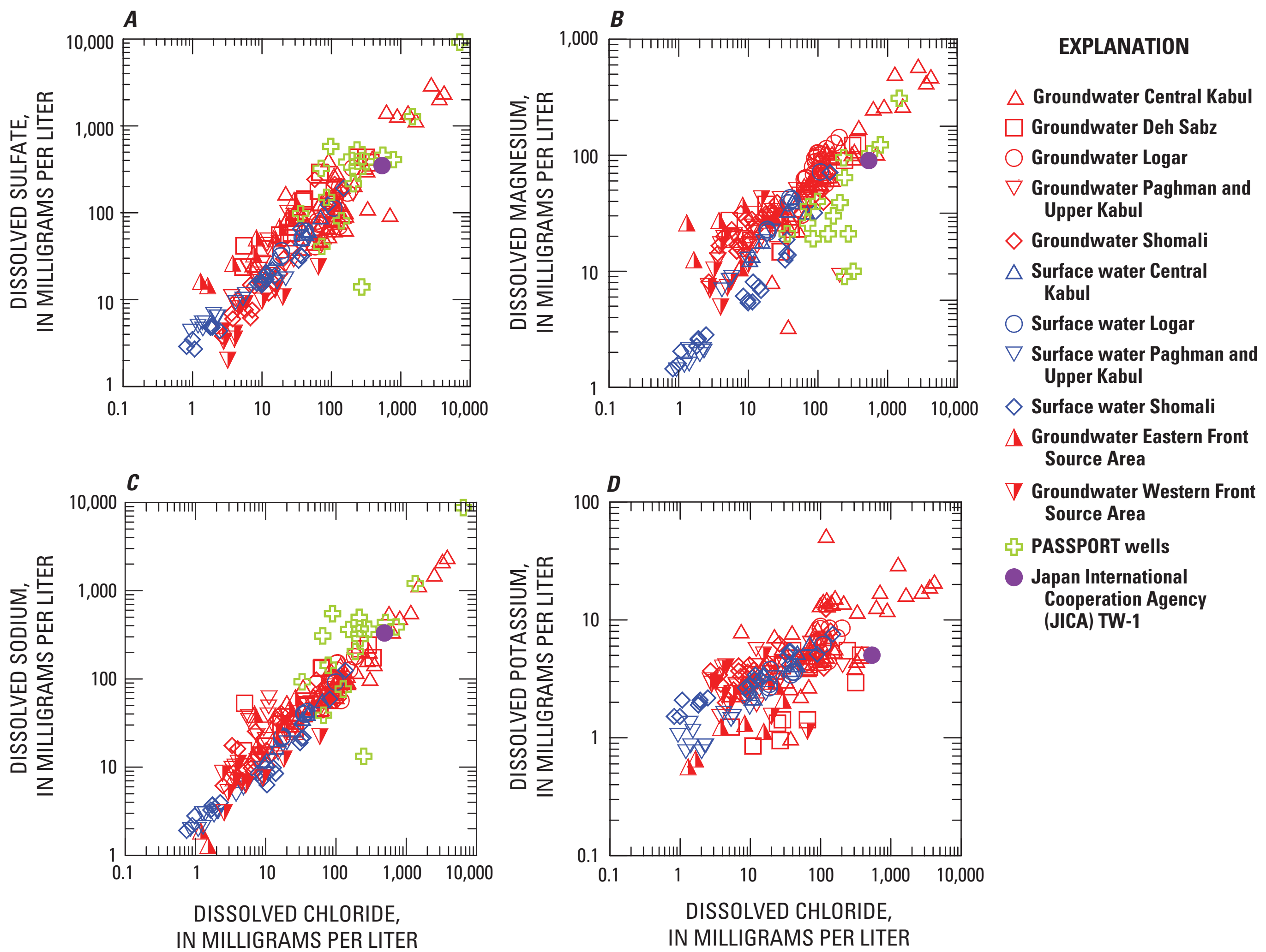


Figure 24. Mass concentrations of dissolved (A) sulfate, (B) magnesium, (C) sodium, and (D) potassium in surface water (blue), shallow groundwater (red), and deep groundwater (green and purple) from the Kabul Basin as a function of dissolved chloride mass concentration. The concentrations in water sampled from the PASSPORT wells in (C) are for sodium and potassium combined; concentrations of potassium were not determined separately for water from the PASSPORT wells.

Origin of dissolved solutes in the Kabul Basin groundwater

1. The average ratios of concentrations of some of the dissolved major solutes (particularly Na and SO_4) to chloride are similar to the corresponding average ratios in surface water; this similarity suggests that surface water is the predominant source for most of the groundwater sampled in the basin to depths of at least 650 m.
2. Variations in the concentration ratios for other solutes (particularly Ca, HCO_3, and to some extent Mg) indicate a relatively small effect by common water-rock reactions, including calcite precipitation and cation exchange in shallow groundwater.
3. Higher ratios of silica to chloride in groundwater relative to surface water indicate dissolution of primary silicate minerals or other siliciclastics that are abundant in the rocks and alluvial deposits of the Kabul Basin.
4. Arsenic appears to be partially removed by geochemical processes in the groundwater environment—probably by sorption on iron-manganese oxyhydroxides.
5. CFCs and tritium were detected in all of the 35 groundwater samples analyzed for CFCs and tritium, even in samples with chloride mass concentrations greater than 2,000 mg/L; this result indicates a young (post-1950s) source of water recharging the shallow groundwater system.
6. Solute concentrations in many groundwater samples exceeded those measured in surface water by factors of as much as 100 or more. Because there is no evaporative signal in the stable isotope data, the high solute content is attributed to extraction of water by vegetation (transpiration) along the rivers and surface-water drainage areas and near irrigated crop land, where plant-root systems can reach the water table. Transpiration removes water without altering the stable isotopic composition of the residual water; thus, the solutes are concentrated without a detectable shift in stable isotopic composition.

Chlorofluorocarbons and Tritium in Groundwater and Surface Water

Mass fractions (pg/kg) of CFC-11, CFC-12, and CFC-113 were measured to obtain information on groundwater ages (International Atomic Energy Agency, 2006). Groundwater was sampled from 35 wells between May 2006 and June 2007; from 6 springs in May and June 2006; and from 14 surface-water sites in February and June 2007 (fig. 6). CFCs also were determined in 6 air samples, all from the Kabul region. Tritium, ^{3}H (^{3}H concentration greater than 0.5 TU, where 1 TU is $n(^{3}H) / n(^{1}H)$ of 10^{-18} mol/mol), was determined in 45 water samples from wells and springs and in 7 surface-water samples. Additional tritium measurements completed late in this study are included in appendix 10; these data are consistent with the rest of the tritium collected in this study. The presence of tritium indicates waters that are post-1955 in age or waters that are mixtures of old (pre-1955) water with post-1955 water. The presence of CFC-11 or CFC-12 indicates waters that are approximately post-1945 in age or are mixtures of old (pre-1945) water with post-1945 water, and the presence of CFC-113 indicates post-1957 water, or mixtures of old (pre-1957) water with post-1957 water. All of the water samples analyzed (from the upper aquifer, springs, and surface water) contained CFCs and tritium and can be considered young water. Old water is water recharged pre 1945, young water was recharged post-1945, and modern water is water of a few years in age or residence time. The CFC and tritium data are summarized in Appendix 13.

On the basis of stable isotope and mass-concentration-ratio data (above), it was concluded that much of the groundwater sampled as a part of this study had infiltrated from rivers and streams. The CFC concentrations in groundwater recharge will be equal to the respective concentrations in surface water at time of recharge. Depending on local land-use activities at time of recharge, the streams and irrigation canals may have contained additional anthropogenic sources of CFCs, leading to a young bias in the interpreted age of the recharged groundwater. Multiple cycles of recharge and discharge of water to and from groundwater reservoirs near streams and canals can be driven by alternating low- and high-flow conditions. These processes have likely affected both tritium and CFC concentrations in Kabul Basin groundwater.

The median mass fractions of CFC-11, CFC-12 and CFC-113 in the 41 groundwater samples (35 wells and 6 springs) were 309, 221, and 39 pg/kg, respectively, corresponding to volume fractions of 150, 474, and 45 parts per trillion (ppt). In unmixed samples (samples not diluted by mixing with old water), these median CFC volume fractions correspond to median groundwater ages of 30, 21, and 21 years, respectively. The lowest CFC volume fractions in any one groundwater sample (well 54) were 64, 165, and 20 ppt for CFC-11, CFC-12, and CFC-113, corresponding to piston-flow ages of 36, 35, and 28 years, respectively. Because most of the samples are pumped from open boreholes, the CFC mass fractions are measured in mixed water, and thus the interpreted age reflects this mixture. In this case, the age is referred to as the median or apparent age. (See appendix 13 for further discussion of the interpretation of ages based on environmental-tracer data collected from samples of mixed water).

The median tritium concentration in the groundwater samples was 11.0 TU. It is estimated that modern precipitation in the Kabul Basin contains about 8 to 9 TU. The slightly higher value for groundwater suggests the presence of some water from the 1960s to mid-1980s with tritium concentrations higher than are measured in precipitation. In addition, the concentrations of tritium in groundwater decrease with time because the isotope is radioactive (half-life of 12.32 years; Lucas and Unterweger, 2000). Because of radioactive decay, the average tritium concentration of any groundwater sample derived from precipitation recharged since about 1982 in the Kabul Basin would be about 8 TU if measured today; however, because of the release of tritium to the atmosphere from atmospheric testing of nuclear weapons peaked in 1963, groundwater recharged between 1963 and 1964 would contain several hundred TU today, if not diluted or otherwise mixed. The ranges of tritium concentrations measured are 0.4 to 20.1 TU for groundwater, 11 to 18 TU for water from springs, and 6.5 to 11.2 TU for surface water. If the water samples are from the mid-1960s, then they have been diluted by mixing with older, low-tritium water. An alternate explanation is that the water samples might contain relatively high fractions of younger post-1970s water and thus lower concentrations of tritium.

Overall, it appears that most of the groundwater samples from the Kabul Basin are relatively young, as they contain CFCs and tritium, or are mixtures that contain a young fraction. Most appear to have infiltrated from streams and rivers within the past 30 years, but they have been affected by mixing processes. Groundwater age increases with depth below the water table (fig. 25); however, the results for one sample (from the Eastern Front Source Area) did not follow the general depth and age trend. This sample was from a deep well at the eastern area of the Deh Sabz subbasin where there is likely to be relatively little direct recharge and no recharge from irrigation leakage. The anomalously young age of this sample indicates a source of rapid recharge from groundwater inflow from the adjacent Kohe Safi Mountains.

The observed depth-age gradients suggest infiltration rates, adjusted for an assumed porosity of 25 percent, of 0.35 to 0.7 m/yr. Using an assumed porosity of 30 percent, a recharge rate of 0.4 to 0.8 m/yr was estimated. These rates are considerably higher than estimated basinwide recharge rates because the samples were collected primarily from irrigated areas where infiltration of surface water may locally contribute a large portion of the total recharge, and probably are not representative of the basinwide recharge rate.

Groundwater ages in the Kabul Basin

1. All of the water samples analyzed (from groundwater, springs, and surface water) contained CFCs and tritium, and therefore at least a fraction of the sampled water had been recharged since the 1950s.
2. Of the 41 groundwater samples (from 35 wells and 6 springs) analyzed for CFCs, the median apparent age was 21 years based on volume fractions of CFC-12 and CFC-11
3. The oldest water, with an apparent CFC age of 28–36 years, was from well 5
4. Tritium concentrations ranged from 4 to 21 TU in groundwater, 11 to 18 TU for water from springs, and 5 to 12 TU for surface water, and indicate that the groundwater samples likely contain relatively high fractions of post-1970s water.
5. Today the CFC concentrations in local surface waters are in near equilibrium with the modern atmosphere, but in the past there may have been local inputs of CFC-12 and CFC-11 that resulted in enrichment with respect to CFC-12, and to a lesser extent, CFC-11, as was measured in some of the groundwater samples.
6. The results suggest that little modern water was sampled. Most of the samples either predate the turnover in CFC air curves in the early 1990s or are dilutions of young water.
7. Seventeen groundwater samples were interpreted as mixtures of young and old water on the basis of CFC-113 and CFC-12 and found to contain relatively high fractions of young water with ages of 16 to 21 years. The fraction of young water in mixtures decreases with depth below the water table.
8. The average piston-flow ages based on CFC-12 concentrations range from 20 years (Paghman and Upper Kabul subbasin) to 28 years (Deh Sabz and Central Kabul subbasin), and from 15 to 19 years (Shomali subbasin) to 26 years (Central Kabul subbasin) based on CFC-113 concentrations (table 7). The ratio-based ages are slightly younger than the piston-flow ages (table 7).
9. Age gradients imply a vertical component of recharge of 0.35 to 0.7 m/yr, for an assumed porosity of 25 percent, infiltration of water beneath streams and rivers.

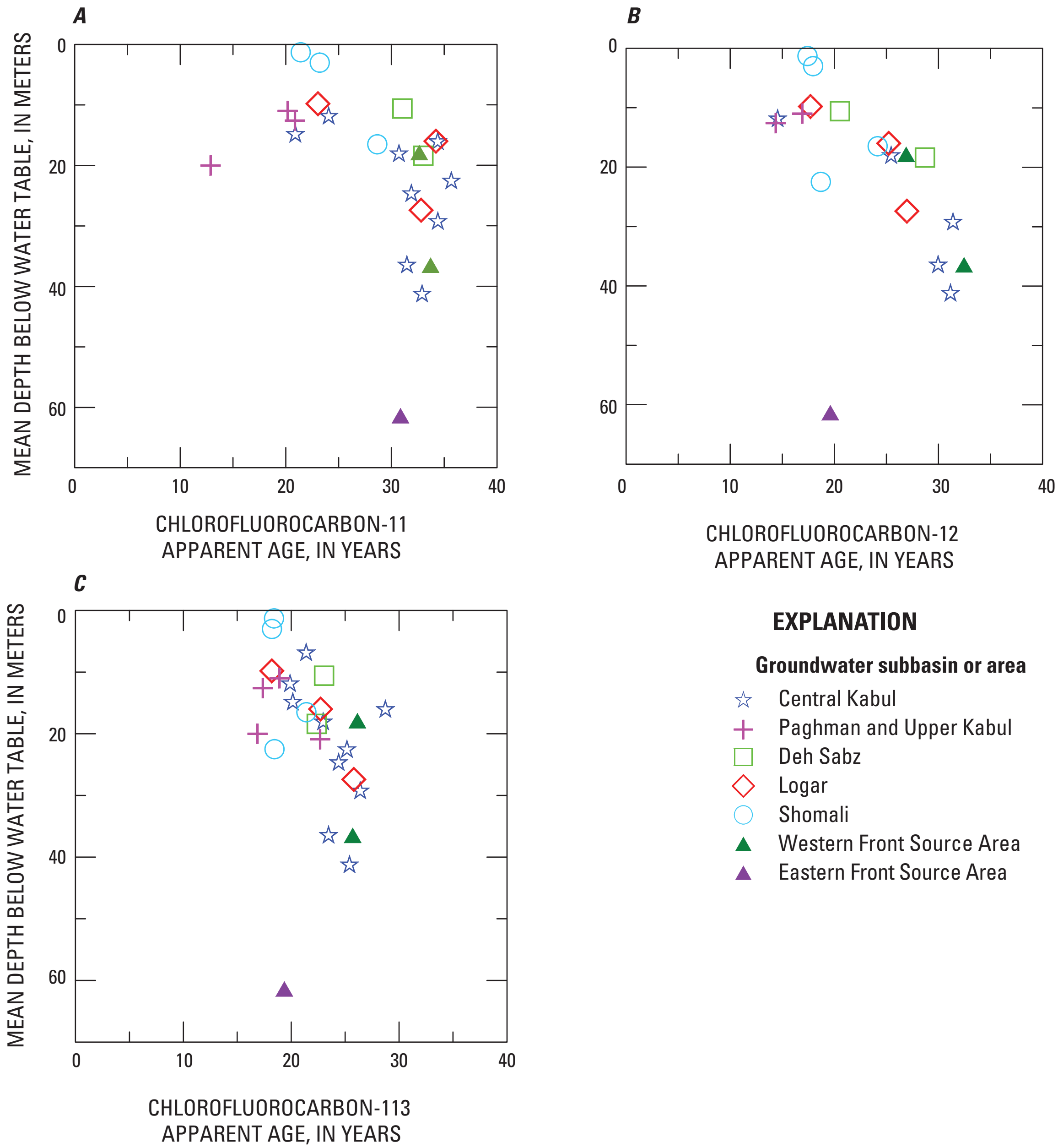


Figure 25. Apparent (piston-flow) ages as a function of depth below the water table. Symbols are at the midpoint of the saturated interval intercepted by the well. The ages were based on (A) CFC-11, (B) CFC-12, and (C) CFC-113.

Table 7. Summary of average ages, percentages of young water, and percentages of modern water, based on concentrations of chlorofluorocarbons and tritium in groundwater and water from springs by subbasin and source area in the Kabul Basin, Afghanistan.

[Location of basins shown on figure 6. CFC, chlorofluorocarbon; CFC-11, trichlorofluoromethane; CFC-12, dichlorodifluoromethane; CFC-113, trichlorotrifluoroethane; TU, Tritium Unit]

Groundwater subbasin or area	Average piston flow ages in years[1]			Average ratio-based ages and percent young water [1]				Average percent modern[2]			Tritium in TU
	CFC-11	CFC-12	CFC-113	Age from CFC-113/CFC-12 ratio	Percent young water from CFC-113	Age from CFC-113/CFC-11 ratio	Percent young water from CFC-113	CFC-11	CFC-12	CFC-113	
Eastern Front Source Area	30	21	20	20	95	11	84	55	81	67	6.1
Western Front Source Area	28	23	21	23	77	17	71	85	86	68	12.0
Shomali	23	21	19	15	87	14	81	86	88	81	13.5
Deh Sabz	33	28	24	20	61	16	80	38	52	40	7.6
Central Kabul	34	28	26	17	66	18	65	63	394	39	8.4
Paghman and Upper Kabul	22	20	20	21	55	14	77	89	162	72	12.1
Logar	27	21	21	22	92	14	75	65	79	67	10.4

[1] Averages of all samples that could be dated using CFCs, excluding CFC contaminated samples.

[2] Average of all samples that could be dated using CFCs, including CFC contaminated samples.

Water Use

There is little to no direct data available for quantification of water use in the Kabul Basin. Water use in the Kabul Basin can be grouped into two main categories, domestic and agricultural. Total annual agricultural water use in the Kabul Basin is likely to be an order of magnitude greater than total annual domestic water use.

Municipal and Domestic

Total current domestic water use was estimated from the estimated population and an assumed annual average per person water-use rate of 30 L/d (11 m^3/yr) in rural areas and 40 L/d (15 m^3/yr) in the city of Kabul (table 3). Subkilometer-scale population estimates developed by the Oak Ridge National Laboratory's LandScan (2007) project for 2004 (Bhaduri and others, 2002; Dobson and others, 2000) were used to distribute population and water-use estimates spatially in the Kabul Basin. The LandScan population estimates were based on available census counts and modeled relations between population and land cover, roads, and nighttime lights. Estimated population counts by GIS 1-km grid cell (fig. 26) ranged from 0 to 10 in rural areas to about 62,000 in urban areas and were used to estimate total domestic water use at the kilometer scale. The current population patterns in the Kabul Basin (fig. 26) reflect locations where water is more readily available from karezes, streamflow diversions, or shallow groundwater. Presently there are no wastewater systems in the Kabul Basin, water used is returned on site or in nearby drainage ditches.

The future population is estimated to increase at a rate of 4 percent per year through 2012 (Mr. Rashid Fakhri, Central Statistics Office, written commun., 2007). This high rate of population growth is likely caused in part by many refugees returning to the Kabul area. The population of Kabul is expected to continue to grow, but estimates of population beyond 2012 were not available from provincial or national planners. The United Nations Population Division estimates a national population-growth rate of less than 1 percent per year and a total population for Afghanistan of 97 million by 2050 (United Nations Population Division, accessed July 16, 2008, at http://unstats.un.org/pop/dVariables/DRetrieval.aspx). The population of Kabul is currently about 10 percent of the country's total population and may continue to grow at rates greater than the national rate; however, growth projections are uncertain, and the actual growth rate will likely be a value between the provincial and countrywide rate projections. If the population grows at current rates (4 percent per year) for the next 5 years and 2 percent per year thereafter, the population in the study area may more than double from 3.3 million in 2007 to about 9 million by the year 2057.

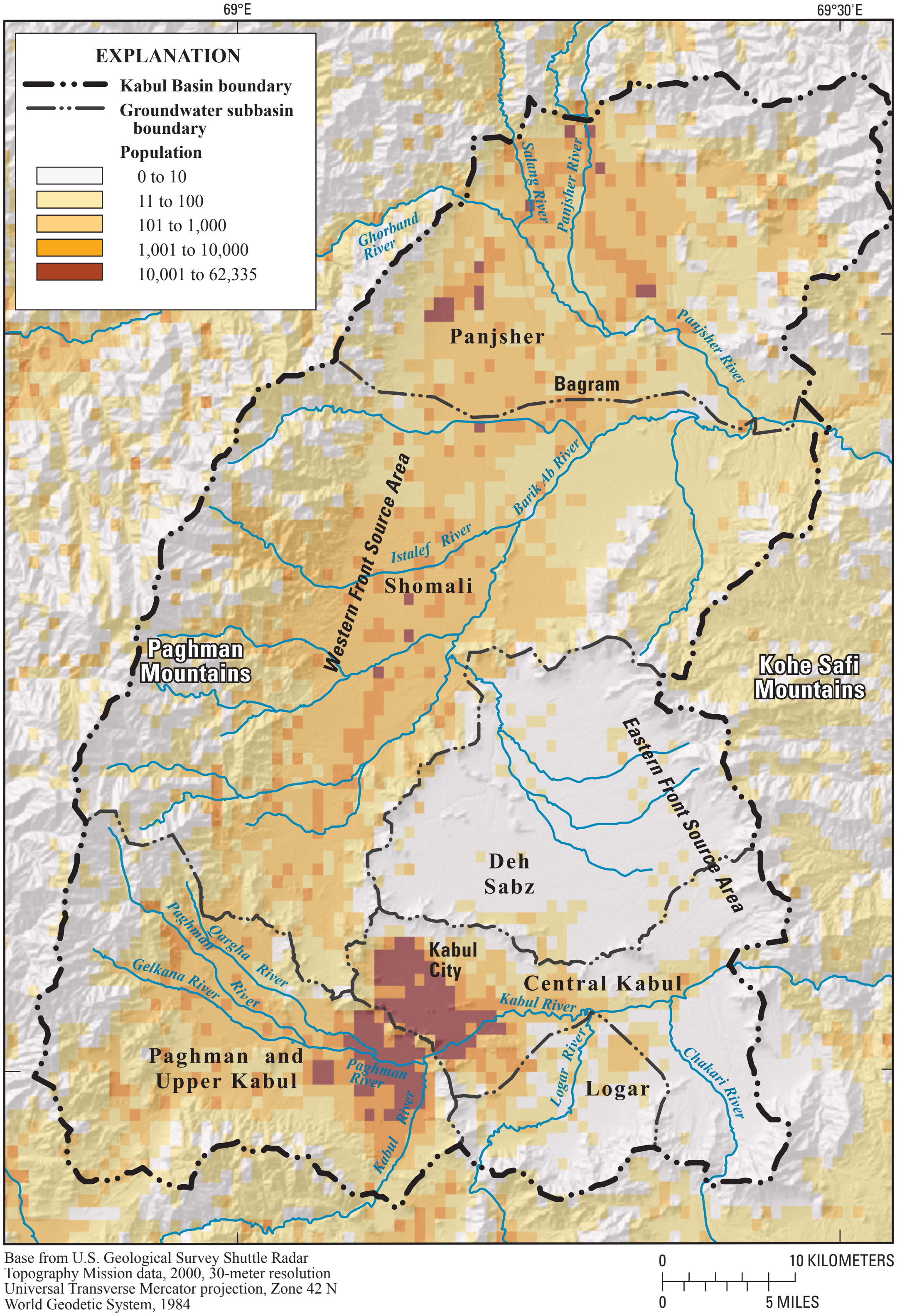


Figure 26. Estimated 2005 population in the Kabul Basin, Afghanistan (modified from Oak Ridge National Laboratory, 2007).

The per capita domestic water use may increase at a greater rate than the population because of increases in the standard of living and infrastructure. For example, the United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP) estimates that the per capita water-use rates of many other Central and West Asian countries are at least twice that of Afghanistan (accessed September 5, 2008, at http://www.unescap.org/stat/data/syb2007/26-Water-use-syb2007.asp). The per capita water-use rate used by this study, 30 L/d (or 11 m^3/yr), is about half of that estimated for Afghanistan by the UNESCAP (20.3 m^3/yr). Therefore, the per capita use rate of other nearby countries may be even greater than twice Afghanistan's rate. Under the assumptions of this investigation, the per capita water-use rate was assumed to increase 2 percent per year to 78 m^3/yr by the year 2057. The water demand for the city of Kabul has been estimated to increase to 330,000 m^3/d by the year 2025 (Lashkaripour and Hussaini, 2008). Based on the assumed population and water-use increases, municipal and domestic water use in the Kabul Basin was estimated to increase from approximately 112,000 in 2007 to 725,000 m^3/d annually by 2057. Future water use, therefore, was assumed to be about six times the current use and was distributed in proportion to current population patterns (fig. 26).

Agricultural

Irrigation water use has not been measured in the Kabul Basin. Agricultural water in Afghanistan is almost entirely supplied by streamflow diversions to irrigation canals (Banks and Soldal, 2002). In the study area, some irrigation water is supplied by karezes, but very little is supplied by groundwater withdrawals because of the lack of wells. Although many wells have been installed in the Kabul Basin, the use of groundwater for irrigation is still likely to be low because of the prohibitive cost of fuel for pumps. The amount of water used by crops, the actual evapotranspiration (AET), has been estimated by Senay and others (2007) for three major agricultural regions in the Kabul Basin (fig. 7), and water use in those regions was estimated on an annual and seasonal basis from 2000 to 2005 (Senay and others, 2007). The growing season is usually between May and September, and the 2005 season appeared to be a median year for agricultural water use in the Kabul Basin. In 2005, the total water use during the growing season for the three agricultural regions was more than 1,300 mm per region.

Irrigation efficiency in Afghanistan has been estimated to be as low as 25 to 30 percent because of leaking canals, evaporation losses, and inefficient terracing (Banks and Soldal, 2002). For example, Böckh (1971) attributes a 38-percent decline in flow in a reach of the Logar River in October 1963 to streamflow infiltration though permeable loam sediments. Because this loss occurred after the growing season, when agricultural water use should have been low, it can be attributed primarily to infiltration. It has been estimated that annual streamflow losses compose 72 percent of total groundwater recharge (Proctor & Redfern, Int., 1972, reported by Houben and Tunnermeier, 2005). The amount of water diverted from streams for irrigation is probably much greater than the amount that is actually used by crops.

Conceptual Groundwater-Flow Simulation and Water Availability

The conceptual groundwater-flow model integrates data and results from components of this study and other investigations to describe the groundwater-flow system in the Kabul Basin and estimate water availability. Because of limited data, the simulation model was not considered fully calibrated; for this reason, the results can be considered to provide only a conceptual understanding of the groundwater-flow system and a general representation of probable groundwater-flow conditions. The model is not suitable for application on a local or site-specific scale. The model was evaluated against historical base flows and historical and current water levels to assess how reasonably it approximates general groundwater flow conditions. The components of the groundwater-flow model are shown in figure 8, and the numerical representation and simulation of the fluxes, and model limitations, are discussed in detail in Appendix 14.

Conceptual Model

Total base flows, river inflows, estimated upland drainage, and estimated direct recharge were compared to outflows at the Panjsher River at Shukhi and the Kabul River at Tang-i-Gharu from the northern and southern basins, respectively (table 8). The total inflow to the northern subbasins is about five times the magnitude of the total inflow to the southern subbasins. Most of the flows in table 8 likely represent groundwater that has moved through the aquifer system and discharged at the outlets to the basins.

Total monthly recharge has been estimated to be about 0.001 to 0.002 m/d, for February, March, and April, with no recharge assumed to occur from May through October as a result of greater ET (Houben and Tunnermeier, 2005). Recharge estimates in this study were based on the mean monthly water balance, precipitation and evapotranspiration trends, and simulated mean annual groundwater flow from the subbasins. The mean annual rate of direct recharge on subbasin surface areas, not including irrigation leakage, was estimated to be about 0.0007 m/d. A mean monthly recharge rate was estimated to range from zero from June through September, to about 0.0005 m/d in November and May, to a high of 0.002 m/d in April (table 8). Table 8 does not differentiate aquifer recharge caused by irrigation leakage from other components of recharge because this component of the water balance is in the base flows listed in the table.

Table 8. Monthly mean base flows and balance of water in the (A) northern and (B) southern subbasins of the Kabul Basin, Afghanistan.

[Streamgage locations shown on figure 4; m/d, meters per day; km^2, square kilometer; m^3/d, cubic meter per day; –, not calculated or not applicable]

(A) Northern subbasin areas - Panjsher River and Shomali subbasins													
		Base flow at Gorband River	Base flow at Salang River	Base flow at Panjsher River at Gulbahar	Base flow at Shatul River	Total base flows	Upland drainage at Western Front[1]	Estimated recharge on subbasin surfaces[2]	Total Inflows	Outflow base flow at Panjsher River Shuki	Difference between flows in and recharge, and flow out[3]		Loss estimated actual evapo-trans - piration
Drainage or surface area		4,032 (km^2)	435 (km^2)	3,538 (km^2)	202 (km^2)		321 (km^2)	1,698 (km^2)		10,857 (km^2)		Inflow as a percent of outflow	700 (km^2)
Month	Recharge rate (m/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(percent)	(m^3/d)
October	0	767,703	290,363	1,488,090	28,455	2,574,611	30,145		2,604,757	2,382,786	221,970	109	0
November	5.1E-04	877,824	258,792	1,240,996	20,274	2,397,886	16,516	849,000	3,263,402	2,508,174	755,228	130	0
December	1.0E-03	840,068	243,078	1,050,498	16,758	2,150,402	12,341	1,698,000	3,860,743	2,783,094	1,077,649	139	0
January	1.0E-03	748,825	223,430	900,032	18,096	1,890,384	17,197	1,698,000	3,605,581	2,922,885	682,696	123	0
February	1.5E-03	744,322	256,248	886,425	27,922	1,914,917	33,375	2,547,000	4,495,292	2,631,050	1,864,242	171	0
March	1.5E-03	1,131,496	613,754	1,086,389	126,620	2,958,259	196,602	2,547,000	5,701,862	2,973,717	2,728,144	192	0
April	2.0E-03	2,509,114	1,654,895	2,302,261	503,230	6,969,499	814,661	3,396,000	11,180,160	6,605,295	4,574,864	169	0
May	5.1E-04	4,185,710	2,151,822	5,516,150	780,390	12,634,072	1,272,763	849,000	14,755,835	12,479,446	2,276,389	118	1,929,503
June	0	4,924,349	2,209,309	12,573,996	1,097,143	20,804,796	1,825,734	–	22,630,531	18,266,334	4,364,197	124	2,374,715
July	0	2,771,753	1,227,033	10,997,789	624,653	15,621,228	1,065,607	–	16,686,835	13,032,252	3,654,582	128	2,543,911
August	0	1,078,638	564,093	4,531,912	194,767	6,369,410	323,708	–	6,693,118	4,613,074	2,080,044	145	2,311,418
September	0	725,424	353,322	2,112,545	47,229	3,238,521	67,318	–	3,305,838	2,606,662	699,176	127	1,825,513
Annual mean	6.7E-04	1,775,435	837,178	3,723,924	290,461	6,626,999	468,686	1,940,571	8,231,996	6,150,398	2,081,599	134	915,422
median	–	–	–	–	–	–	–	–	5,098,577	2,948,301	–	–	–

Table 8. Monthly mean base flows and balance of water in the (A) northern and (B) southern subbasins of the Kabul Basin, Afghanistan.—Continued

[Streamgage locations shown on figure 4; m/d, meters per day; km^2, square kilometer; m^3/d, cubic meter per day; –, not calculated or not applicable]

(B) Southern subbasin areas - Paghman, Kabul, and Logar River subbasins

Month	Recharge rate	Base flow at Paghman River	Base flow at Kabul River at Tangi Saidan	Base flow at Logar River	Base flow at Chakari River	Total base flows	Rivers and uplands	Estimated recharge on subbasin surfaces[2]	Total inflows	Outflow base flow at Kabul River at Tangi Gharu	Difference between flows in and recharge, and flows out[3]	Inflow as a percent of outflow	Loss estimated actual Eeapo-trans-piration
Drainage or surface area		424 (km^2)	1,663 (km^2)	11,461 (km^2)	302 (km^2)			780 (km^2)		14,556 (km^2)			110 (km^2)
	(m/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)		(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(percent)	(m^3/d)
October	0	6,948	30,837	197,697	26,724	262,207	–		262,207	159,020	103,187	165	0
November	5.0E-04	16,682	77,070	607,755	28,126	729,633	–	390,000	1,119,633	598,598	521,035	187	0
December	1.0E-03	31,062	125,501	993,429	12,042	1,162,035	–	780,000	1,942,035	1,113,143	828,893	174	0
January	1.0E-03	37,806	203,671	1,265,263	3,629	1,510,369	–	780,000	2,290,369	1,505,014	785,355	152	0
February	1.5E-03	39,368	223,111	1,351,579	7,853	1,621,911	–	1,170,000	2,791,911	1,716,568	1,075,343	163	0
March	1.5E-03	89,940	448,219	1,398,709	14,682	1,951,550	–	1,170,000	3,121,550	2,004,793	1,116,757	156	0
April	2.0E-03	230,948	1,206,439	1,511,726	36,649	2,985,763	–	1,560,000	4,545,763	3,028,203	1,517,560	150	0
May	5.0E-04	106,731	851,258	711,711	47,015	1,716,715	–	390,000	2,106,715	2,124,058	-17,344	99	101,554
June	0	13,362	360,894	117,465	43,468	535,190	–	–	535,190	475,357	59,832	113	140,397
July	0	8,685	69,564	64,252	32,168	174,668	–	–	174,668	130,624	44,044	134	141,450
August	0	6,369	25,817	29,655	28,766	90,607	–	–	90,607	39,755	50,852	228	129,868
September	0	6,382	24,455	35,750	27,807	94,394	–	–	94,394	41,080	53,313	230	105,298
Annual mean	6.7E-04	49,524	303,903	690,416	25,744	1,069,587	–	891,429	1,589,587	1,078,018	511,569	147	51,547
Median	–	–	–	–	–	–	–	–	1,530,834	855,870	–	–	–
							Rivers and uplands	Recharge	Total inflows	Outflows	Difference		ET Loss
Total annual mean flows							8,165,271	2,832,000	9,821,583	7,228,415	2,593,168		966,969

[1] Western Front shown on figure 1. Upland drainage calculated based on a monthly base flow per unit area for the Shatul River drainage.

[2] Assuming recharge varies from October to September as indicated in table column 2.

[3] Because of changes in storage, unknown components in the water balance, and because inflow and outflows were mean values, inflows do not necessarily equal outflows.

During the nongrowing season, October through March, aquifers in the subbasins gain water. From November through February, aquifers in the northern subbasins gain water at a rate of about 10 to 30 percent of the inflows, whereas aquifers in the southern basins gain water at a rate of about 40 percent of inflows. This water is stored in the aquifer, and it is used or discharged later in the year. From March through April, inflows are 50 to nearly 100 percent more than outflows, and the aquifer systems gain water at higher rates. During the growing season (May through September), the sum of agricultural water use (AET) and ET (in nonagricultural areas) may be equal to or greater than the difference between inflows and outflows. During September, AET water use is greater than the difference between inflows and outflows and may also be augmented by groundwater discharges to streams and karezes. Unaccounted inflows to the aquifer system are likely to occur early in the growing season as some portion of high flows (fig. 14), which are not represented by the base flows shown in table 8, are applied to irrigated areas and result in additional leakage to the aquifers. In the northern subbasins, the monthly AET water use is generally similar in magnitude to the balance of available inflows (inflows minus outflows). The monthly AET is greater than the balance of available inflows in the southern basins because of the smaller inflows and is therefore a larger component of the overall water balance than in the northern basins. Leakage in irrigated areas may also account for the monthly water-balance differences and was estimated at an annual rate to be about 0.0012 m/d. Isotopic analysis of groundwater sampled from different depths in the Kabul Basin supports a total annual recharge rate equal to direct recharge plus irrigation leakage of about 0.002 m/d.

Steady-state groundwater-flow in the aquifer system was simulated on the basis of mean annual inflows and outflows from the system (table 8). Simulated groundwater heads for the uppermost model layer, shown in figure 27A, represent the water table in the surficial aquifer, which is composed of unconsolidated Quaternary and recent sediments. Figure 27B shows simulated heads in the Neogene aquifer in the lower altitude areas and bedrock in the upland areas. The simulated groundwater heads, which were generally within 10 m of the observed groundwater levels in the lower altitude areas near the centers of the subbasins, matched regional water-level patterns well (appendix 14). Larger errors were apparent near the valley walls where some simulated levels were much lower than the observed levels. Groundwater-flow conditions are often difficult to represent accurately near valley walls or other areas with contrasts in hydrologic environments. Although heads simulated by the conceptual model may not be accurate at a local scale, the model can be used to calculate regional heads in the groundwater-flow system and the effects of changes on the system.

Recharge in the Kabul Basin varies spatially and was simulated with a mean annual rate of 0.0007 m/d for direct recharge plus an additional 0.0012 m/d in agricultural areas (table 8). Some areas of the Kabul Basin, such as the Deh Sabz or eastern Shomali subbasins, have much less water available than areas near the major rivers. For example, the western Central Kabul subbasin, the central and western Deh Sabz subbasin, and the eastern Shomali subbasin are likely to recieve very little recharge. The widely spaced water-table contours in these areas in figure 27A indicate that groundwater-head horizontal gradients are relatively low. Areas of groundwater discharge to the major rivers are also indicated by the curvature of the simulated contours (fig. 27A). In the eastern parts of the Paghman and Upper Kabul and eastern Central Kabul subbasins, groundwater discharges to the Kabul River. In the eastern parts of the Shomali and Panjsher subbasins, groundwater discharges to the Panjsher River.

In some areas near the Western and Eastern Front Source Areas, groundwater levels, perennial flow through karezes, and groundwater-sample analyses indicated that there were additional sources of groundwater inflow to the basins. Simulated groundwater levels at the Eastern Front Source Area in the Deh Sabz subbasin were low in areas where groundwater heads have been measured 20 to 40 m below land surface, and karezes are known to flow perennially. There is essentially no upland drainage from the Kohe Safi Mountains into the Deh Sabz subbasin because the surface-water drainage divide is close to the valley wall, and all surface water from this mountain range flows east to the Panjsher River outside of the Kabul Basin. Groundwater, however, flows into the eastern Deh Sabz subbasin from the Kohe Safi Mountains and was simulated in the model (fig. 8). The altitudes of the land surface at the Eastern Front Source Area, the center of the Deh Sabz subbasin, and the ridge at the edge of the valley are generally about 1,900, 1,800, and 2,500 m, respectively. Although surface drainage east of the ridge is away from the Kabul Basin, the area east of the ridgeline is higher than the Deh Sabz subbasin, and some groundwater likely flows through the sedimentary rock of the Kohe Safi Mountains to the Eastern Front. Along the Eastern Front, groundwater may flow from the Deh Sabz subbasin toward the Central Kabul subbasin (fig. 27A). Groundwater likely flows through the gaps in the ridgeline between the Deh Sabz and Central Kabul subbasins into the central area of the Deh Sabz subbasin (fig. 27A). The gaps between the ridges that separate these subbasins, where groundwater can readily flow through unconsolidated sediments, however, are narrow (about 1,000 m wide). Groundwater flow into the Deh Sabz subbasin from the Central Kabul subbasin is a small fraction of total recharge to Deh Sabz. The source of recharge in this basin is primarily infiltration of winter precipitation. Chemical analyses of groundwater samples from this area indicate little evaporative concentration, probably because depths to water are greater than in other subbasins, and vegetation is relatively sparse.

Simulated groundwater levels (fig. 27A) illustrate the effects of recharge to the surficial aquifer from leakage from perennial streams that drain into the valley from the Paghman Mountains. Chemical analyses indicate that additional sources of recharge are also likely at the Western Front Source Area adjacent to the Paghman Mountains (figs. 1 and 8). The Paghman Mountains are composed of metamorphic rocks which generally have relatively low groundwater storage and transmissivity. Because there are a number of faults along the western front of the Paghman Mountains (fig. 3), the bedrock is likely to be more highly fractured and to have higher groundwater storage and transmissivity than metamorphic rocks elsewhere in the Kabul Basin. The faulted zone at the base of the Paghman Mountains may enhance groundwater inflows to the surficial and Neogene aquifers at the Western Front as indicated by the simulated head surface in the Neogene aquifer (fig. 27B).

Estimated Water Availability

Estimating the water availability in the Kabul Basin requires estimating the balance of flow in the system. A general water balance consisting of monthly mean base flows in and out of the rivers in the Kabul Basin was calculated for the northern and southern subbasin areas (table 8). On an annual basis, base flows into the Kabul Basin are about equal to or slightly greater than base flows out of the basin. The difference may be a result of agricultural water use and ET. In the southern basins, with less agricultural use and possibly less ET, inflows were essentially balanced by outflows.

Inflow into the northern basins is from the rivers and tributaries that drain into the Panjsher River at Shukhi (fig. 13) and from precipitation to the Shomali, Deh Sabz, and Panjsher subbasins (figs. 1 and 8); inflow into the southern basins is from the rivers that drain to the Kabul River at Tang-i-Gharu and direct recharge onto the Paghman and Upper Kabul, Central Kabul, and Logar subbasins (figs. 1 and 8). Mean monthly base flows were calculated from historical streamflow-gaging data (fig. 13, appendix 8). Mean monthly base flows in perennial streams discharging from the Paghman Mountains to the Western Front Source Area (fig. 1) were calculated per unit area based on the Shatul River drainage area (fig. 13, table 2); the Shatul drainage-area baseflows represent median unit discharges for the smaller watersheds draining into the Kabul Basin. The area contributing to perennial streams draining the Paghman Mountains (321 km^2) at the Western Front (fig. 1) is slightly larger than the Shatul River drainage area (202 km^2). Upland-drainage discharge was not calculated for the Kohe Safi Mountains along the Eastern Front because of the limited upland area and lack of perennial streams.

Integrating information about the sources of recharge to the Kabul Basin with the estimates of the hydraulic properties of the aquifer and of the thickness of the unconsolidated sediments provides a conceptual representation of the potential water availability in the basin (fig. 28). Information about the components of the groundwater-flow system was incorporated into the availability analysis on the basis of the estimated contribution to the flow for each component including sediment thickness, aquifer geometry, and sediment and bedrock hydraulic properties calculated by the groundwater-flow model. This information was integrated with additional information provided by the isotopic and geochemical analysis of groundwater (appendixes 11 and 12) and model calibration (appendix 14). The components determined by this study to the be most important characteristics contributing to groundwater availability in the Kabul Basin were: sediment and bedrock hydraulic characteristics, faults and lineaments in bedrock areas, areas of streamflow leakage, irrigation leakage, groundwater inflow from the mountain fronts (represented by distance from the mountain fronts), and aquifer thickness. Components of the groundwater-flow system were assigned a relative rank of 0 for no contribution to 10 for a relatively high contribution to the flow system and were added together (by using the Weighted Sum routine in ArcMap). For example, to account for potential for sustained streamflow leakage, northern perennial streams with source areas outside the Kabul Basin, including the Panjsher River and its tributaries, were given a high rank (10); southern perennial streams with source areas outside the Kabul Basin, including the Kabul and Logar Rivers, were ranked 7; streams which originate in the Paghman Mountains were given a moderate rank (5); and ephemeral streams that drain areas with little to no upland area, such as those in the Deh Sabz subbasin, were given a rank of 0.

Simulated groundwater-head contours in the Neogene aquifer (fig. 27B) have been superimposed on the colored areas representing potential water availability to show the relation between the two parameters. More water is estimated to be available in northern areas of the Kabul Basin adjacent to the Panjsher River and its tributaries. Potential water availability is also relatively high along the Western Front Source Area as a result of stream leakage, groundwater inflows from the Paghman Mountains, and aquifer sediments that are estimated to be thick. Potential water availability in the Deh Sabz subbasin is generally low because there is essentially no stream or agricultural leakage in this area. Figure 28, however, indicates some groundwater inflow to the Deh Sabz subbasin from the Kohe Safi Mountains to the east. Potential water availability in the Central Kabul subbasin is also low, although aquifer sediments are more than 300 m thick, except where the Paghman, Kabul, or Logar Rivers and adjacent irrigated areas provide leakage to the underlying aquifer.

A **Model layer 1**

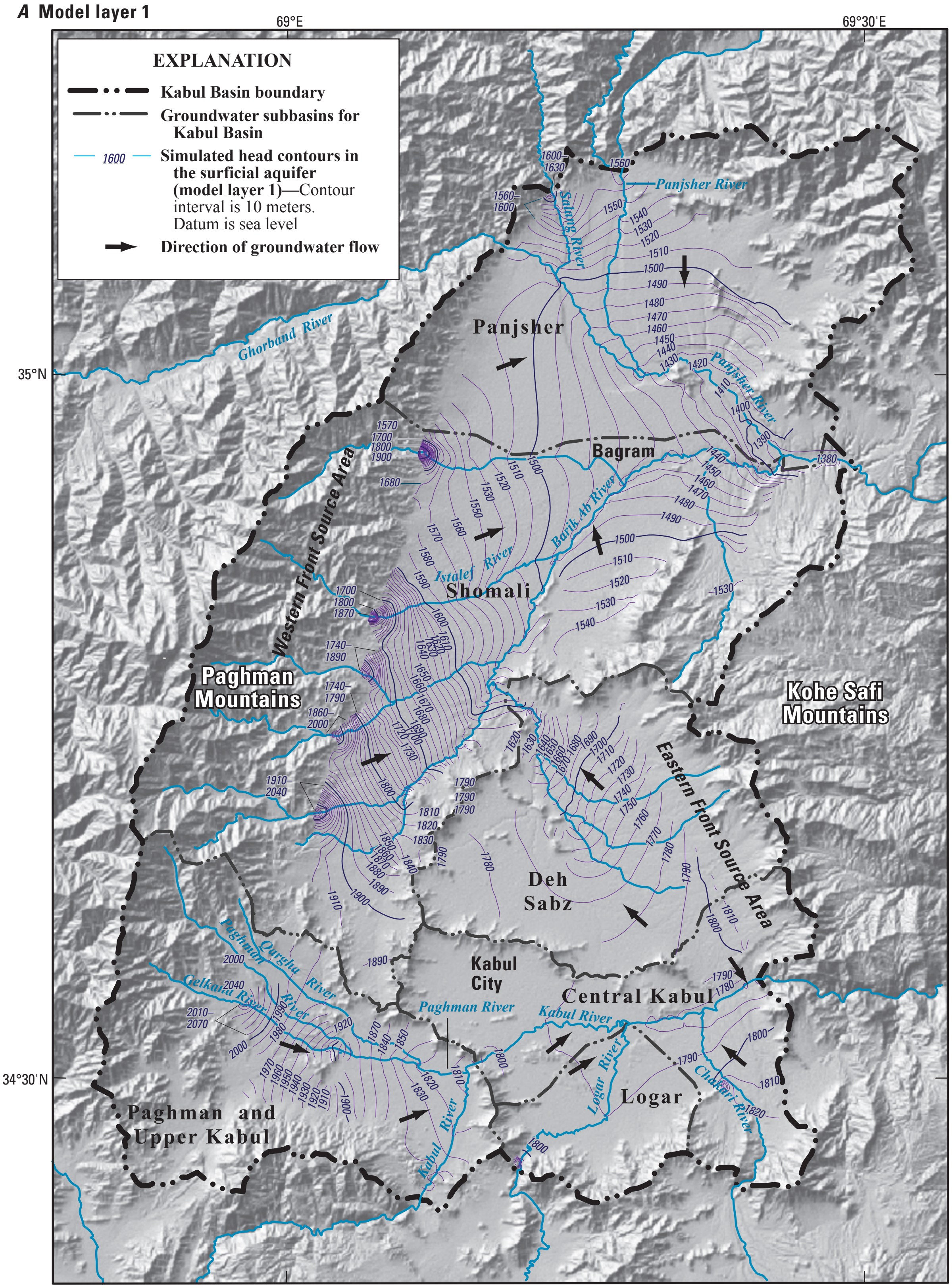
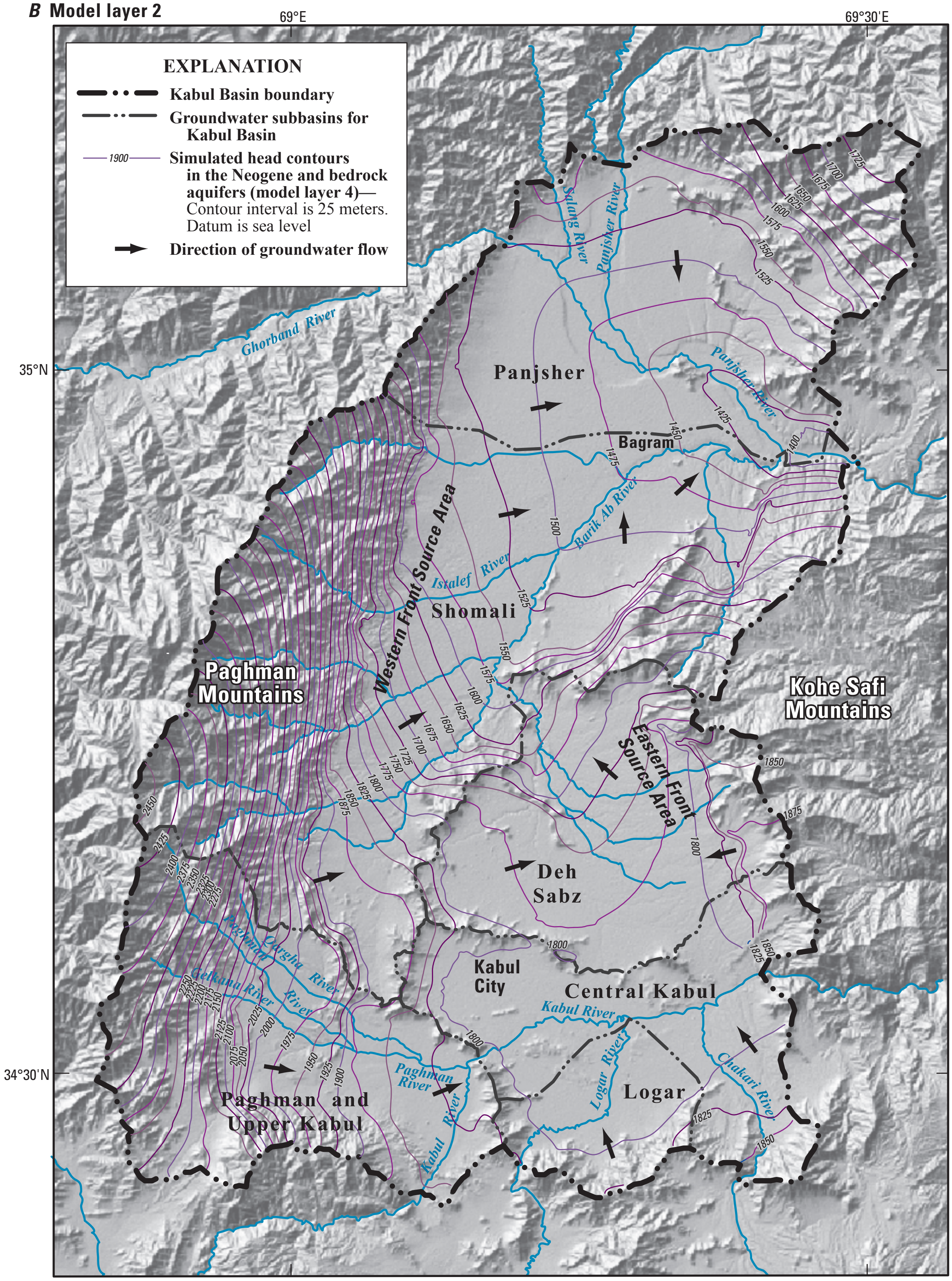


Figure 27. Simulated groundwater heads in (A) model layer 1, representing the water table in unconsolidated sediments in the subbasins, and (B) model layer 2, representing the head surface in the Neogene aquifer in the lower altitude areas and the bedrock aquifer in the upland areas of the Kabul Basin, Afghanistan.

B **Model layer 2**



Base from U.S. Geological Survey Shuttle Radar Topography Mission data, 2000, 30-meter resolution
Universal Transverse Mercator projection, Zone 42 N
World Geodetic System, 1984

0 10 KILOMETERS
0 5 MILES

Figure 27. Continued.

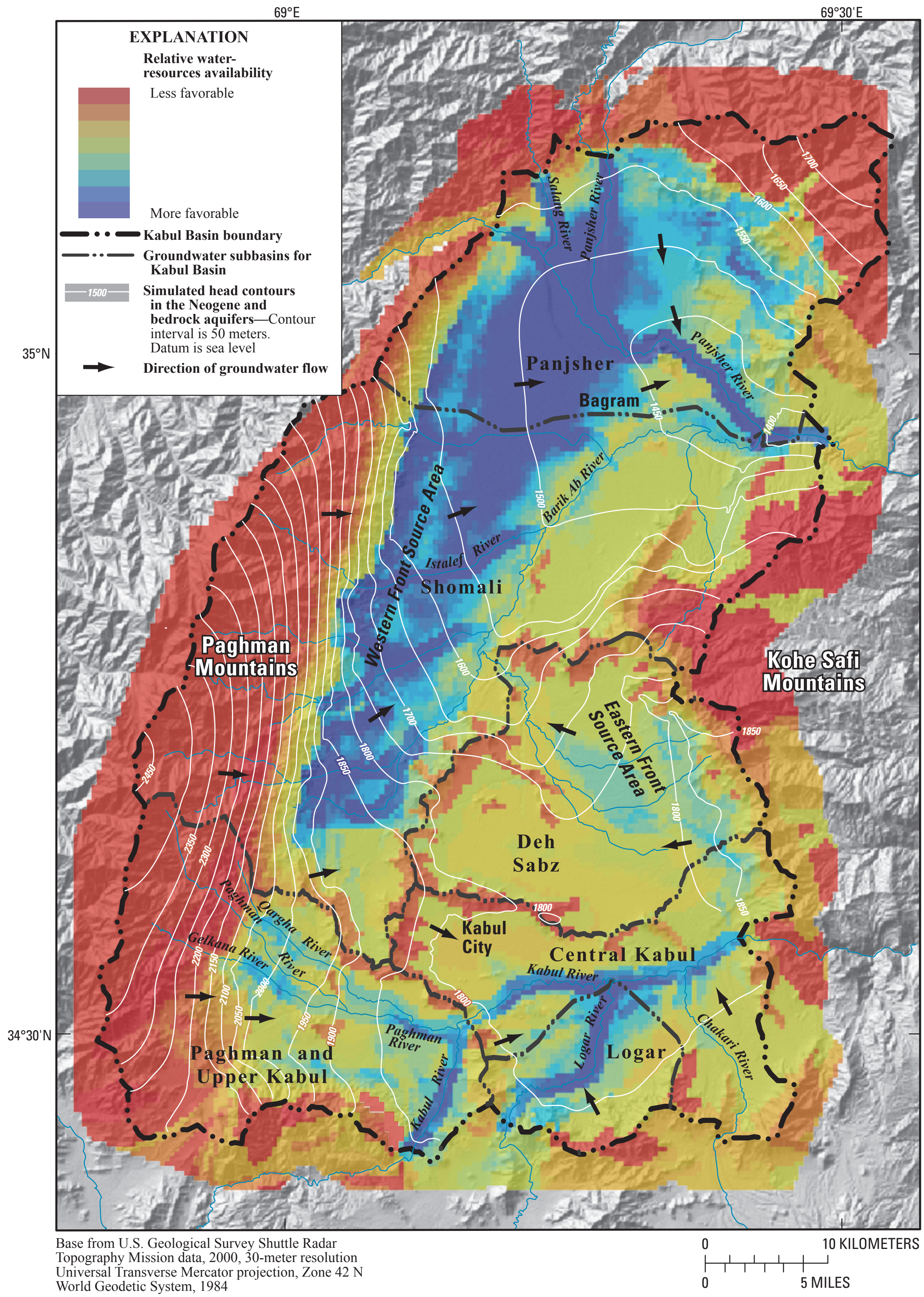


Figure 28. Water-resources availability based on an integration of estimated hydraulic properties, stream leakage, irrigation leakage, inflows from mountain fronts, and aquifer thickness in the Kabul Basin, Afghanistan.

Simulated Effects of Population Growth on Water Resources

The population in the Kabul Basin is expected to increase by 20 percent, from approximately 3.3 to 4 million, in the next 5 years. Population growth and increasing per capita water use were assumed to result in about a sixfold increase in total annual municipal and domestic water use by the year 2057. The effect of the increased 2057 population on water resources was simulated by increasing domestic and municipal withdrawals in the surficial aquifers by a factor of 6 and assuming a population distribution in the Kabul Basin similar to the recent (2005) population pattern (fig. 26). A steady-state simulation was used for future withdrawals to represent the regional long-term effects of increased withdrawals in the surficial aquifer. For purposes of this analysis and comparison of simulations, the extents of irrigated areas and the irrigation water-use rate were assumed to be the same as under current conditions. Although the amount of irrigated land area may increase or decrease in the future because of climate-related factors, the water-use rate for irrigation was held constant to isolate the effect of one variable—increasing domestic and municipal water needs—on regional water availability.

The groundwater-head contours in figure 29 show the simulated steady-state drawdown resulting from the hypothetical sixfold increase in groundwater use in the Kabul Basin. Groundwater levels in rural, less populated areas of the model were simulated to decline by about 1 m or less. In the more populated areas, declines were simulated to be more than 2 m (fig. 29). Large declines of 10 to about 40 m were simulated for the western areas of the Central Kabul subbasin (fig. 29). Presently, the water in most local supply wells is shallow, less than 10 m deep. This hypothetical scenario indicates that many such wells could possibly become dry under the simulated conditions.

Simulated groundwater-level declines were large in the western part of the Central Kabul subbasin near the interbasin ridges because this area receives very little recharge from direct precipitation, and the dense population creates the greatest water demand. The area receives some recharge from streamflow leakage; however, such leakage may not be adequate to supply the western area of Central Kabul subbasin.

The simulated groundwater declines caused by increased municipal and domestic use would be greatest in urbanized areas and would affect shallow supply wells more than deep wells. The mean depth of NGO-installed wells in the Kabul Basin is approximately 22 m, and the mean depth to water in such wells is about 12 m. Groundwater levels in the surficial aquifer typically fluctuate about 0.5 to 3 m annually in the more urban areas (Akbari and others, 2007; Safi and Vijselaar, 2007). Drawdowns of 5 to 25 m have been measured at pumped supply wells (Akbari and others, 2007). Therefore, the saturated lengths of casing or of aquifer thickness in tube wells or dug wells may typically be less than 10 m, and shallow supply wells may typically draw groundwater from only the top few meters of the aquifer. Of the more than 1,000 shallow supply wells in the Kabul Basin, more than half (54 percent) would undergo water-level declines of more than 0.5 m, and 36 percent would undergo declines of more than 1 m. Simulated groundwater-level declines caused by increased withdrawals, without the additional effect of prolonged droughts, may result in about 40 percent of existing shallow supply wells, primarily in urbanized areas, becoming seasonally inoperable or completely dry.

The withdrawals simulated in this manner may be greater than the actual withdrawals that could be obtained from the surficial aquifer at specific locations because of local geologic factors such as impermeable sediments or rock or a prohibitive depth to water. Additionally, future withdrawals are likely to be supplied by large groundwater-withdrawal operations at high-yielding areas of the aquifer system and not by the pattern of wells simulated in this analysis. This study also does not assess the placement of individual withdrawal wells but evaluates the potential hydrologic effects of increasing withdrawals from the regional aquifer.

Simulated Effects of Withdrawals from the Upper Neogene Aquifer

The potential effects of groundwater development in the Neogene aquifer were assessed by simulating additional withdrawals from hypothetical wells under steady-state conditions in the upper Neogene aquifer. The hypothetical wells were arbitrarily placed at population centers in six subbasins (at the centers of the drawdown areas shown in fig. 30), to illustrate the effects of withdrawals in different areas of the Kabul Basin and do not represent suggested or potential well locations. The simulated wells were pumped at a rate of 10,000 m^3/d from the top 100 m of the Neogene aquifer. The analysis used current (2007) estimated municipal and domestic and agricultural water-use rates from the surficial quaternary aquifer.

The effects of simulated withdrawals from the Neogene aquifer are illustrated by groundwater-level declines (fig. 30) relative to the current simulated head surface (fig. 27A) in the surficial aquifer. Simulated declines were limited by the thickness and low permeability of the upper Neogene aquifer; however, water levels in shallow supply wells would be affected in areas where declines are indicated. Simulated declines were generally less than 0.2 m in the Shomali and Panjsher subbasins. Simulated drawdowns were greater (0.4 m or more) in the smaller subbasins and in areas with less direct recharge, such as the Paghman and Upper Kabul, Central Kabul, and Deh Sabz subbasins. Nearly all shallow supply wells would be affected to some degree by the simulated withdrawals from the Neogene aquifer in these three subbasins. Simulated drawdowns in the Central Kabul and the Paghman and Upper Kabul subbasins affected a larger area than drawdowns elsewhere in the Kabul Basin because the extent of the Neogene aquifer is limited to the small area underlying these subbasins. Simulated drawdowns in the Deh Sabz subbasin affected a larger area because the recharge in this subbasin is lower than the recharge in the other subbasins.

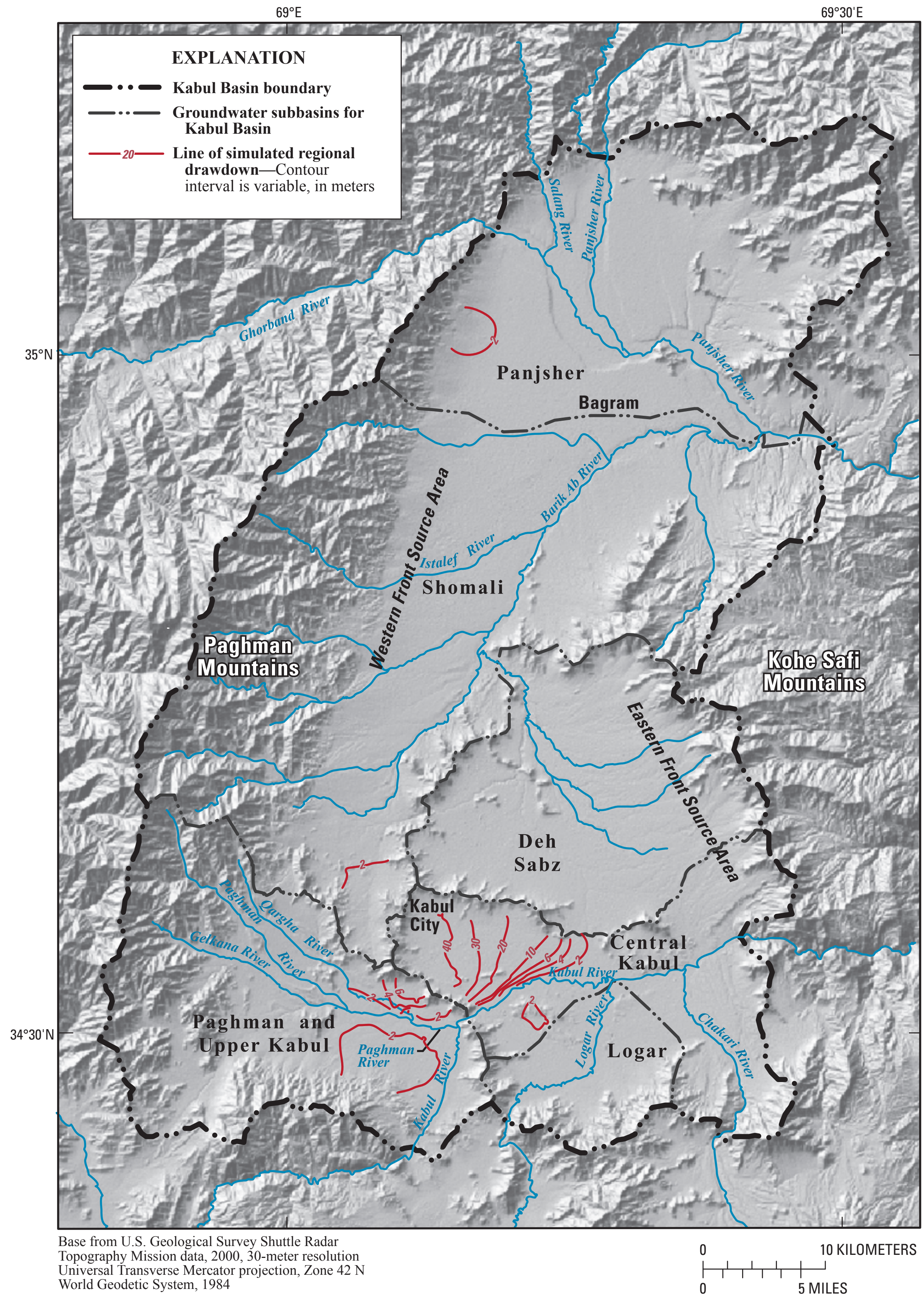
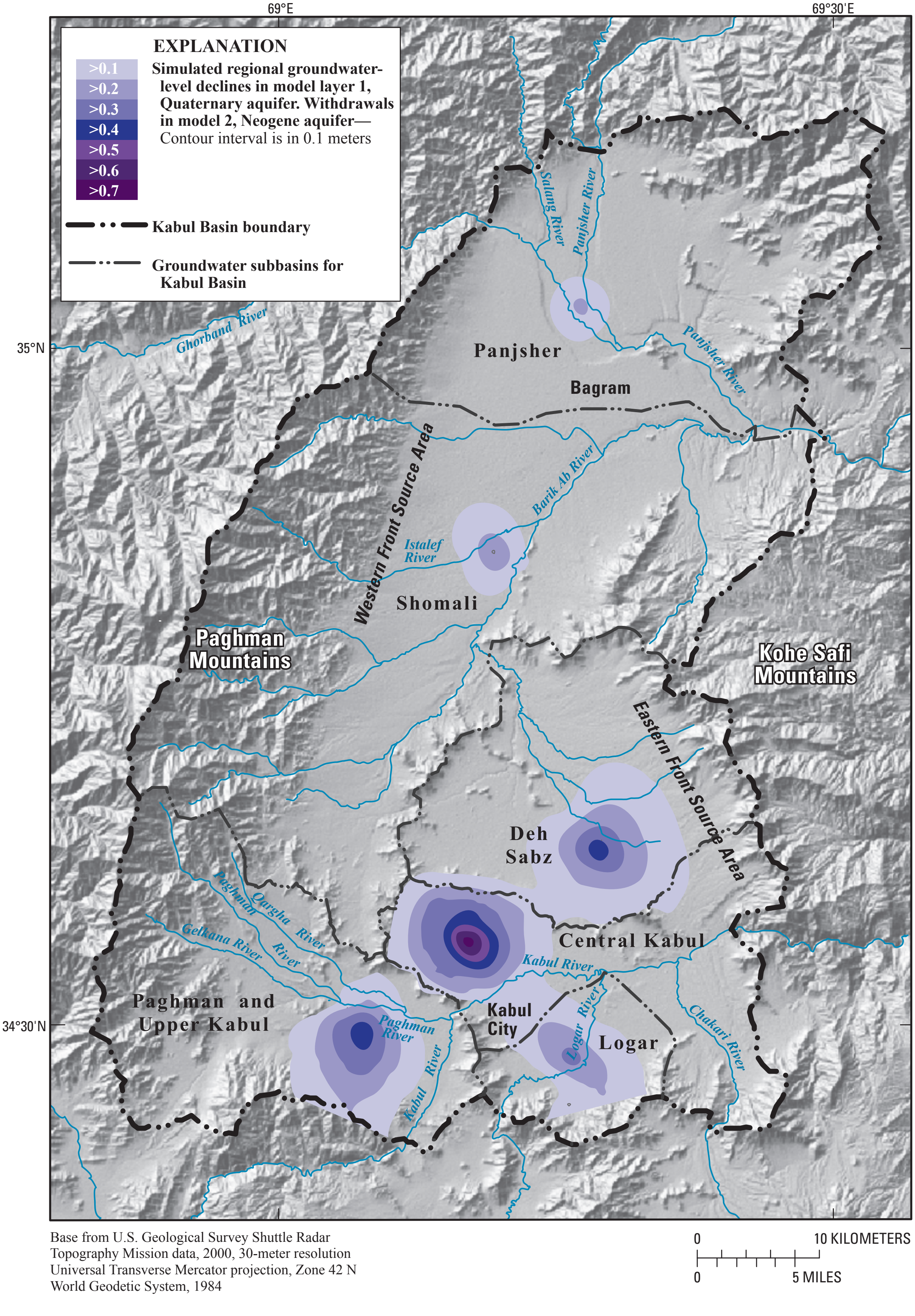


Figure 29. Simulated regional drawdown in the surficial aquifers caused by a hypothetical sixfold increase in water use in the Kabul Basin, Afghanistan.



Base from U.S. Geological Survey Shuttle Radar Topography Mission data, 2000, 30-meter resolution
Universal Transverse Mercator projection, Zone 42 N
World Geodetic System, 1984

Figure 30. Regional groundwater-level declines caused by withdrawals from the upper Neogene aquifer simulated by the conceptual model of the Kabul Basin, Afghanistan.

Potential sources of water to withdrawals in the upper Neogene aquifer within the regional groundwater-flow system were assessed in the Kabul Basin by particle-tracking methods (Pollock, 1994). In the Panjsher subbasin, the simulated groundwater flow in the upper Neogene aquifer is supplied by inflows from the large rivers entering the Kabul Basin. In the Shomali subbasin, the source of water to the upper Neogene aquifer is simulated as originating from leakage from perennial streams and groundwater inflows from upland areas. The source of water to withdrawals in the upper Neogene aquifer in the Paghman and Upper Kabul, Deh Sabz, and Logar subbasins was simulated as primarily originating from groundwater inflows from upland areas outside the subbasins. The simulated source of water to the Central Kabul subbasin was primarily direct recharge on the area west of the subbasin. Withdrawals in the upper Neogene may create a downward head gradient in the subbasin and induce flow from the river; however, simulations indicate that the water captured at a well in the upper Neogene aquifer may not necessarily be from a nearby river. The simulated groundwater-level declines in the Central Kabul subbasin illustrate a scenario in which withdrawals in the upper Neogene aquifer induce river infiltration.

The age of groundwater along simulated flowpaths can be calculated by using the groundwater-flow model; and a conceptual understanding of the relative age of groundwater in the upper Neogene aquifer, can be gained from the results of simulations. The results of the simulations are controlled by numerous variables such as hydraulic conductivities, porosity, and simulated fluxes; the values of these variables, however, are not well known, particularly for the Neogene aquifer. Recent (2008) chemical and isotopic analysis (including tritium and carbon 14 sampling of groundwater from two wells in the Bagram area by the AGS and USGS) provide new information (not included in Appendix 10) on the age of groundwater at the base of the surficial (Quaternary) aquifer or at the top of the Neogene aquifer. The interpreted residence times of groundwater samples from depths of 73 and 100 m were 300 and 2,800 years with modern fractions of 84 and 58 percent respectively (Neil Plummer, USGS, written commun., 2009). Given the results of recent sampling and the low recharge rates at the surface, the age, or residence time, of groundwater in the upper Neogene aquifer is most likely several orders of magnitude greater than the age of groundwater in the surficial aquifer. Additional isotopic-age analysis of groundwater from the Neogene aquifer would be necessary to provide confidence in the results of flowpath ages. The sustainability of groundwater in the Neogene aquifer in subbasin areas like the western part of the Central Kabul subbasin, which is bounded by interbasin ridges, may be much less than that of the groundwater in the Neogene aquifer in the northern and western areas of the Kabul Basin, which are bounded by large mountains. Recharged by river leakage and mountain-front recharge in the northern Kabul Basin, groundwater flowing into the upper Neogene aquifer in the western areas of the Shomali and Panjsher subbasins and in the eastern area of the Deh Sabz subbasin is likely to be younger than groundwater in the upper Neogene aquifer in central subbasin areas bounded by interbasin ridges. For example, groundwater in the more populated western area of the Central Kabul and the eastern area of the Paghman and Upper Kabul subbasins is likely to be much older, possibly tens of thousands of years older, than groundwater in the other subbasins; the water is older because it has flowed farther from the source of recharge.

Simulated Effects of Climate Change

Potential changes in groundwater conditions caused by climate change were simulated for a 2057 scenario. Potential climate change may affect both the total annual recharge to the Kabul hydrologic system and also the timing of recharge during the year. Although water demand for the year 2057 is projected to be higher than current demand, the simulated climate change was evaluated on the basis of current water-use conditions to allow assessment of the impact of climate change alone, as a single variable, without other complicating factors. Projected climate conditions simulated in this investigation included changes in precipitation amounts and patterns, ET rates, and growing-season length (fig. 10), all of which could result from rising temperatures (fig. 9). The effects of such climate changes on regional precipitation rates were based on the research of Milly and others (2005) for southeast Asia and similar watershed simulations for the Helmand Basin of Afghanistan (Vining and Vecchia, 2007). By the year 2057, total monthly precipitation is estimated to decline by about 10 percent; however, the timing of peak runoff, and therefore peak recharge in the Kabul Basin, is expected to occur earlier in the year with increasing temperatures (fig. 9), as is indicated in figure 16. The earlier inflows from earlier peak runoff may shift a portion of the peak recharge from April into March.

The potential effect of climate change on water availability in the Kabul Basin aquifer system was assessed by simulating a 10-percent reduction in precipitation. The steady-state analysis was based on current estimated water-use rates, and the results were compared to simulated current groundwater conditions (fig. 27A). A regional reduction in precipitation would also affect the external drainage basins and adjacent upland areas that contribute inflows to the Kabul Basin. Climate change was simulated by reducing the following inflows to the model by 10 percent: (1) direct recharge from precipitation, (2) inflows from perennial streams draining upland areas, (3) inflows from rivers entering the Kabul Basin, and (4) irrigation recharge, which is likewise dependent on the surface-water inflows.

A 10-percent reduction in recharge results in a decline in groundwater levels throughout the Kabul Basin (fig. 31). Declines of more than 0.5 m were simulated for most of the model area. Declines of more than 10 m, and in places more than 20 m, were simulated for the Western Front Source Area and in the upper areas of the Paghman and Upper

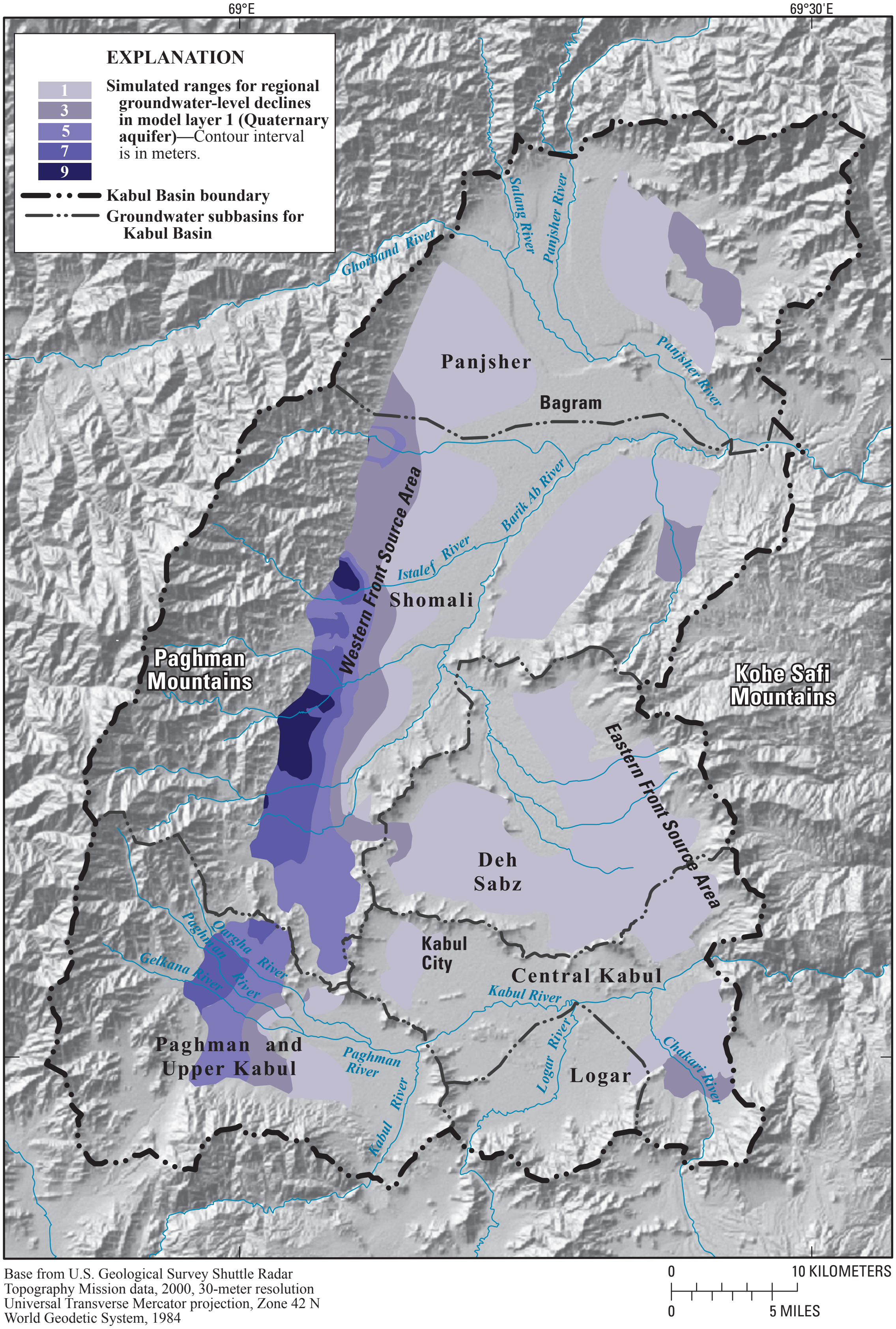


Figure 31. Simulated regional groundwater-level declines in subbasin surficial aquifers following a reduction in recharge caused by potential climate change in the Kabul Basin, Afghanistan.

Kabul subbasin; these declines were caused by reductions in inflows from perennial streams and upland drainages from the Paghman Mountains. Large groundwater-level declines (more than 10 m) at the Western Front Source Area would reduce stream and karez flows into the valley. The simulation results (fig. 31) indicated that mean annual changes in the hydrologic system and more pronounced changes in the flow system would occur seasonally, particularly during low-flow periods. Although not simulated, the reduced precipitation would also affect the timing of peak snowmelt and therefore peak recharge. Peak recharge earlier in the spring or late winter would result in less groundwater discharge (from storage) to streams and karezes during summer dry periods.

Simulated declines in the Deh Sabz subbasin—1 to 3 m—were generally less than elsewhere in the Kabul Basin because this subbasin currently receives little direct recharge and no stream or irrigation leakage; therefore, total recharge is largely unchanged. Declines were least—less than 0.5 m—along the Panjsher River because the Panjsher River flows are large relative to leakage from the river. The simulated inflows from the large rivers, such as the Panjsher and Logar Rivers, were reduced; because the leakage from these inflows is relatively small in comparison to the total flow in the river, however, the reductions in recharge from river leakage were less apparent. Declines were relatively small, generally less than 0.5 m, along the Logar River and in groundwater-discharge areas such as the easternmost areas adjacent to the Kabul River in the Central Kabul subbasin.

The simulated groundwater declines caused by climate change would affect, to varying degrees, nearly all wells in the Kabul Basin. Of the wells affected, shallow supply wells would be most at risk. As indicated previously in this report, the groundwater in shallow supply wells is typically withdrawn less than 1 to few meters below the water table in the surficial aquifer. Based on simulated climate conditions, and in the absence of droughts or increasing withdrawals, 61 percent of existing shallow supply wells would undergo water-level declines of more than 0.5 m and 39 percent would undergo declines of more than 1 m. On the basis of the simulations, groundwater-level declines may cause about one quarter of all shallow supply wells to become inoperable either seasonally or over a long time period. The effects would be greatest near the base of the Paghman Mountains (Western Front Source Area) (fig. 31). The simulations showed that in the headwater areas of the Paghman and Upper Kabul and Shomali subbasins, more than 50 percent of shallow supply wells would become inoperable. On the basis of the simulations, anticipated increases in groundwater withdrawals by a larger population in the future would further increase the number of wells made inoperable as a result of potential climate change.

Summary and Conclusions

The United States (U.S.) U.S. Geological Survey (USGS) has been working with the Afghanistan Geological Survey (AGS) and the Afghanistan Ministry of Energy and Water (MEW) on water-resources investigations in the Kabul Basin under an agreement supported by the United States Agency for International Development (USAID). This collaborative investigation compiled, to the extent possible in a war-stricken country, a varied hydrogeologic data set and developed limited data-collection networks to describe Kabul Basin's water resources. This report presents the results of a multidisciplinary assessment to address questions of future water availability in the presence of population growth and the potential impacts of climate change on the resources of the Kabul Basin. The investigation integrated recently acquired remotely-sensed data and satellite imagery, including glacier and climatic data; recent climate-change analyses; recent geologic investigations; analysis of streamflow data; groundwater-level analysis; surface-water- and groundwater-quality data, including data on chemical and isotopic environmental tracers; and estimates of municipal and domestic and agricultural water uses. The data and analyses were integrated through a conceptual analysis by a groundwater-flow model for assessing current and future water availability.

Geomorphology and Geology

The Kabul Basin, Afghanistan, is in a northeast-trending basin-and-range setting bounded primarily by crystalline, and to a lesser extent, sedimentary rocks. The basin that forms the study area is filled by sand, silt, and gravel and encompasses about 3,600 km^2. The study area has been delineated into six subbasins based on local drainage divides: Central Kabul, Logar, Deh Sabz, Paghman and Upper Kabul, Shomali, and Panjsher subbasins. Additionally, two hydrologic zones of lesser extent are recognized on the basis of stable-isotope data—the Eastern and Western Front Source Areas along the eastern and western margins of the basin. Quaternary sands and gravels, generally less than 80 m thick, make up the primary surficial aquifer in the valley. Underlying Neogene sediments, consisting of a poorly sorted and semiconsolidated conglomerate of sand, silt, clay, and gravel 600 to about 1,000 m thick, compose a secondary aquifer.

Trends in Temperature and Climate

The climate of the Kabul Basin is arid to semiarid with cold winters and hot summers. Average annual precipitation in the Kabul Basin is approximately 330 mm/yr, whereas growing-season evapotranspiration rates are much higher.

Basinwide annual total recharge by infiltration of precipitation is probably about 30 mm. Mean monthly precipitation has historically been highest in the spring (February to April, 58 to 84 mm), moderate in the late fall and winter months (November to January, 21 to 33 mm), and very low in the summer months (June to October, 1 to 5 mm).

The Intergovernmental Panel on Climate Change, however, has identified patterns that include warming trends for southwest Asia, particularly over continental land masses. Increased surface temperatures in mountainous regions may affect the timing of snowmelt and reduce snowpack. During the next 50 years, a 10-percent reduction in total annual precipitation is anticipated in Afghanistan. Ongoing decadal climate change has been indicated by the reducted extents of glaciers in the Panjsher River watershed and the absence of glaciers in the Kabul River watershed in recent years. Comparisons of past (1961–1991) and recent (2003–2007) mean monthly temperatures show differences that may indicate warming throughout the year in the Kabul Basin. The greatest changes in mean monthly temperature from 1961 to 2007 occurred in February (+5°C) and March (+3°C). Analyses of vegetation patterns (Normalized Difference Vegetation Index) for the periods 1982–1985 and 1999–2002 indicate a shift in spring vegetation growth from April to March. This shift was followed by earlier vegetation senescence in June and July, indicating drier summer conditions in recent years.

Streamflow

The Kabul River watershed covers more than 25,500 km^2 upstream of and including the Kabul Basin study area; several large rivers flow into the study area and play a major role in the hydrology of the basin. Major tributaries include the Ghorband and Panjsher Rivers, which flow into and through the northernmost area of the basin with watersheds that cover approximately 4,000 and 3,500 km^2, respectively. Other major tributaries include the Kabul and Logar Rivers, which flow into and through the southernmost area of the basin, with watersheds that cover approximately 1,600 and 10,000 km^2, respectively. Small tributaries with drainage areas of 500 km^2 or less flow into the Kabul Basin from the Paghman Mountains to the west and from drainage areas to the north. Within the Kabul Basin study area, twelve streamgages were operated between 1959 and 1980. Fifteen to 20 years of daily streamflow record were collected at most of these streamgage sites. Analysis of historical mean annual and monthly runoff rates were used to calculate maximum and minimum flow rates and recurrence intervals. The average annual runoff per square kilometer of drainage area during the historical period of record was 0.020 m^3/s for the northern stations and 0.004 m^3/s for the southern stations. The watersheds to the north in the Hindu Kush Mountains are at a higher altitude and accumulate more precipitation, particularly snow, than the southern watersheds. The northern watersheds also include some glaciers. Because of their higher elevation and greater snow cover, the northern watersheds produce later peak discharges than the southern watersheds, which include the lower altitude Paghman and Dasht-i-Nawur Mountains. Three streamgages were reestablished in the study area in 2005, and one of these recorded streamflow data for the Panjsher River at Shukhi; however, trends cannot be defined from these limited data.

Flows for the Panjsher River at Shukhi for the 2006 water year, a year with near-normal precipitation, were compared to historical mean flows (for water years 1966 through 1980). Historically, the peak monthly flows had generally occurred during April in the southern watersheds and in June in the northern watersheds. The monthly mean peak flow for 2006 occurred in May as opposed to June during the period 1966–1980, and the 2006 summer flows were lower (the June flow was 36 percent lower, and the July flow was 54 percent lower) than flows in the mean historical record. This comparison of historical and recent records was cursory and did not identify trends between 1966 and 2006.

Groundwater Levels

Declines of a few meters to 10 m have been reported between the 1960s and early 2000s for some parts of the study area. Groundwater levels in the Kabul Basin have fallen dramatically as a result of below-normal precipitation in the early 2000s. The greatest declines in the early 2000s were measured in the central part of the city of Kabul in areas of increasing population. Since 2004, with more normal amounts of precipitation, some monitoring wells in rural areas have shown water-level increases of a few meters. The total population in the Kabul Basin was estimated to be approximately 3.5 million in 2002, with about 80 percent of the population in the city of Kabul, and is anticipated to increase by approximately 20 percent by the year 2012. To meet the increasing demand for water, approximately 1,500 shallow (water-table) domestic supply wells have been installed in recent years in the Kabul Basin, with the majority of these inside the city limits of Kabul. About 25 percent of these shallow supply wells, however, have been reported to be dry or inoperative. Based on United Nations projections, the population in the Kabul Basin is estimated to increase from about 3.3 million in 2007 to about 9 million by the year 2057. Projected increases in municipal and domestic water use associated with the anticipated population growth were simulated with a numerical model. The simulations showed water-level declines that may cause more than half of the shallow supply wells to become inoperative.

Water Quality

Seventy-seven surface-water samples were collected from 8 sites, and 92 groundwater samples were collected primarily from individual wells, springs, and karezes in the Kabul Basin in 2006 and 2007. Surface-water quality was not statistically different among the subbasins; the major ion chemistry was generally of the calcium-magnesium-bicarbonate type. Specific conductance of surface waters ranged from 67 to 1,497 µS/cm with a median value of 398 µS/cm. Nitrate concentrations ranged from 0.4 to 5.9 mg/L as N with a median of 1.7 mg/L. Total coliform and *E. coli* were detected in all stream samples. *E. coli* concentrations in excess of 2,420 colonies per 100 mL were detected in the Istalef River, the Kabul River in the Central Kabul subbasin, and at the Barik Ab River near Bagram.

The major ion chemistry of groundwater also was generally of the calcium-magnesium-bicarbonate type. The concentrations of many constituents in samples collected in the Central Kabul subbasin were higher than in samples from the other subbasins, and the samples often showed indications of anthropogenic contaminants. Samples from the Central Kabul and Deh Sabz subbasins and one sample from the Paghman and Upper Kabul subbasin consisted of a sodium-chloride-type water; other samples collected in the same subbasin also showed intermediate water compositions. The differing chemistries indicated mixtures of anthropogenic contaminants, constituents resulting from poor well construction, or increased concentrations of ions caused by water uptake by vegetation. In the Deh Sabz subbasin, higher concentrations of sodium and sulfate or chloride may be indicative of a transpiration rate by vegetation greater than elsewhere in the basin. In the study area, the specific conductance of groundwater ranged from 248 to 7,350 µS/cm with a median value of 799 µS/cm. In general, the conditions in the aquifer appeared oxic with dissolved oxygen concentrations ranging from 0.1 to 1.9 mg/L with a median value of 0.1 mg/L. Nitrate concentrations ranged from 0.6 to 40.2 mg/L as N with a median value of 3.3 mg/L as N. The highest nitrate concentration, 40.2 mg/L as N, was observed in samples from a well in the Central Kabul subbasin. Total coliform bacteria were detected in nearly all groundwater samples, and concentrations higher than 100 colonies per 100 mL were detected in six of the seven the subbasins. *E. coli* was detected in 97 percent of the groundwater samples; however, the concentrations of *E. coli* appeared to be randomly distributed in the basin. Concentrations of arsenic, lead, selenium, and uranium exceeded World Health Organization guidelines in 1, 3, 1, and 3 percent of the samples, respectively. Groundwater quality in the Kabul Basin is affected by anthropogenic activities, particularly in urban areas, where untreated wastewater and possible fertilizer applications remain of highest concern. The high rate of bacteria detections indicated that poor well-construction practices or wellhead contamination may be common.

Chemical and Isotopic Analysis

Considerable information concerning the hydrology of the Kabul Basin was determined from an analysis of chemical and isotopic data. On the basis of data on stable isotopes and mean-concentration ratios, much of the groundwater in the Kabul Basin appears to have infiltrated from surface water. Stable hydrogen and oxygen isotopic compositions were used to identify local rivers and streams as sources of groundwater recharge, with little surface water or groundwater evaporation. Groundwater sampled near the Paghman Mountains most likely was recharged from snowmelt and runoff from the mountains. Groundwater sampled in the Shomali subbasin most likely was recharged by leakage from tributaries to the Barik Ab River and flow diverted to irrigated areas. Some groundwater flows into the Kabul Basin at depth from adjacent mountains; however, this source of recharge most likely moves slowly and follows long flowpaths. Groundwater sampled near the eastern valley wall in the Deh Sabz subbasin had likely been recharged by inflows from the upland mountainous areas to the east, although little upland surface area drains to the Deh Sabz subbasin. The chemistry of sources of groundwater sampled in the Paghman and Upper Kabul, Central Kabul, and Logar subbasins was consistent with the chemistry of samples from the local-source rivers; this similarity indicated that infiltration from these rivers is a primary source of the groundwater.

The average ratios of mass concentrations of some dissolved major solutes (particularly Na and SO_4) to chloride in groundwater samples were similar to the same ratios in surface-water samples collected in the same subbasin. This result suggests that surface water is a predominant source for most of the groundwater sampled to depths of at least 650 m. Small variations in mass-concentration ratios for other solutes (particularly Ca, HCO_3, and to some extent Mg) indicate a lesser role for common water-rock reactions, including calcite precipitation and cation exchange in shallow groundwater. Solute concentrations in many of the groundwater samples exceeded those measured in surface water by factors of 100 or more. Because no evaporative signal was observed in the stable isotope data, the higher solute concentrations were attributed to the extraction of water by vegetation (transpiration) along the rivers and in surface-water drainage areas near irrigated crop land where plant-root systems can reach the water table. Transpiration removes water without altering the stable isotopic composition of the residual water; thus, the solutes are concentrated without a detectable shift in stable isotopic composition.

Chlorofluorocarbon (CFC)-12 volume fractions in most of the groundwater samples were consistent with recharge by post-1970s water. Leakage of saline waters into the basin as a source of the high solute concentrations is unlikely on the basis of the measured tritium and CFC concentrations and cation/anion mass ratios. On the basis of the chemical, stable isotope, and environmental tracer data, the infiltration of surface water, with subsequent concentration through uptake of water by vegetation in irrigated areas, is the most likely source of recharge for most of the groundwater sampled throughout the Kabul Basin as part of this study.

The CFC analysis permitted estimation of the age and fraction of young to old groundwater for some samples. Depending on the particular CFC ratios assessed, the average age of the young component of groundwater in the study area was about 16 to 21 years. Young groundwater composed about 58 to 76 percent of the water in the samples, and the groundwater was unmixed in more than half of the groundwater samples tested. The average ages of groundwater in the subbasins differed slightly depending on the CFC analysis method used but were approximately 20 years in the Paghman and Upper Kabul subbasin, 28 years in the Deh Sabz and Central Kabul subbasins, and 15 to 19 years in the Shomali subbasin. The CFC data indicate that groundwater age increased with depth, and that the fraction of young water in groundwater mixtures pumped from wells decreased somewhat with depth. On the basis of the interpreted CFC ages and the depths at which samples were collected below the water table, basinwide recharge rates were estimated to be 0.4 to 0.8 m/yr, and 0.35 to 0.7 m/yr for assumed porosities of 30 and 25 percent, respectively. These estimates of recharge included irrigated areas, where infiltration of irrigation water may have contributed a large portion of the local recharge.

Water Use

The per capita water-use rate in the Kabul Basin was assumed to increase from about 11 to 15 m^3/yr in 2007 to about 78 m^3/yr by 2057. Based on the assumed population and water-use increases, municipal and domestic water use in the Kabul Basin was estimated to increase from approximately 112,000 in 2007 to 725,000 m^3/d annually by 2057, or about six times the current use.

Agricultural water use occurs primarily in three areas of the Kabul Basin. Although many wells have recently been installed in the Kabul Basin, the use of groundwater for irrigation is still likely to be low because of prohibitive costs; irrigation water is almost entirely supplied by karezes and streamflow diversions. In the northern part of the study area, irrigation is supported by diversions from the Panjsher River and its tributaries. Agriculture in the Shomali subbasin, in the middle of the study area, is supported by flows from the Paghman Mountains. Agriculture in the southern part of the study area is supported by streamflow diversions from the Kabul River and its tributaries. The total water used seasonally by crops, the actual evapotranspiration, has been estimated to be more than 1,300 mm in the Shomali subbasin. The total annual agricultural water use in the Kabul Basin is likely to be an order of magnitude greater than the total annual domestic water use. Irrigation efficiency may be as low as about 50 percent as a result of evaporation losses and infiltration at leaking canals. In the irrigated areas, inflows to the basin are redistributed, and a portion of the inflow infiltrates to underlying aquifers. With increasing population, the need for irrigation water can be expected to increase. In some areas of the Kabul Basin that are supplied by small tributaries or ephemeral streams, such as southern areas of the Shomali subbasin and the Deh Sabz subbasin, increases in irrigated extent may not be possible.

Conceptual Groundwater-Flow Simulation

The groundwater-flow system was investigated conceptually by constructing a simplified steady-state groundwater-flow model. This model was used to account for and estimate the components of groundwater flow in the Kabul Basin. Geological information was provided by previous investigations and collaborative work between the USGS and the AGS. The conceptual model was calibrated to historical streamflow and water-level information compiled by this investigation and to recent water levels measured during the AGS and USGS collaboration.

The surficial aquifer in the conceptual model of the Kabul Basin consists of highly permeable, coarse-grained sands and gravels adjacent to the major river channels and finer-grained windblown sediments covering most of the valley floor. The coarse-grained sediments adjacent to river channels form the primary surficial aquifer, in which the larger municipal wells have been completed. Many shallow supply wells have been installed in sediments throughout the basin. The surficial sediments are underlain by older, weathered Neogene sediment and bedrock approximately 600 to 1,000 m thick. The quality of the water in this secondary aquifer is largely unknown, but the water is thought to be older than the groundwater in the primary aquifer and to contain a higher concentration of dissolved solids. The basin-fill sediments are bounded primarily by crystalline and metamorphic bedrock and lesser amounts of sedimentary rock that form the basin walls and interbasin ridges. The bedrock has little primary porosity and contains groundwater in fractures. Groundwater storage may be higher in areas where the bedrock is more highly fractured, such as the Paghman Mountain front, where groundwater from the surrounding upland areas may flow to the subbasin aquifers. The potential water availability is greater in these areas—the northern and western areas of the basin—than elsewhere in the Kabul Basin.

The primary, or shallow, surficial aquifer is recharged by winter and spring precipitation and leakage from rivers and irrigated areas. The mean annual rate of recharge through infiltration of precipitation directly through the subbasin sediments was estimated to be about 0.0004 m/d. Surface-water inflows through streamflow leakage, drainage from upland areas, or irrigation leakage may contribute about 0.0012 m/d of recharge annually to some areas of the Kabul Basin; this amount of recharge is greater than the infiltration of precipitation. Therefore, the total annual recharge differs widely with location in the Kabul Basin, may originate from a combination of sources, and may be as much as 0.8 m/yr, as indicated by the results of the isotopic analysis. In the eastern areas of the Kabul Basin, direct recharge is likely to be near zero.

Streamflow leakage likely contributes large amounts of recharge near stream channels during periods with sustained streamflows. Perennial streams draining upland areas at the basin flanks form a source of surface-water inflow to the valley that may be considerable depending on the size of the adjacent upland area. Recharge by streamflow leakage, however, is limited by the rate at which water can infiltrate the streambed. During periods of low flow, most of the flow may infiltrate to underlying aquifers; however, during periods of high flow, most of the flow may bypass the aquifer system. Irrigation likely enhances natural surface-water infiltration and thus increases recharge by providing a greater surface area. Irrigated areas may also provide a mechanism for capturing a portion of the flow that, without the additional surface area, would bypass the valley. The volume of water used by crops, however, is the largest of all the water-use types in the Kabul Basin; this water is a loss from the flows leaving the Kabul Basin. In northern areas of the basin, streamflow diversions for irrigation draw water from the Panjsher River and its tributaries. In the Shomali subbasin, irrigation water is obtained from tributaries draining the Paghman Mountains. In the southern areas of the Kabul Basin, including the Central Kabul, Logar, and Paghman and Upper Kabul subbasins, irrigation water is supplied by the Kabul, Paghman, and Logar Rivers. The Deh Sabz subbasin supports very little irrigation and therefore produces little additional recharge, because there are no perennial rivers flowing into or through this area. Additionally, upland watershed areas in the Deh Sabz subbasin and other eastern areas of the Kabul Basin are too small to produce additional surface-water drainage or lateral groundwater inflow into the subbasin. As a result, total recharge to the study-area subbasins and water availability vary considerably and primarily depend on proximity to a sustained surface-water source, such as streams and irrigated areas; proximity to upland areas with perennial or intermittent streams; and proximity to upland areas that contribute lateral groundwater inflows through adjacent bedrock.

The groundwater-flow model developed for this study was used to account for and estimate the components of groundwater flow in the Kabul Basin. Water leaves the Kabul Basin primarily as streamflow discharge in the Panjsher and Kabul Rivers. The total annual base flow in the Panjsher River and its tributaries was about six times that of the Kabul River. In the southern part of the study area, the average annual base flow at the Kabul River outflow point at Tang-i-Gharu was approximately equal to the base flows in the major rivers entering the basin (the Paghman, Kabul, Logar, and Chakari Rivers). In the northern part of the study area, the sum of the average annual base flows for the major rivers entering the basin (the Panjsher, Ghorband, Salang, and Shatul Rivers) was greater than the base flow at the Panjsher River outflow point at Shukhi. Unmeasured groundwater inflows to the Kabul Basin from upland areas would also increase the likelihood of negative balances at the two outflow-measurement stations. The negative balance indicates that consumptive water uses, actual evapotranspiration (irrigation water use), and evapotranspiration were important components of the water balance of the study area.

Water Availability

The population in the study area, which included the city of Kabul and surrounding areas, was 3.3 million in 2007 and has been growing at a rate of about 4 percent a year during the past 5 years. Population estimates were not available for 2057; however, high growth rates are expected to continue, and a population of 9 million was estimated for the purposes of this study for the Kabul Basin in 2057. The municipal and domestic water-use rate was estimated to increase about sixfold from the current (2007) rate by 2057 because of population growth and increasing rates of per capita water use. The total water-use rate for the entire Kabul Basin was estimated to increase from about 112,000 to 725,000 m^3/d by 2057.

Based on simulations, groundwater supplies are expected to be available in the primary surficial (Quaternary) aquifer during years of normal amounts of precipitation, with the greatest relative water availability in areas that receive recharge by streamflow infiltration or upland drainage at the valley flanks. Water resources are limited in other areas such as the Deh Sabz subbasin or southeastern parts of the Shomali subbasin. During years with below-normal amounts of precipitation, such as the early to mid-2000s, the surficial aquifer becomes stressed and groundwater levels decline in shallow wells. Simulations of a sixfold future increase in groundwater withdrawals from the surficial aquifer indicated that during years with normal amounts of precipitation, groundwater levels in the central areas of those subbasins with major population centers may decline by 1–2 m in less urban areas and as much as 40 m in urban areas. On the basis of the simulations, many wells will not provide an adequate supply of water in more densely populated areas because the mean depth of small community wells installed in recent years is 20 m. Simulated future water-level declines indicate that more than half of the current shallow supply wells may likely become inoperative.

The Neogene aquifer is currently not used as a source of water in the Kabul Basin. Because of its considerable thickness, the Neogene aquifer stores more water than the overlying surficial aquifer but has not been used because of its low permeability and questionable water quality. Some previous and recent investigations, however, have found evidence of coarse-grained lenses within the Neogene aquifer. If such lenses can be located and are locally extensive, it may be possible to withdraw groundwater at rates sufficient for municipal use. If the lenses are not regionally extensive, well yields are likely to be limited because of the low permeability