Groundwater Flow and Quality at Camp Lemonnier, Djibouti

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Gary LeCain, Hydrologist, USGS

Gary Patterson, Hydrologist, USGS

Table of Contents

Figures

Tables

Introduction

This report presents the results from a hydrologic analysis of the groundwater-flow system at Camp Lemonnier, Djibouti. The report includes results from a numerical (computer-generated) groundwater-flow model developed to evaluate the effects of groundwater pumping, on the water table, and results from an evaluation of the Total Dissolved Solids (TDS) data from the Camp Lemonnier Wells. Figure 1 presents an aerial view of the Djibouti City area and Camp Lemonnier. Camp Lemonnier is located in the south-central portion of the photo just south of the airstrip.

Figure 1. Aerial photograph Camp Lemonnier and the Djibouti City area (adapted from Google Earth)

The regional hydrology of Camp Lemonnier and the Djibouti City area is documented in the 2011 report by Batch and others. However, it is not the regional groundwater flow system that is of interest here, but the shallow-localized aquifer extending approximately 3 km from the Wadi Ambouli west under Camp Lemonnier to the coast with an average thickness of around 30 m. Figure 2 presents an aerial view of Camp Lemonnier and the 11 Camp wells (7 supply wells, and 4 injection wells) drilled from 2007–2013. Presently, groundwater is pumped from Well 6 with Well 4 as a backup. The injection wells, originally drilled to dispose of the salt-water discharge from the reverse osmosis water purification unit (ROWPU), were never used and have been grouted.

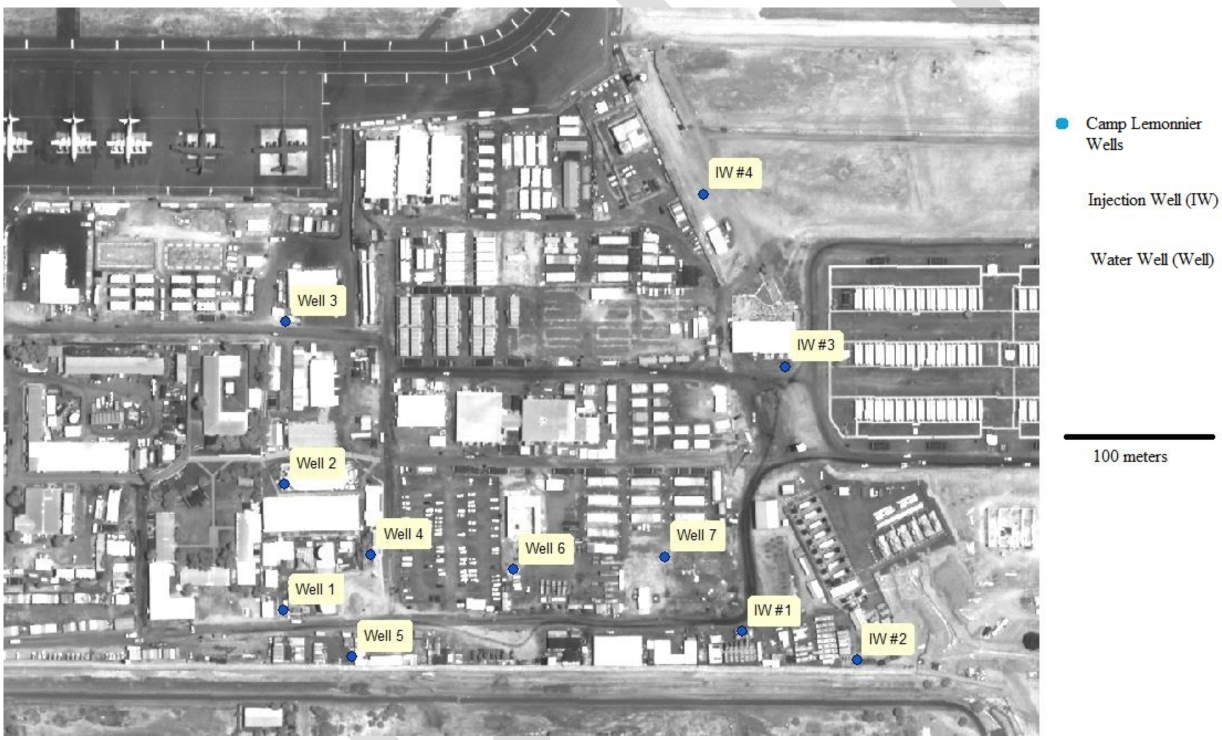

Figure 2. Camp Lemonnier water wells (Well) and injection wells (IW) (From Batch and others, 2011)

Geography

Batch and others (2011) provide a summary on the geography of Djibouti. The Republic of Djibouti is a small coastal country (23,051 square kilometers) located in the Horn of Africa on the Gulf of Tadoura, which opens on to the Gulf of Aden near the entrance to the Red Sea. The 2009 census lists a population of 818,159 with a majority (567,000) living in the capital, Djibouti City (Communication Officielles Des Resultats Du Recensement General De La Population, 2010). Djibouti is bordered on the southeast by Somalia, on the northwest by Eritrea, and on the south and west by Ethiopia. The topography ranges from gently sloping plateaus, near Djibouti City, to highlands and mountains in the north and south. Overall, the topography is rugged and the country is bisected by numerous ephemeral (intermittent) stream channels. Elevation ranges from –155 m (below sea level) at Lake Assal to 2029 m at the Mousa Ali volcano in the north. Elevation over the Camp Lemonnier area ranges from sea level to approximately 18 m in the western area of the Camp. The country is arid with warm winters and hot summers; temperatures may reach 50°C at Djibouti City. The rainy season is from September through March. Precipitation is a function of wind direction and elevation; average annual precipitation ranges from as low as 100 mm/yr near the coast to greater than 300 mm/yr in the highlands. Djibouti City, and Camp Lemonnier, fall between the 150 and 200 mm/yr precipitation bars (Muller and others, 1983).

Geology

Batch and others (2011) provides a summary on the geology of Djibouti. Djibouti is located in the Afar Triangle at the juncture of three major rift zones (Red Sea rift, Gulf of Aden rift, and the East African rift) (Beyene and Abdelsalam, 2005). Rifts are geographic areas where the Earth's plates are spreading; in general, Africa is moving away from Arabia, and the Horn of Africa (Somalia and eastern Ethiopia) is tearing away from Africa. As the plates spread (rift) volcanic rock (magma) rises to fill in the newly created space between the plates. Due to this rifting (spreading), the area is subject to seismic and volcanic forces. Because this is a rift zone the seismic forces are generally moderate, but the volcanic activity has been extensive. As a result of these forces, and the associated volcanic eruptions, the basement rock of the Djibouti City and Camp Lemonnier area is volcanic, mainly 3.4–1.2 million year old basalt. Figure 3 shows the surface geology of Djibouti City and Camp Lemonnier area. The geologic map (Fournier and others, 1982) shows that the eastern areas are covered by alluvium and marine deposits. The alluvium consists of clay, silt, sand, and gravel deposited by the Ambouli River and numerous ephemeral streams; these deposits have been reworked during periods when the Ambouli stream channel flowed more to the east than does the present north-flowing channel. Camp Lemonnier is underlain by these reworked marine and alluvial deposits. The reworked alluvium and marine deposits can make highly permeable aquifers provided the clay content is not too great. The alluvium and marine deposits are underlain by volcanic rock, mostly fractured basalt identified in the dark green on fig 3. Because basalt tends to fracture during the cooling phase, following eruption, basalt generally forms good aquifers.

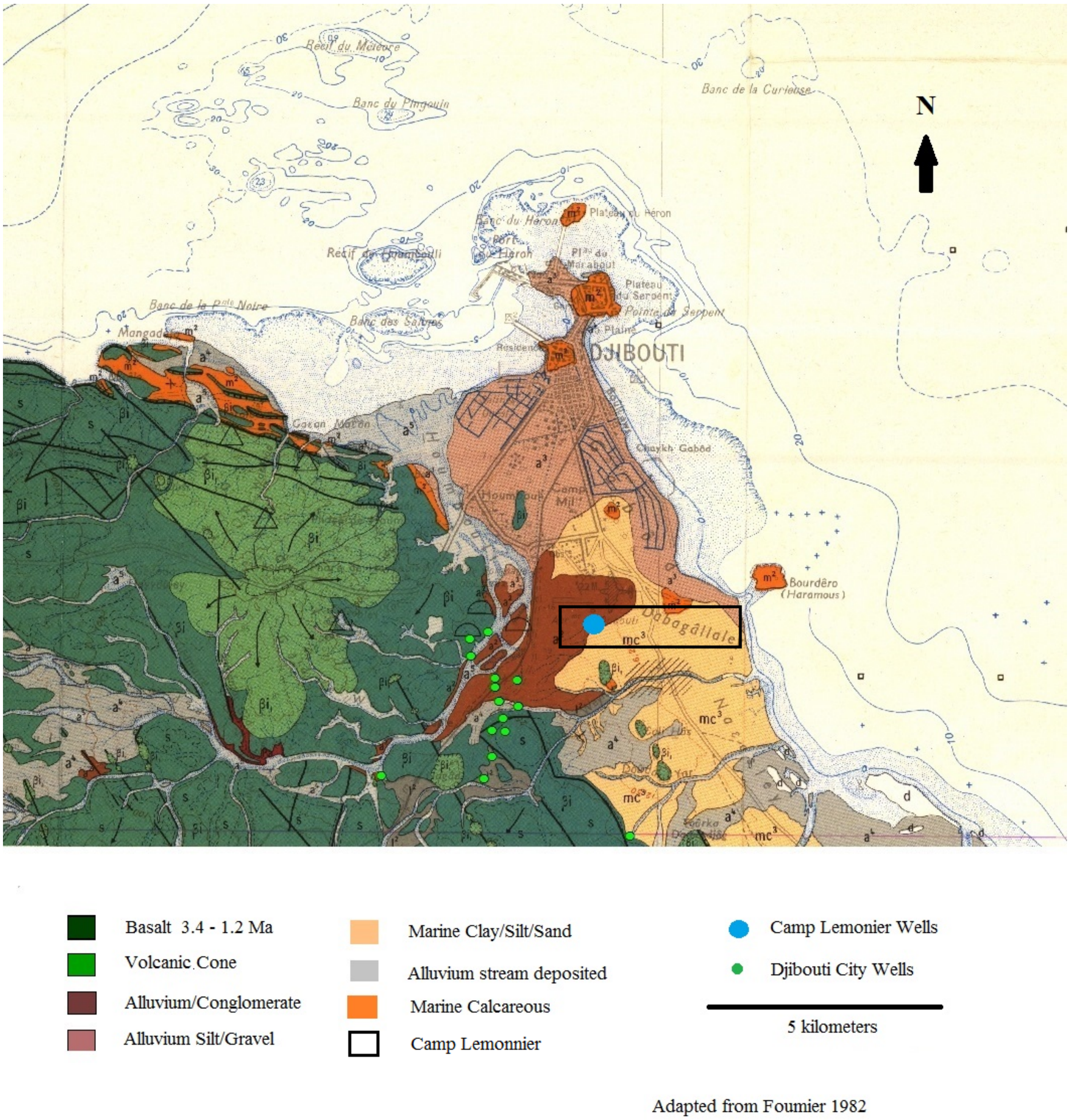

Figure 3. Surface geology of Djibouti City, Camp Lemonnier and the study/model area (adapted from Fournier and others, 1982)

A review of the drilling logs from the 11 boreholes drilled at Camp Lemonnier showed that the thickness of the reworked marine and alluvial deposits ranges from 15 m to 49 m. The clay deposits may be alluvial or they may be derived from decomposition of the basalt. Some of the clay deposits are derived from paleosoils (ancient soils) that formed from weathering and decomposition of the basalt when it was at ground surface. Rainfall and subsequent transport by the Ambouli River and numerous ephemeral stream flows have eroded, transported, and deposited the clay, silt, sand, and gravel. These deposits are most visible in the large alluvial fan at the mouth of the Wadi Ambouli (see figs. 1 and 3), in several smaller wadis, and in the alluvial deposits that makeup the surface deposits that underlay Djibouti City and Camp Lemonnier.

Hydrology

The regional hydrology of the Djibouti City area is documented in the 2011 report by Batch and others. The groundwater flow system under Camp Lemonnier consists of two geologic units: a shallow (15-m to 49-m thick) hydrogeologic unit of reworked alluvial and marine deposits, and a deeper hydrogeologic unit of fractured basalt. The overall groundwater flow gradient is from the southwest to the northeast where the groundwater discharges in to the Gulf of Aden just east of Camp Lemonier. Table 1 presents the data base for the Djibouti City water supply wells (adapted from Batch and others, 2011) and the Camp Lemonnier wells. Table 1 includes the well locations, land-surface elevations, well depths, static water depth, pumped interval lengths, and hydraulic conductivity estimates derived from pump-drawdown tests. The hydraulic conductivity (ability to conduct water) values are based on an analysis of the drawdowns and pump rate values (Theis and others, 1963). The methodology requires assumptions about the well radius (0.5 ft) and aquifer storativity (0.1) but provides a reasonable estimate of the aquifer hydraulic conductivity near the well bore.

The Table 1 well data is divided in to three groups. The first group (Djibouti City Shallow Wells) represents Djibouti City wells located in the alluvium of the Wadi Ambouli; calculated hydraulic conductivity values for the 16 wells range from 1.5–110 m/day with arithmetic and geometric average values of 45 and 29 m/day, respectively. The second group (Djibouti City Deep Wells) represents Djibouti City wells located in the deeper basalt aquifer; calculated hydraulic conductivity values of the eight wells range from 0.3–7.1 m/day with arithmetic and geometric average values of 1.7 and 0.9 m/day, respectively. The data indicate that wells located in the shallow marine and alluvial deposits (see Fig. 3) have higher hydraulic conductivity values. The third group (Camp Lemonnier Wells) consists of the Camp wells shown in Figure 2. The Camp wells are predominately screened in the reworked marine and alluvial deposits; however, several of the deeper wells do penetrate the basalt aquifer. The calculated hydraulic conductivity values of the Camp Wells range from 13–230 m/day with arithmetic and geometric averages of 100 and 60 m/day, respectively.

The reworked alluvium and marine deposits (shallow aquifer) that underlie Camp Lemonnier contain a layer of water with TDS levels less than 10,000 mg/liter, which indicates fresh-water recharge. The source of the fresh water may be the Wadi Ambouli, located just west of Camp Lemonnier. Figure 1 shows that the Wadi Ambouli is located less than 1 km west of the western boundary of Camp Lemonnier and approximately 1.2 km from Wells 4, 5, and 6. The Wadi Ambouli contains a large water shed (approximately 775 sq. km) and therefore has the potential to provide large quantities of fresh water for recharge of the shallow aquifer. A June, 2014 field visit to the wadi found that the alluvium of the wadi was contiguous with the reworked alluvium and marine deposits that underlie the Camp. Although Wadi Ambouli was not flowing at the time, standing fresh water in the wadi channel indicated a recharge source for the shallow alluvium and marine deposits that underlie Camp Lemonnier. Figure 4 is a June, 2014 photo that shows the standing water in the wadi and the alluvial gravel and boulder material that make up the wadi geology. This alluvial material appears to be connected to the reworked alluvium and marine deposits that underlie Camp Lemonnier. Such a connection would provide a highly permeable flow path for surface waters from Wadi Ambouli to seep in to the ground and flow eastward through the reworked marine and alluvial deposits (shallow aquifer) that lies under Camp Lemonnier.

Figure 4. Photograph of standing water in Wadi Ambouli, June, 2014

Table 1. Database for the Djibouti City and Camp Wells including calculated hydraulic conductivity values. [(modified from Batch, and others, 2011, * Crawley and Rogan, 2010); ND, No Data]

Djibouti City Shallow Wells

Well Number	Latitude	Longitude	Well Altitude	Well Depth	Static Water Depth	Top Screen Depth	Bottom Screen Depth	Construction Date	Pump Rate	Drawdown	Time	Transmissivity	* Hydraulic Conductivity
			(m)	(m)	(m)	(m)	(m)		(m^3/hr)	(m)	(days)	(m^2/s)	m/day
RG 1	11° 32' 28.579" N	43° 8' 2.247" E	11.0	34.9	16.2	ND	ND	Jun-72	11.1	9.32	0.25	3.3E-04	1.5
RG 2	11° 32' 12.198" N	43° 7' 50.047" E	18.0	51.1	19.6	ND	ND	May-72	45	0.68	0.25	1.8E-02	50
RG 3	11° 32' 23.942" N	43° 7' 49.573" E	22.0	47.6	20.7	ND	ND	Jul-72	32.2	14.81	0.25	6.0E-04	1.9
E1	11° 31' 55.842" N	43° 8' 22.428" E	26.0	30.6	20.4	ND	ND	Jul-62	49	3.61	0.25	3.8E-03	31
E2	11° 31' 50.731" N	43° 8' 6.919" E	25.0	30.2	22.8	ND	ND	About 1962	30	1.58	0.25	5.3E-03	61
E3	11° 31' 20.223" N	43° 8' 14.413" E	30.0	37.2	17.5	ND	ND	Jul-63	45	3.63	0.25	3.4E-03	15
E5	11° 31' 41.024" N	43° 8' 10.448" E	26.0	37.5	23.8	ND	ND	Jun-64	31.44	1	0.25	8.7E-03	55
E7	11° 31' 21.109" N	43° 8' 5.465" E	29.0	42.6	27.9	ND	ND	About 1965	43.3	3.18	0.25	3.8E-03	22
E11	11° 30' 47.558" N	43° 8' 0.140" E	31.0	49.8	30.8	ND	ND	Mar-70	39.4	1.46	0.25	7.5E-03	34
E12	11° 31' 56.785" N	43° 8' 7.011" E	24.0	46.5	23.0	ND	ND	About 1966	30.1	1.84	0.25	4.5E-03	17
E18	11° 30' 9.054" N	43° 9' 41.163" E	19.0	30.0	16.1	ND	ND	Nov-75	82	1.31	0.25	1.7E-02	110
E19	11° 29' 28.067" N	43° 10' 9.408" E	24.0	33.6	21.2	ND	ND	May-98	78.4	5.52	0.25	3.9E-03	27
E24	11° 27' 33.632" N	43° 12' 33.391" E	28.0	31.0	22.1	ND	ND	May-05	28	0.77	0.25	1.0E-02	97
E25	11° 27' 39.814" N	43° 12' 49.254" E	22.0	29.0	19.3	ND	ND	Feb-76	50.1	1.27	0.25	1.1E-02	96
E26	11° 27' 30.365" N	43° 13' 13.925" E	27.0	32.0	20.8	ND	ND	Jan-79	72.2	2.66	0.25	7.5E-03	58
E31	11° 28' 24.675" N	43° 10' 40.466" E	32.0	47.0	27.8	ND	ND	About 1993	56.2	1.52	0.25	1.0E-02	46

Mean = 45

Djibouti City Deep Wells

Well Number	Latitude	Longitude	Well Altitude	Well Depth	Static Water Depth	Top Screen Depth	Bottom Screen Depth	Construction Date	Pump Rate	Drawdown	Time	Transmissivity	* Hydraulic Conductivity
			(m)	(m)	(m)	(m)	(m)		(m^3/hr)	(m)	(days)	(m^2/s)	m/day
E35	11° 23' 17.205" N	43° 8' 23.808" E	152.0	198.0	142.5	ND	ND	May-98	35	7.37	0.25	1.3E-03	2.0
E36	11° 22' 56.388" N	43° 9' 6.555" E	137.0	185.0	127.2	ND	ND	May-98	12.6	17.44	0.25	2.0E-04	0.3
Z_26	11° 23' 26.229" N	43° 7' 34.343" E	150.0	214.8	159.5	ND	ND	Mar-03	50	3.03	0.25	4.6E-03	7.1
FU1	11° 33' 6.685" N	42° 59' 40.901" E	193.0	265.0	133.6	ND	ND	Nov-98	54.6	20.43	0.25	7.4E-04	0.5
FU1b	11° 33' 6.685" N	42° 59' 40.901" E	193.0	237.0	138.4	ND	ND	Jun-05	36	10.87	0.25	9.2E-04	0.8
FU2b	11° 33' 23.768" N	42° 59' 3.557" E	173.0	240.0	117.4	ND	ND	Jun-05	26	9.61	0.25	7.5E-04	0.5
FU3	11° 33' 31.276" N	43° 0' 3.330" E	177.0	202.8	118.8	ND	ND	Nov-98	22.2	20.21	0.25	3.0E-04	0.3
FU7	11° 32' 13.362" N	42° 30' 41.643" E	0.0	142.0	106.9	ND	ND	Jul-83	56	20.1	0.25	7.7E-04	1.9

Mean = 1.7

Camp Lemonnier Wells

Well Number	Latitude	Longitude	Well Altitude	Well Depth	Static Water Depth	Top Screen Depth	Bottom Screen Depth	Construction Date	Pump Rate	Drawdown	Time	Transmissivity	* Hydraulic Conductivity
			(m)	(m)	(m)	(m)	(m)		(m^3/hr)	(m)	(days)	(m^2/s)	m/day
Well 1	11° 32' 31.5" N	43° 08' 58.8" E	13.4	57.9	12.3	38.7	57.0	Dec-02	79.5	0.91	0.25	2.4E-02	110
Well 2	11° 32' 34.2" N	43° 08' 58.8" E	15.5	61.0	12.8	46.7	61.0	Feb-03	83.4	0.64	0.25	3.6E-02	220
Well 3	11° 32' 37.7" N	43° 08' 58.8" E	16.8	39.0	13.6	42.7	61.0	Jan-03	75.0	0.41	0.13	4.8E-02	230
Well 4	11° 32' 32.7" N	43° 09' 00.7" E	14.0	39.0	11.6	9.1	27.4	Jul-07	90.9	ND	ND	ND	ND
Well 5*	11° 32' 30.5" N	43° 09' 00.3" E	14.9	51.2	10.9	14.6	39.0	Dec-07	5.7	0.46	1.00	3.8E-03	13
Well 6*	11° 32' 32.4" N	43° 09' 03.8" E	12.2	50.9	9.5	13.1	36.6	Jan-08	6.3	0.30	1.00	6.3E-03	23
Well 7*	11° 32' 32.7" N	43° 09' 07.1" E	12.2	61.0	11.0	42.7	61.0	Oct-08	6.3	0.61	1.00	3.2E-03	15
IW #1	11° 32' 31.1" N	43° 09' 08.8" E	12.2	67.9	12.0	49.4	67.7	Feb-03	93.2	ND	ND	ND	ND
IW #2	11° 32' 30.5" N	43° 09' 11.3" E	11.0	67.0	9.0	48.8	61.0	Feb-03	75.0	ND	0.02	ND	ND
IW #3	11° 32' 36.8" N	43° 09' 09.7" E	10.4	67.7	11.0	49.4	67.7	Jan-03	32.5	0.33	0.03	2.3E-02	110
IW #4	11° 32' 40.5" N	43° 09' 07.9" E	11.6	72.3	10.5	51.5	69.8	Jan-03	ND	ND	ND	ND	ND

Mean = 100

Groundwater Model

To evaluate the potential hydraulic effects of groundwater pumping at Camp Lemonnier a numerical (computer) groundwater-flow model was developed. The model is based on an earlier numerical model of the Camp and Djibouti City area developed in 2011 (Batch and others, 2011). The model uses the ModelMuse (Winston, 2009) graphical user interface for MODFLOW 2005 (Harbaugh, 2005). Figure 5 shows an aerial photo of Camp Lemonnier with the numerical model boundary overlain.

Figure 5. Camp Lemonnier with numerical model grid overlain (adapted from Google Earth).

Model Development

Starting with the numerical model presented in Batch and others (2011), and using the data presented in Table 1, a numerical model was developed to provide estimates of the Camp Lemonnier pumping effects on the Camp area water table. The model grid is 3 km by 3 km (Fig. 5) with the individual model cells set at 30 m by 30 m with a finer grid of 2 m by 2 m for the cells immediately around the Camp wells (Fig. 2). The finer grid is needed to accurately estimate the drawdown in the area immediately adjacent to a pumped well but is not critical at distances of more than 100 m. Based on the geologic data from the Camp Lemonnier well logs, the well depths, and the well-screen intervals, the model consisted of two layers: a shallow aquifer, to represent the reworked marine and alluvial deposits, and a deeper basalt aquifer. The shallow aquifer was assigned a thickness of 30 m. The deeper basalt aquifer was assigned a thickness of 70 m. The model was oriented the same as the Batch and others, 2011, model, with the northwest and southeast model boundaries as no-flow boundaries running parallel to the southwest to northeast groundwater flow gradient. The hydraulic gradient across the model area (0.7 m/km) is the same as used in Batch and others (2011).

The model was calibrated using the drawdown data from Camp Wells 5 and 6 during a one week period of pumping in Camp Well 4 (Crawley and others, 2010). The pumping cycle for Camp Well 4 was approximately 6 hours on and 6 hours off with a pump rate of 400 gpm (gallons per minute). The head responses in wells 5 and 6 showed a cyclic drawdown and recovery that averaged 0.12 m in well 6, located 93 m east of pumping well 4, and 0.15 m in well 5, located 71 m south of pumping well 4 (see fig. 2). The model calibration indicates that the hydraulic conductivity of the shallow aquifer falls between 140 and 190 m/day, with a storativity value of 10^{-5}. Interestingly, the 10^{-5} is smaller than the 10^{-2}–10^{-3} values expected for a shallow alluvial aquifer. However, model calibration using larger storativity values (10^{-2} and 10^{-3}) indicated that the water levels in Camp Wells 5 and 6 did not fully recover between the pumping periods. The failure to fully recover during the no-pump periods resulted in a gradual decrease in the water table elevation, which was not observed in the data. Based on the calibration data, and to insure that the model predictions represent a conservative long-term steady-state flow system, the shallow aquifer was assigned a hydraulic conductivity of 90 m/day and a storativity of 10^{-5}. The deeper basalt aquifer was assigned a hydraulic conductivity of 1.7 m/day and a storativity of 10^{-5}, based on the statistical results presented in Table 1. Pumping scenarios included single-well pumping in well 6 at 200k, 330k, 400k, 600k, 800k, and 1M gallons per day (gpd), and two-well pumping where wells 6 and 4 were each pumped at 330k, and 400k gpd (660k and 800k combined groundwater withdrawal). The model assumes that the water flowing in to the pumped well, or wells, is distributed evenly across the 30-m thickness of the shallow aquifer. The model time period was 30 days, which was sufficient to reach steady-state conditions. The numerical model results are limited to hydraulic effects (water-level changes), and therefore the model does not directly simulate, or predict, water-quality changes; however, potential effects to water quality can be inferred. In general, it is the hydraulic effects that ultimately control changes in water quality; minimal hydraulic effects generally equate to minimal water-quality effects.

Model Results

The numerical model simulations quantify the cones of depression (drop in water-table elevation) created by pumping in a single well (Well 6) and from 2 wells (Wells 4 and 6 pumped simultaneously). The model results can be used to evaluate the potential effects on the area water table, and to optimize the location of future water wells.

Figure 6 presents the results from a model simulation that assumes no pumping at Camp Lemonnier. The figure shows steady-state groundwater flow from the southwest to the northeast with a flow gradient of 0.7 m/km. The color code and the contour lines represent the water-table elevations relative to the model hydraulic gradient, not a true elevation relative to sea level, and provide the baseline values (elevations) for the simulated water table. The northeast boundary (blue) is defined as the zero elevation reference point and therefore the model head at the southwest boundary (red) is equal to 2.1 m (3 km × 0.7 m/km). The figure 6 contour lines are parallel indicating that the groundwater flow from the southwest to the northeast is even and regular.

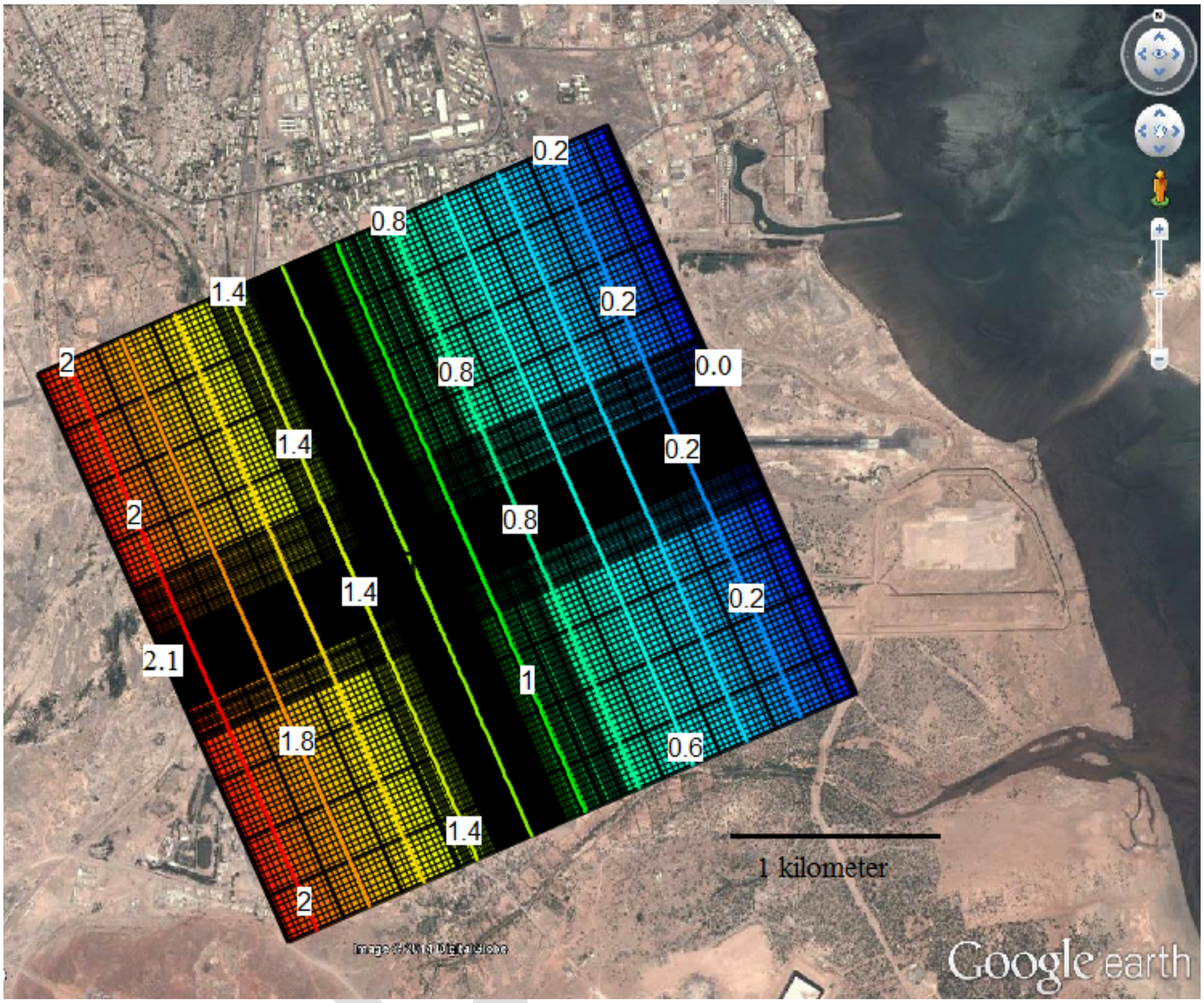

Figure 6. Baseline model results with no pumping at Camp Lemonnier (units are the water-table elevations, in meters, relative to the model hydraulic gradient)

Figure 7 presents the model results for the Camp Well 6 pumping rate of 330k gpd. As in Figure 6, the color code and the contour lines represent the water-table elevation relative to the model, not the true water-table elevation above sea-level. The effect of the well 6 pumping is seen in the distortion of the contour lines near Well 6. As expected, Figure 7 shows that the simulated Camp Lemonnier Well 6 pumping has resulted in additional drawdown (lowered water table) in the area immediately surrounding Well 6. Figure 8 zooms in on the area of Wells 4, 5, and 6. The additional drawdown at Well 6 is shown as a decrease in the contour line elevation (0.8 m) and as a slight change in color from green to blue-green. The model indicates that the drawdown at pumped Well 6 is approximately 0.63 m and the drawdowns at wells 4 and 5 are 0.21 and 0.20 m respectively (Table 2). As the pumping rate increases, the drawdown in the pumping and surrounding wells will become larger.

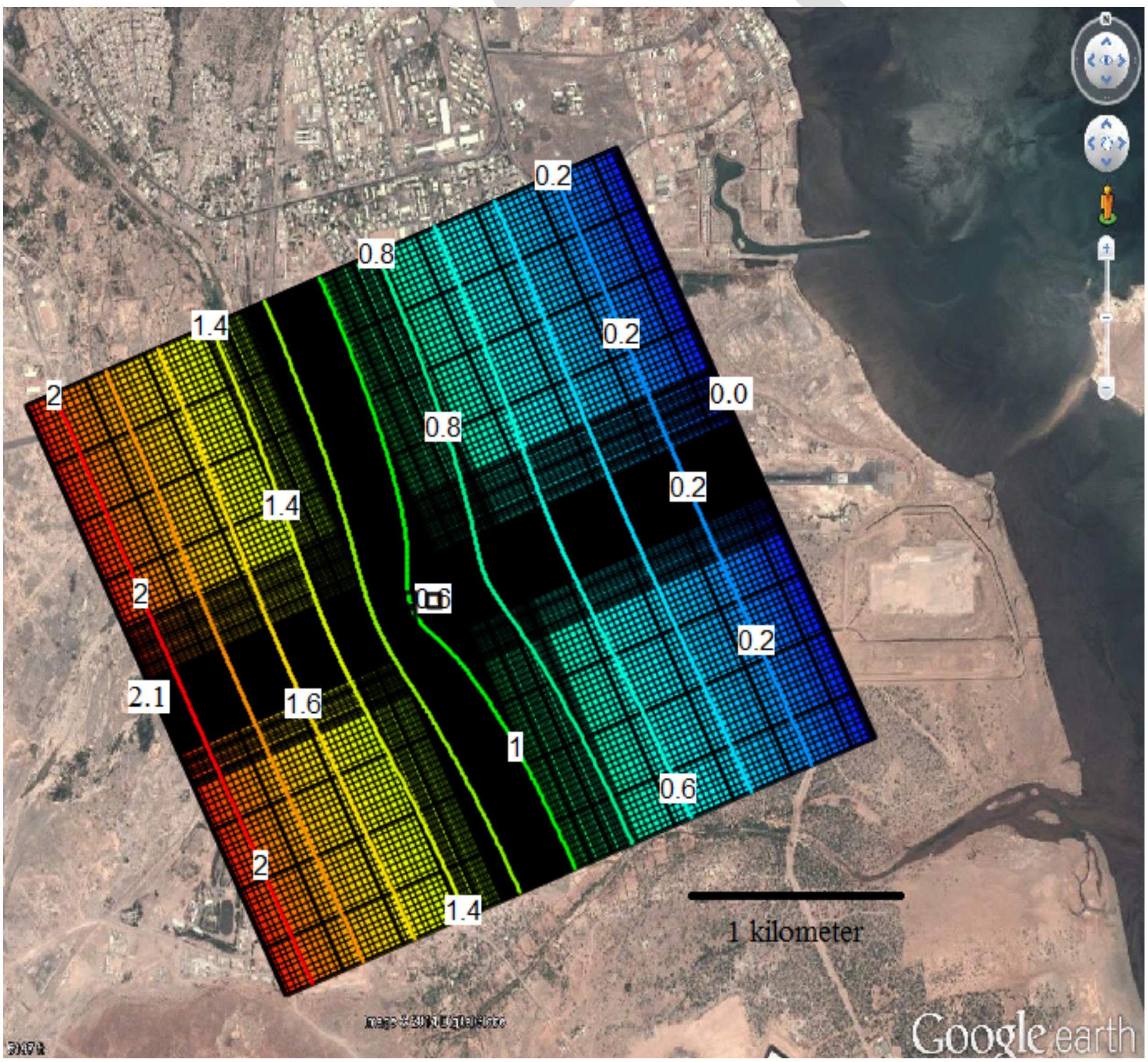

Figure 7. Model results for a Camp Lemonnier Well 6 pumping rate of 330,000 gpd (units are the water-table elevations, in meters, relative to the model hydraulic gradient)

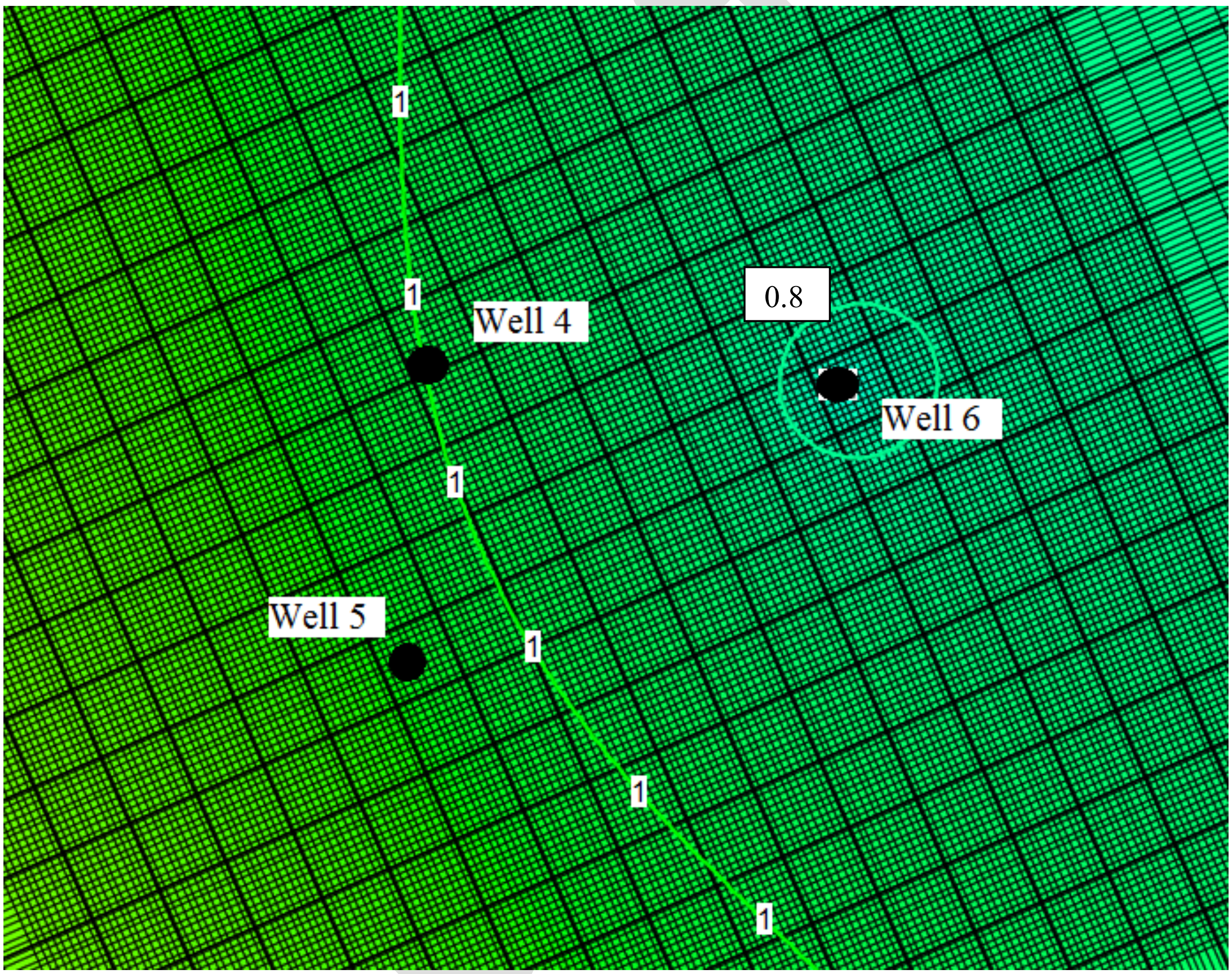

Figure 8. Model results for wells 4, 5, and 6 with Camp Lemonnier Well 6 pumping rate of 330,000 gpd (units are the water-table elevations, in meters, relative to the model hydraulic gradient)

Table 2 presents the simulated water-table drawdowns at Camp Lemonnier Wells 4, 5, and 6 for a for a range of Well 6 pumping rates, and presents a zone of minimal effect. Because the cone of depression created by a pumping water well, in theory, extends for kilometers, it is necessary to define a zone of minimal effect; in this case, a distance from the pumped well (Well 6) where the predicted drawdown is less than 10 cm. Table 2 shows that, as expected, the zone of effect increases proportionally with increased pumping rates. Overall, the model indicates that Well 6 could supply up to 1M gpd with an expected water-table decline at the well of approximately 1.91 m, and water table declines at wells 4 and 5 of 0.64 m and 0.59 m respectively. At the present time, the pump in well 6 has a maximum capacity of 400 gpm and therefore could not supply 1 M gpd; however, the well is capable, assuming that the screen is suitable. The model also indicates that the zone of minimal effect for a 1M gpd pump rate is less than a half a kilometer (460 m). Any water well that has been constructed outside the zone of effect would be expected to experience minimal effect (less than 10 cm of induced water-table drawdown) from pumping in well 6; conversely, pumping at similar rates in a well located outside the zone of effect would have minimal effect on the water levels at wells 4, 5, and 6.

Table 2. Simulated water-table drawdowns at Camp Wells when pumping from Camp Well 6.

Well 6 Pump Rate (m^3/day)	(gal/day)	Drawdown Well 4 (m)	Drawdown Well 5 (m)	Drawdown Well 6 (m)	Zone of Minimal Effect (m)
757	200,000	0.13	0.12	0.38	80
1249	330,000	0.21	0.20	0.63	130
1514	400,000	0.26	0.24	0.76	200
2271	600,000	0.38	0.36	1.14	330
3028	800,000	0.51	0.48	1.53	400
3785	1,000,000	0.64	0.59	1.91	460

Table 3 presents the simulated water-table drawdowns and the zones of minimal effect at Camp Lemonnier Wells 4, 5, and 6, when wells 4 and 6 are pumped simultaneously at equal rates. Comparison of the Table 2 with Table 3 800k gpd simulations show that use of two production wells instead of just one alters the cone of depression. The zone of minimal effect is not changed; however, the drawdown at the individual wells is effected. Because well 4 is now a pumping well, the drawdown at well 4 increases from 0.51 m to 1.02 m; however, the drawdown at well 6 has decreased from 1.53m to 1.02 m. The overall effect is that the use of multiple wells will spread the cone of depression over a larger area, but the drawdown at all points in that larger cone of depression will be less than when a single pump is used. This can be important where there is a risk of the water table dropping below the pump intake.

Table 3. Simulated water-table drawdowns at Camp Wells when pumping from Camp Wells 4 and 6 simultaneously

Well 6 and 4 Pump Rates (m^3/day)	Sum of wells 6 and 4 pumping (gal/day)	Drawdown Well 4 (m)	Drawdown Well 5 (m)	Drawdown Well 6 (m)	Zone of Minimal Effect (m)
1249	660,000	0.84	0.43	0.84	375
1514	800,000	1.02	0.52	1.02	400

Model Limitations

Because a numerical groundwater-flow model is a mathematical representation of a complex groundwater-flow system, the model will always be a simplistic representation of the true groundwater-flow system, and will be subject to errors and limitations related to assumptions and data inputs. For example, the model assumes that both the shallow alluvial aquifer and the deeper basalt aquifer are isotropic and homogeneous; this is not completely accurate, but for the purpose of the model, and the available data, these are reasonable assumptions. In addition, while the model has been calibrated to water-table fluctuations during pump tests, the model is not calibrated to a groundwater discharge, or flux rate. The model simulates recharge as a constant-rate lateral-flow component controlled by constant-head boundaries. The model indicates a large flux (volume) of water moving from southwest to northeast, but it does not provide an estimate of how much of that flux is freshwater recharge from the Ambouli or how much is part of the larger regional groundwater flow system. To minimize groundwater storage effects, the model assumes that the storativity of the shallow alluvial aquifer and the deeper basalt aquifer are both 10^{-5}. These assumptions, and data inputs, are necessary simplifications required for the development of the numerical groundwater-flow model. However, because of these assumptions, and limited data, the use of the model simulations must always be tempered with an understanding of the purpose, and limits, of the model.

Groundwater Quality

Batch and others (2011) discusses some of the water quality issues confronting both the City of Djibouti and Camp Lemonnier. Table 4 presents the depths, screen intervals, TDS values, and pump depths for the Camp Wells. The October, 2010 TDS values and pump depths were obtained from the ROWPU operators on a field visit to Camp Lemonnier. The June, 2014 TDS values are from L. Batch (Naval Facilities Engineering Command, June 2014, written commun.). The June, 2014 pump depths are from an illustrated poster hanging in the Camp Public Works offices.

Table 4. Camp Lemonnier Wells Total Dissolved Solids (TDS) data. [ND, No Data]

	Altitude	Total Depth	Water Depth	Top Screen	Bottom Screen	Pump Depth Oct 2010	TDS Oct 2010	Pump Depth June 2014	TDS June 2014
	(m)	(m)	(m)	(m)	(m)	(m)	(mg/liter)	(m)	(mg/liter)
Well 1	13.4	57.9	12.3	38.7	57	54.9	45,000	ND	ND
Well 2	15.5	61	12.8	46.7	61	ND	42,000	ND	ND
Well 3	16.8	39	13.6	42.7	61	ND	ND	ND	ND
Well 4	14	39	11.6	9.1	27.4	18.3	7,000	21	7,000
Well 5	14.9	51.2	10.9	14.6	39	ND	8,000	46	50,000
Well 6	12.2	50.9	9.5	13.1	36.6	30 or 36	10,000	34	15,000
Well 7	12.2	61	11	42.7	61	ND	40,000	ND	ND

The Table 4 TDS data indicate a correlation between screen depth and TDS. Wells with screen intervals in the 38.7–61 m range (Wells, 1, 2, 3, and 7) had October, 2010 TDS values greater than 40,000 mg/liter. Wells with screen intervals in the 9.1–39 m range (Wells 4, 5, and 6) had significantly lower October, 2010 TDS values. The June, 2014 TDS data shows that Well 4 continues to have the lowest TDS values (7,000 mg/liter), while the Well 5 TDS value has risen to 50,000 mg/liter and the Well 6 TDS value has risen to 15,000 mg/liter. Well 4, with the shallowest screen depth, and the shallowest pump depth, had the lowest TDS values. Well 6 is the next shallowest, and although the TDS values have increased from 10,000–15,000 mg/liter, the values are less than the deeper wells. Well 5 is an outlier because the October, 2010 TDS value is low (8,000 mg/liter), yet the TDS value increased to 50,000 mg/liter in June of 2014. The depth of the pump in Well 5, during the October, 2010 sampling is unknown, but we do know that the depth of the pump in June, 2014 was 46 m (Table 4). One possible explanation for the smaller TDS value in Well 5 during the October, 2010 sample collection is that the pump may have been installed at a depth less than 46 m. Overall, the data indicate that the water quality is a function of the screen and pump depth. The Table 4 data indicates that in the area of Wells 4, 5, and 6 the depth to water is approximately 11 m, and that there is an interval of water with TDS values of approximately 7,000 mg/liter that extends down to a depth of 21 m and an interval of water with TDS values around 15,000 mg/liter from 21–34 m. The data indicate that the TDS values increase with depth, and that by a depth of 46 m, the groundwater has TDS value greater than the TDS value of the Red Sea; approximately 35, 000 mg/liter. The elevated TDS values (40,000 mg/liter and greater) are the result of salt dissolution from the marine deposits of the shallow aquifer. Salt dissolution and increasing TDS values is especially important as it relates to the lower TDS water (7,000 mg/liter) pumped from the shallow aquifer under Camp Lemonnier. Groundwater recharge from the Wadi Ambouli begins as fresh water, but as the fresh water comes in contact with the high-salt-content marine deposits, dissolution of the marine salt occurs, and the TDS content of the fresh water increases. The numerical model flow gradient from southwest to northeast combined with the TDS data indicate that water recharging the shallow aquifer, from the Wadi Ambouli, may become increasingly high in TDS as it flows under the Camp and to the sea. Therefore, wells located closest to the source of fresh-water recharge (Wadi Ambouli) will have the lowest TDS values. The analysis and TDS data also indicate that adjustment of the pump depths and use of multiple pump wells (4, 5, and 6) may be the best way to lower the overall TDS values and minimize the drawdown in any one pumped well.

Summary

This report presents the results from a hydrologic analysis of the groundwater flow system at Camp Lemonnier, Djibouti. The report includes results from a numerical (computer) groundwater-flow model developed to evaluate (1) the hydraulic effects of groundwater pumping on the area water table and (2) the Total Dissolved Solids (TDS) data from the Camp Wells.

Camp Lemonnier is underlain by reworked marine and alluvial deposits. The reworked alluvium and marine deposits can form highly permeable aquifers, provided the clay content is not too great. The alluvium and marine deposits are underlain by volcanic rock, mostly fractured basalt. The reworked alluvium and marine deposits that underlie Camp Lemonnier contain a layer of water with TDS levels lower than sea water. The source of the lower TDS groundwater appears to be recharge from the surface water of the Wadi Ambouli located immediately west of Camp Lemonnier.

The numerical model was calibrated using water-table drawdown data from Camp Lemonnier wells. The shallow marine and alluvial deposits aquifer was defined to be 30 m thick and assigned a hydraulic conductivity of 90 m/day and a storativity of 10^{-5}. The deeper basalt aquifer was defined as 70 m thick and assigned a hydraulic conductivity of 1.7 m/day and a storativity of 10^{-5}. Pumping scenarios included single-well (Well 6) and multiple well (Wells 4 and 6) pumping scenarios. The model simulations indicate that well 6 could supply up to 1M gpd (gallons per day) with an expected steady-state water-table decline at the well of approximately 1.91 m, and water table declines at wells 4 and 5 of 0.64 m and 0.59 m, respectively. The model simulations also indicate that the zone of minimal effect (less than 10 cm of induced water-table drawdown) for 1M gpd is less than a half a kilometer (460 m). Any well located outside the zone of effect would be expected to experience minimal effect from pumping in well 6; conversely, pumping at similar rates in a well located outside the zone of effect would have minimal effect on the water levels at wells 4, 5, and 6. The simulations also show that the use of multiple wells will spread the cone of depression over a larger area, but the drawdown at all points in that larger cone of depression will be less than when a single pump is used. This can be important where there is a risk of the water table dropping below the pump intake.

The TDS values are a function of screen depth and pump depth. Shallower screen intervals and shallower pump depths correlate with lower TDS water. The numerical model results, combined with the TDS data, indicate that water recharging the shallow aquifer from the Wadi Ambouli may become increasingly high in TDS as it flows under the Camp and to the sea. Therefore, wells located closest to the Wadi Ambouli will have the lowest TDS values. Overall, the analysis and TDS data indicate that adjustment of pump depths and use of multiple pump wells (4, 5, and 6) may be the best way to lower the overall TDS values and minimize the water-table drawdown in any one pumped well.

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