HYDROLOGIC AND HYDROGEOLOGIC ASSESSMENT OF THE SURFACE WATER AND GROUNDWATER RESOURCES AFFECTING THE MOAB CITY SPRINGS AND WELLS, MOAB, UTAH: PHASE 1: HYDROLOGIC AND ENVIRONMENTAL SYSTEM ANALYSIS (HESA) AND CONCEPTUAL MODELS

Authors:
Dr. Kenneth E. Kolm, Hydrologic Systems Analysis, LLC., Golden, Colorado
and
Paul K.M. van der Heijde, Heath Hydrology, Inc., Boulder, Colorado

Prepared For:
City of Moab, Utah

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1 INTRODUCTION

Under an agreement with City of Moab, Utah, Hydrologic Systems Analysis LLC (HSA) of Golden, Colorado, in conjunction with Heath Hydrology, Inc. (HHI) of Boulder, Colorado, was tasked to: 1) Perform a Hydrologic and Environmental System Analysis (HESA) of the Moab City Springs and Wells (MCSW) area, supported by GIS databases and maps, to develop a comprehensive and updated understanding of hydrogeologic and hydrologic characteristics of the groundwater system, using currently available data and published analyses; 2) Collect hydrological, hydrogeological and other data necessary to construct a water budget for the MCSW area, and develop an as-accurate-as-possible water budget for the MCSW area as the region affecting the City's springs and wells; and 3) Update three drinking water source protection plans and the delineations of the drinking water source protection zones, one for the City's Skakel Spring, one for the City's Springs 1, 2, and 3 near the golf course (referred to as "City of Moab Springs", and one for the City's wells (Wells 4, 5, 6, 7, and 10), also near the golf course (see Figure 1 for the current delineation of the Moab Drinking Water Source Protection (DWSP) Zones for the wells and springs). Each of these tasks constitutes a phase of the project. This report contains the results of Phase 1, Hydrologic and Environmental System Analysis (HESA).

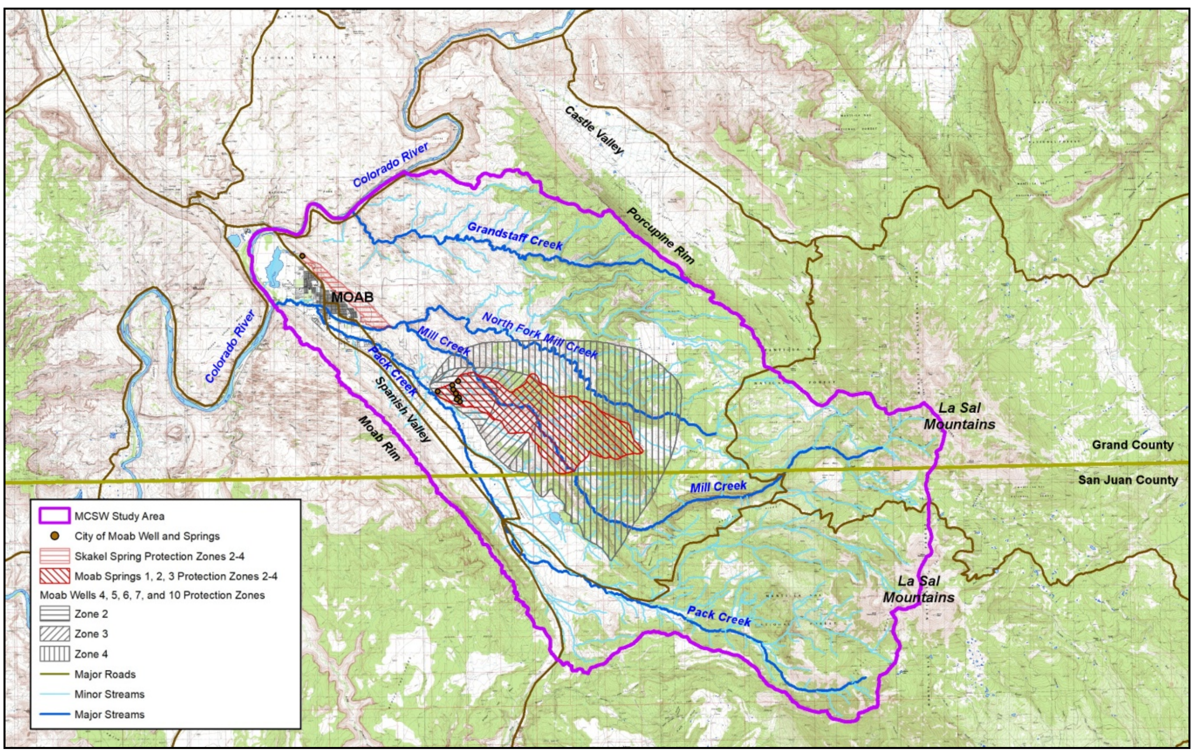

Figure 1. Topographic Map Showing the Moab City Springs and Wells (MCSW) Study Area, and the Location of the City of Moab Springs and Wells and Related Drinking Water Source Protection (DWSP) Zones.

The study area is located between the La Sal Mountains to the southeast, the Colorado River to the northwest, the Porcupine Rim to the northeast, and the Moab Rim to the southwest (Figures 1 and 2). The delineation of the study area is based on the nature and extent of the major hydrogeological systems present, the surface hydrology of the area, and water resources related land use considerations. The area covers the Mill Creek, Grandstaff Creek, and Pack Creek watersheds as delineated in the GIS files downloaded from the data portal of the Natural Resources Conservation Service (NRCS, 2017). The study distinguishes between five hydrologic entities: 1) Southwestern sides of the La Sal Mountains including the Tertiary bedrock units and the glacial/alluvial deposits emanating out from the high peaks; 2) South Mesa and Wilson Mesa regions including alluvial cover and subsurface sedimentary bedrock; 3) Mill Creek Watershed (including the Sand Flats region); 4) Grandstaff Watershed including the Porcupine Rim region; and 5) Pack Creek watershed including the Spanish Valley region alluvial basin and subsurface sedimentary bedrock. The combined Mill Creek Watershed and Glen Canyon aquifer underlying the Sand Flats region will be the setting for the water budget to be developed in a later phase of this study, and the updating of the Water Protection Plans for the springs and wells of the City of Moab.

The HESA of the surface water and groundwater systems in the MCSW study area makes extensive use of existing GIS databases and maps of geologic, hydrogeologic and hydrologic characteristics, collected specifically for this study. Additional data layers and evaluations were needed to illustrate the HESA – particularly with respect to the hydrogeological characteristics of the rock types present and the significance of hydrostructures. The results of the HESA of the MCSW area are documented in this report. The results of the HESA provides support for planning, zoning and other decision-making tasks, including those related to protection of groundwater resources for use as public or communal water supplies, and prepares for the next phases of the study involving water budget quantification and updating of the Moab City Well Protection Plans. The HESA included a few scoping site visits to the study area; additional fieldwork has been conducted as the study progressed.

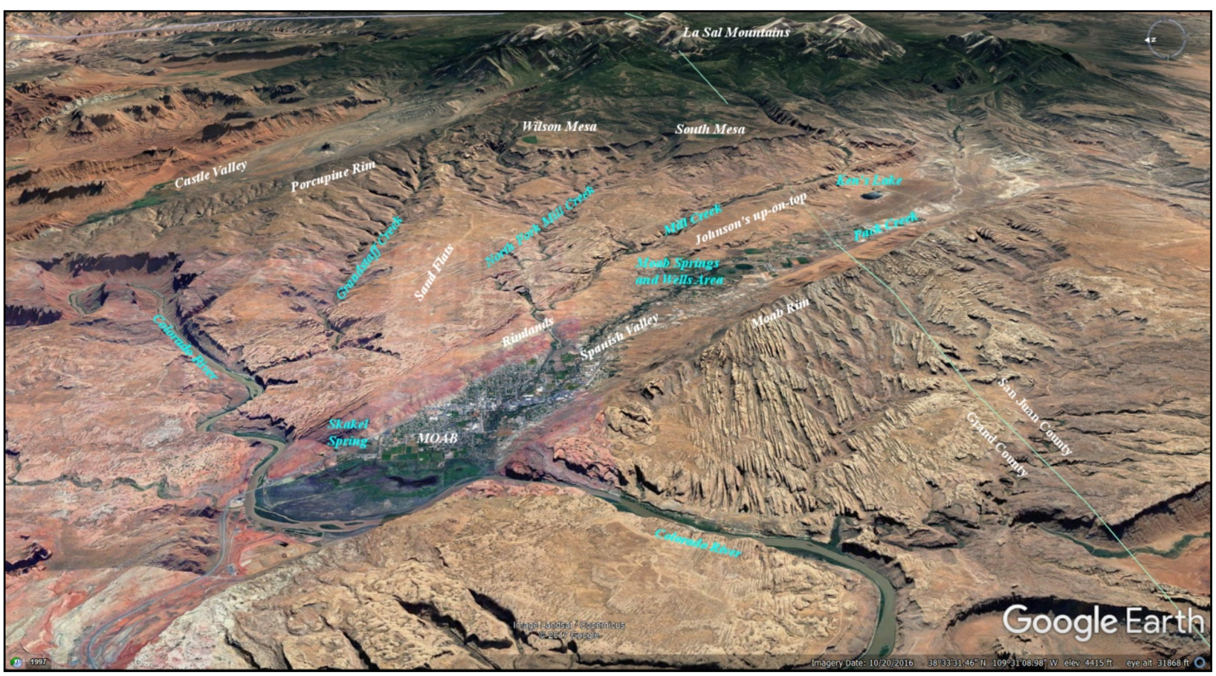

Figure 2. View of the Regional Setting of the Moab City Springs and Wells (MCSW) Study Area (Source: Google Earth, Imagery May 2016).

In conducting this study and preparing this report, extensive use has been made from data layers collected in a Geographical Information System (GIS) using the ESRI® ArcMap™ software. The data sources included Utah AGRC (Automated Geographic Reference Center), Utah Division of Water Rights (UDWR), Utah Division of Environmental Quality (Utah DEQ), Utah Geological Survey (UGS), U.S. Geological Survey (USGS), Natural Resources Conservation Service (NRCS) of the U.S. Department of Agriculture, NOAA National Centers for Environmental Information, City of Moab, and others. In addition, HSA/HHI has prepared a number of data layers specifically for this report through interpretation of existing data sets and field reconnaissance.

It should be noted that that this report will not obviate the need for additional hydrogeologic analysis on a site-specific/parcel-specific basis by developers and/or the City, or in any water right, geotechnical, or environmental study requiring due diligence. The information in this report is intended to be used as indicator only, as part of a multi-step land use decision-making process, and to provide a starting point for further study of the City's surface water and groundwater resources. Additional data bases will be developed as the result of the water budget analysis, and the updating of the Water Protections Plans for the springs and wells for the City of Moab in subsequent phases of this project.

2 DEVELOPMENT OF CONCEPTUAL MODELS OF HYDROLOGIC SUBSYSTEMS OF THE MOAB CITY SPRINGS AND WELLS (MCSW) STUDY AREA

HESA is an approach used to conceptualize and characterize relevant features of hydrologic and environmental systems, integrating aspects of climate, topography, geomorphology, groundwater and surface water hydrology, geology, ecosystem structure and function, and the human activities associated with these systems into a holistic, three-dimensional dynamic conceptual site model (CSM). This watershed-based, hierarchical approach is described by Kolm and others (*1996*) and codified in ASTM D5979 Standard Guide for Conceptualization and Characterization of Ground Water Systems *(ASTM 1996(2008))*. The CSM of the MCSW study area covers elements of climate, topography, soils and geomorphology, surface water characteristics, hydrogeologic framework, hydrology, and anthropogenic activity as related to the surface water and groundwater systems in the study area.

Based on field surveys and a preliminary HESA, a number of hydrogeologic subsystems were identified within the MCSW study area. Each of these subsystems has a unique hydrogeologic setting and groundwater flow system and is described in detail in forthcoming sections of the report. Furthermore, current anthropogenic modifications of the natural hydrologic features in these subsystems are minimal except in the Spanish Valley, and are primarily related to domestic water use (wells, lawn watering and septic systems), agricultural practices and irrigation (surface water diversions and irrigation return flow). A brief discussion of potential modification of natural flow patterns and impacts on water budgets and water quality, particularly salinity, from agricultural and urbanization activities is included.

2.1 Climate

The climate in the study area has both local and regional components and includes effects of elevation and slope aspect (*i.e.*, steepness and orientation with respect to the prevailing winds and sun exposure). The climate in the study area would be semi-arid to arid in its entirety if not for the presence of the La Sal Mountains in the southeastern section. These mountains, rising more than 8000ft above the Spanish Valley floor near Moab, capture significant moisture from passing storm systems in the form of rain and snow.

Relevant NOAA weather stations for the study area are MOAB, UT (USCOO425733) in the town of Moab at 4054ft (formerly known as National Weather Service (NWS) Cooperative Network (COOP) station 425733) and LASAL MOUNTAIN, UT (USS0009L03S) at 9560ft (Figure 3 and Tables 1a, 1b and 1c). These two stations, for which the data are available at NOAA's National Centers for Environmental Information, provide an overlapping period of observations (1982-2017) useful for comparative analysis. These data will be used in the water budget analysis and potential effects of climate change in a later phase of this study.

Data from the NWS COOP network, the NRCS (Natural Resources Conservation Service) SNOTEL network, and local, state, regional, and federal networks were used to prepare a map of spatially distributed precipitation corrected for elevation using PRISM (Parameter - elevation Regression on Independent Slopes Model) developed by Oregon State University for the NRCS (Figure 4). As these data sources show, there is a gradual precipitation gradient in

Moab/Spanish Valley from about 9 inches annually at Moab, UT in the far northwestern boundary of the MCSW study area to about 14 inches near upper end of Spanish Valley, UT, and more than 40 inches at the higher elevation of the La Sal Mountains. Note the enhanced precipitation near the Moab and the Porcupine Rims of a few inches per year and the gradual increase of precipitation from the Spanish Valley and Sand Flats towards the La Sal Mountains.

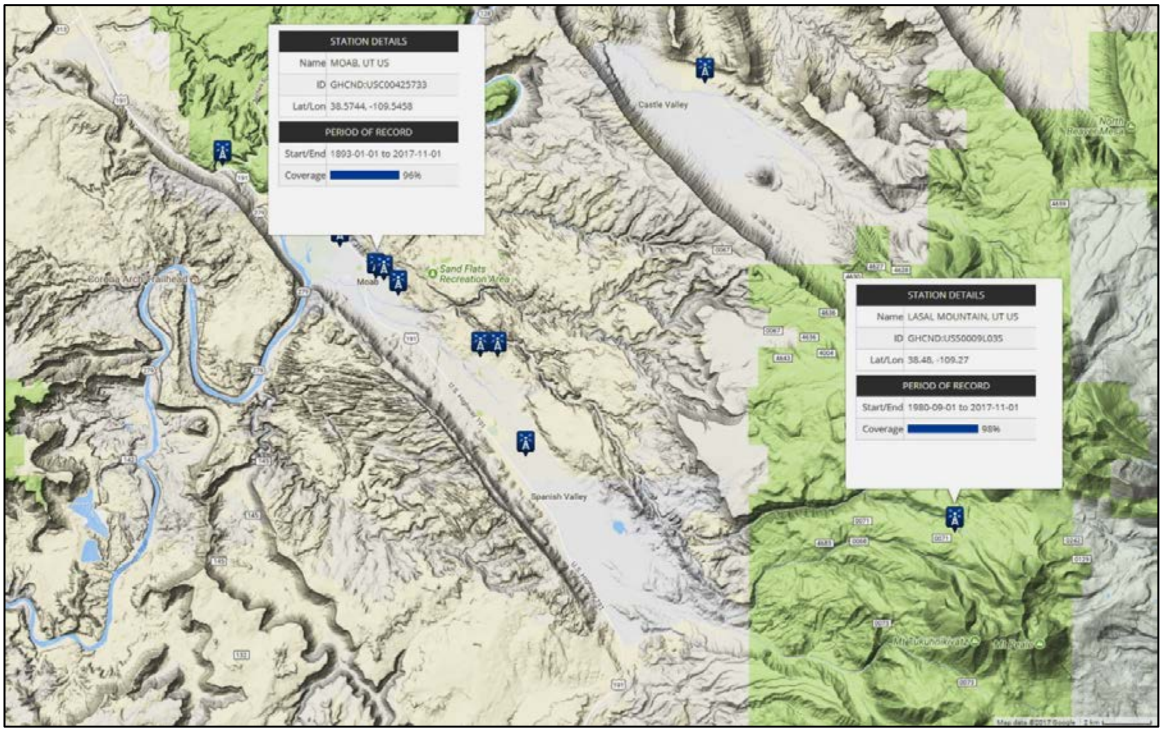

Figure 3. Location of Weather Stations MOAB (GHCND: USC00425733) and LASAL MOUNTAIN (GHCND: USS0009L03S) in the MCSW Study Area.
(Source: NOAA National Centers for Environmental Information, 2017)

MOAB, UTAH (425733)

Period of Record Monthly Climate Summary

Period of Record : 01/01/1893 to 06/08/2016

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max. Temperature (F)	42.4	50.8	62.2	72.2	82.2	92.6	98.2	95.3	86.6	73.3	56.9	44.4	71.4
Average Min. Temperature (F)	18.2	24.7	32.9	40.9	48.6	56.1	63.1	61.2	51.6	39.6	28.3	20.3	40.5
Average Total Precipitation (in.)	0.65	0.61	0.80	0.81	0.72	0.42	0.79	0.85	0.85	1.03	0.69	0.77	9.00
Average Total SnowFall (in.)	3.8	1.5	0.8	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.7	3.0	10.0
Average Snow Depth (in.)	0	0	0	0	0	0	0	0	0	0	0	0	0

Percent of possible observations for period of record.
Max. Temp.: 94.8% Min. Temp.: 94.8% Precipitation: 95.8% Snowfall: 91.2% Snow Depth: 58.7%
Check Station Metadata or Metadata graphics for more detail about data completeness.

Western Regional Climate Center, wrcc@dri.edu

Table 1a. Average Monthly and Annual Maximum and Minimum Temperature, Precipitation, Snow Fall and Snow Depth for MOAB Station (GHCND: USC00425733; COOP425733) for Period 1893-2016.
(Source: Western Regional Climate Center (WRCC), 2017. Desert Research Institute, Reno, Nevada).

U.S. Department of Commerce
National Oceanic & Atmospheric Administration
National Environmental Satellite, Data, and Information Service

Global Summary of the Year 1982 - 2007
Generated on 12/29/2017

National Centers for Environmental Information
151 Patton Avenue
Asheville, North Carolina 28801

Current Location: Elev: 4053 ft. Lat: 38.5744° N Lon: -109.5458° W
Station: **MOAB, UT US USC00425733**

Date	Liquid Precipitation (Inches)			Frozen Precipitation (Inches)					Number of Days		
Elem->	PRCP	EMXP		SNOW	EMSN		EMSD		DP01	DP05	DP10
Year	Total Liquid Content	Extreme Max Precip	Date of Occurrence	Snowfall	Extreme Max Snowfall	Date of Occurrence	Extreme Max Snow Depth	Date of Occurrence	Precip >= 0.01"	Precip >= 0.50"	Precip >= 1.00"
1982	6.63	1.07	Aug-24						60		16
1983	16.44	2.77	Jul-23	0.0	0.0+	Dec-31	0+	Dec-31	77		33
1984	11.26	0.82	Oct-21						60		31
1985	11.40	0.88	Apr-21						66		35
1986	9.66	1.09	Oct-11						68		23
1987	12.11	0.96	Jul-31						81		36
1988	8.14	0.84	Aug-26	12.6	7.0	Jan-05			53		24
1989	4.91	0.53	Aug-18				4	Jan-24	45		16
1992	7.10	0.57	Sep-19	0.0	0.0+	Dec-31			52		23
1993	11.04	1.30	May-31	7.0	4.0	Jan-07	0+	Dec-31	60		31
1994	6.76	0.49	Dec-06	0.3	0.3	Nov-26	0+	Dec-31	63		23
1996	8.48	0.70	Feb-21	0.4	0.3	Dec-23	0+	Dec-31	69		26
1997	13.12	0.72	Sep-06	6.8	4.3	Dec-07			83		42
1998	9.06	1.06	Oct-27						69		26
1999	11.58	1.31	Jul-15						64		36
2000	8.54	0.85	Aug-29	10.8	3.0	Nov-15	2+	Mar-20	65		29
2001											
2002	5.58	1.08	Sep-07	8.3	4.0	Jan-29			51		21
2003	7.72	0.62	Dec-08	8.8	5.0	Nov-22	5	Nov-22	60		24
2004	8.49	0.75	Nov-09	7.4	2.0	Feb-04			70		25
2005	9.57	0.84	Mar-26	0.0T	0.0T+	Dec-19	0	Dec-19	65		33
2006	11.72	1.63	Oct-06	11.8	4.0	Nov-28	4	Nov-28	64		30
2007	10.62	1.19	Apr-09	10.5	3.5	Dec-11	4	Dec-11	52		24

Global Summary of the Year 2008 - 2017
Generated on 12/29/2017

Current Location: Elev: 4053 ft. Lat: 38.5744° N Lon: -109.5458° W
Station: **MOAB, UT US USC00425733**

Date	Liquid Precipitation (Inches)			Frozen Precipitation (Inches)					Number of Days		
Elem->	PRCP	EMXP		SNOW	EMSN		EMSD		DP01	DP05	DP10
Year	Total Liquid Content	Extreme Max Precip	Date of Occurrence	Snowfall	Extreme Max Snowfall	Date of Occurrence	Extreme Max Snow Depth	Date of Occurrence	Precip >= 0.01"	Precip >= 0.50"	Precip >= 1.00"
2008	7.74	1.08	Jun-05	15.2	3.2	Dec-18	1+	Dec-25	48		25
2009	7.04	0.65	Dec-08	19.7	8.0	Dec-08	8	Dec-08	49		21
2010	11.50	0.73	Sep-23	24.8	6.6	Dec-30	7+	Dec-31	78		39
2011	9.05	0.78	Jul-27	1.8	0.8	Dec-13	6+	Jan-02	59		29
2012	5.14	0.67	Oct-12	9.8	4.0+	Dec-24	6+	Dec-28	47		19
2013	10.27	0.90	Nov-23	23.0	7.3	Dec-04	6+	Dec-11	62		29
2014	11.74	1.54	May-11	3.5	2.0	Dec-29	2+	Dec-29	60		32
2015	13.17	0.91	Jun-06	13.2	7.0	Dec-15	3+	Dec-16	81		43
2016	8.63	0.82	Aug-04	10.7	6.0	Feb-01	5	Feb-01	55		28
2017											

(blank) Data element not reported or missing.
+ Occurred on one or more previous dates during the month. The date in the Date field is the last day of occurrence.
A Accumulated amount.
T Trace amount

Table 1b. Annual Precipitation for MOAB Station (GHCND: USC00425733; COOP425733) for Period 1982-2016. (Source: NOAA National Centers for Environmental Information, 2017).

Precipitation type (rainfall versus snowfall), amount, and temporal and spatial distribution are important for determining the amount of recharge that a groundwater system may receive, particularly when it consists of the thick unconsolidated materials or shallow, permeable bedrock under unconfined conditions. The distribution of average annual precipitation is an important indicator of the climate of a particular area, and in the case of the MCSW study area, the climate ranges from semi-arid-to-arid in the valleys and rims, and subhumid to humid in the La Sal Mountains. There is a small natural recharge potential in the valley floors and on the rims, mostly from rain and some snow throughout the late fall, winter, and spring, and a moderate to large natural recharge potential from both rain and snow in the higher elevation areas of the La Sal Mountains. The summer months are characterized by high evaporation rates and are too desiccated for significant groundwater infiltration and recharge in the valley floors and rims, with the exception of an occasional localized intense summer storm, especially on irrigated (high soil moisture content) lands and in the channels of the drainages. Thus, most of the natural groundwater recharge in the near-surface aquifers in the valley floors and rims occurs during a short period of time in the late fall, winter and early spring (October to April). By comparison, the topographically higher terrains surrounding the MCSW study area near the La Sal Mountains are humid-to-subhumid and cool and have excellent groundwater recharge potential, both from rainfall in the spring, summer, and autumn months, and from the melting of snowpack throughout the winter and early spring, especially where covered by gravels and slope deposits. It should be noted that the entire study area has groundwater recharge potential; even the driest areas probably receive approximately 1-2 inches of recharge annually. This is important when considering the ultimate groundwater system flow directions and areas of groundwater recharge, and for calculating water budgets.

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Global Summary of the Year 1982 - 2007
Generated on 12/22/2017

National Centers for Environmental Information
151 Patton Avenue
Asheville, North Carolina 28801

Current Location: Elev: 9560 ft. Lat: 38.4800° N Lon: -109.2700° W
Station: **LASAL MOUNTAIN, UT US USS0009L03S**

Date	Liquid Precipitation (Inches)			Frozen Precipitation (Inches)					Number of Days		
Elem->	PRCP	EMXP		SNOW	EMSN		EMSD		DP01	DP05	DP10
Year	Total Liquid Content	Extreme Max Precip	Date of Occurrence	Snowfall	Extreme Max Snowfall	Date of Occurrence	Extreme Max Snow Depth	Date of Occurrence	Precip >= 0.01"	Precip >= 0.50"	Precip >= 1.00"
1982	36.80	2.00	Oct-26						84		84
1983	52.36	2.20	Feb-18						118		118
1984	39.67	1.40	Sep-17						116		116
1985	39.74	2.20	Apr-20						125		125
1986	33.24	1.30	Sep-23						106		106
1987	41.45	2.00	Nov-05						129		129
1988	29.16	1.40	May-01						97		97
1989	18.46	1.40	Aug-17						62		62
1990	30.85	1.60	Feb-15						98		98
1991	29.94	1.50	Feb-16						118		118
1992	30.34	1.90	Oct-30						112		112
1993	38.23	1.70	Jan-19						120		120
1994	32.26	1.70	Sep-29						92		92
1995	33.52	1.50	Jun-17						127		127
1996	39.24	1.70	Sep-12						117		117
1997	39.56	2.20	Aug-04						121		121
1998	32.55	1.40	Oct-25						127		127
1999	29.77	1.40	Aug-27						93		93
2000	35.47	1.70	Sep-26				52	Mar-20	100		100
2001	36.76	1.40	Jul-08				51	Mar-11	122		122
2002	22.75	1.70	Sep-07				34	Mar-08	79		79
2003	29.45	1.10	May-09				58	Mar-04	108		108
2004	29.94	1.20	Oct-28				49	Feb-29	103		103
2005	32.06	1.00	Jun-03				68	Mar-30	122		122
2006	39.33	2.70	Oct-06				52	Mar-12	102		102
2007	33.15	1.90	Sep-23				36+	Mar-02	97		97

Current Location: Elev: 9560 ft. Lat: 38.4800° N Lon: -109.2700° W
Station: **LASAL MOUNTAIN, UT US USS0009L03S**

Global Summary of the Year 2008 - 2017
Generated on 12/22/2017

Date	Liquid Precipitation (Inches)			Frozen Precipitation (Inches)					Number of Days		
Elem->	PRCP	EMXP		SNOW	EMSN		EMSD		DP01	DP05	DP10
Year	Total Liquid Content	Extreme Max Precip	Date of Occurrence	Snowfall	Extreme Max Snowfall	Date of Occurrence	Extreme Max Snow Depth	Date of Occurrence	Precip >= 0.01"	Precip >= 0.50"	Precip >= 1.00"
2008	28.98	1.70	Dec-22				50	Feb-04	81		81
2009	24.86	1.00	Feb-23				41	Apr-04	88		88
2010	38.28	1.50	Feb-19				60	Feb-21	100		100
2011	32.87	1.50	Nov-05				46	Mar-08	98		98
2012	21.67	1.50	Dec-14				49	Mar-02	59		59
2013	33.38	1.50	Oct-10				50	Feb-23	94		94
2014	31.17	1.50	Sep-27				38	Feb-04	85		85
2015	40.77	2.20	Nov-10				57	Dec-25	91		91
2016	33.94	1.60	Dec-16				52	Feb-01	95		95
2017											

(blank) Data element not reported or missing.
+ Occurred on one or more previous dates during the month. The date in the Date field is the last day of occurrence.
A Accumulated amount.
T Trace amount

Table 1c. Annual Precipitation for LASAL MOUNTAIN Station (GHCND: USS0009L03S) for Period 1982-2016. (Source: NOAA National Centers for Environmental Information, 2017).

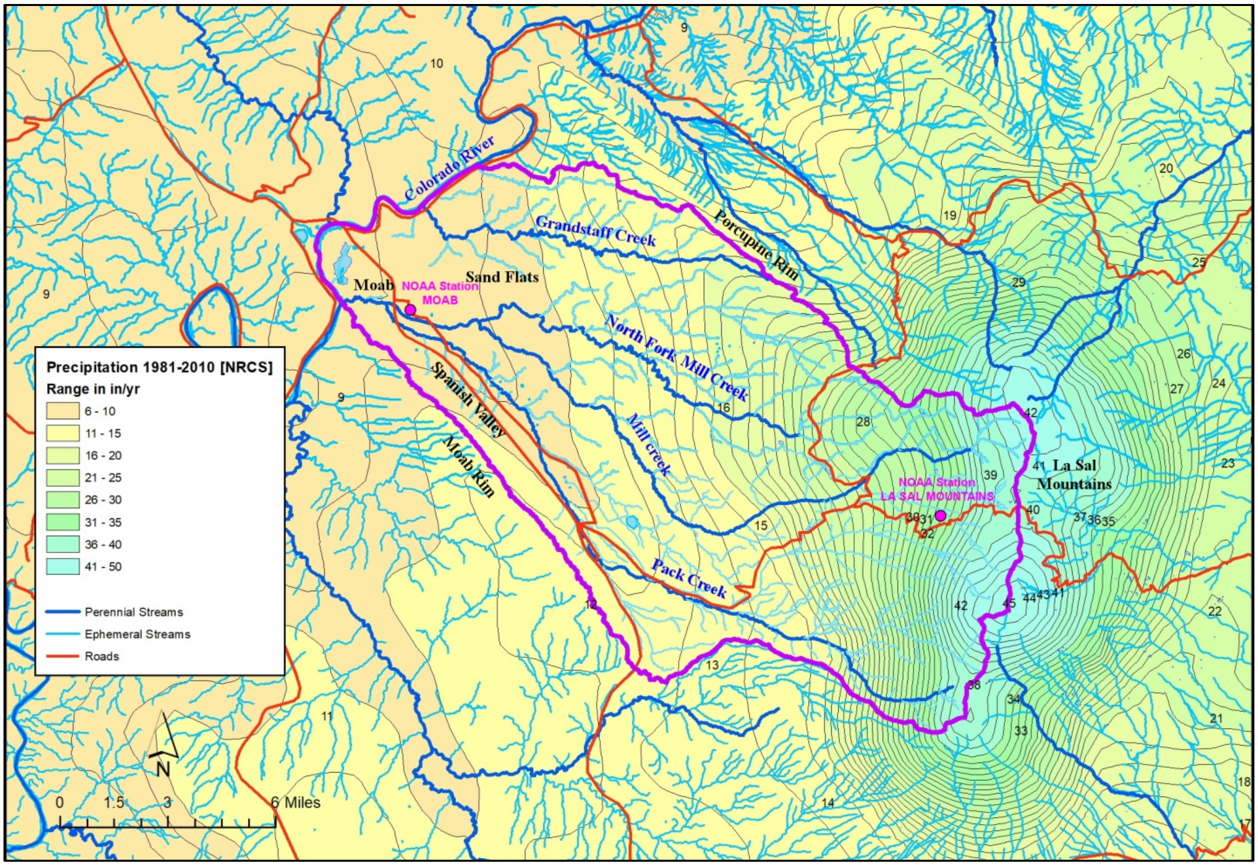

Figure 4. The Spatial Distribution of the Average Annual Precipitation for the Period 1981-2010 in the MCWS Study Area Shows the Influence of the La Sal Mountains on Precipitation Patterns. (Source: Natural Resources Conservation Service, 2017).

2.2 Topography and Geomorphology

The Moab City Springs and Wells study area is located in the Colorado Plateau physiographic province, and geomorphically in the Paradox Basin subprovince (Thornbury, 1965). This subprovince is characterized topographically and geologically as a series of northwest trending salt anticlines with collapse features called grabens (to be discussed in subsequent chapters of the report) that result in landscapes that seem to be torn apart from the earth with gaping holes (valleys) and sharp serrated surrounding rimlands (Figures 1, 2, and 5). This landscape is characterized as abrupt, angular, and discontinuous, and the result is for surface water and groundwater systems to be localized (*i.e.,* non-regional). Spanish Valley, Sand Flats, and the Moab and Porcupine Rims are typical features in this province.

The surface elevation in the MCSW study area ranges from about 1,300 m (≈4,000 ft) in the Colorado River Valley to about 3,700 m (≈12,700 ft) in the La Sal Mountains (Figure 1 and 6). The topography of the study area has four distinct terrains: 1) steeply sloping to gently rolling, dissected bedrock and glacial/alluvial deposits of the foothills and mountains of the La Sal Mountain region to the east of Moab/Spanish Valley; 2) gently sloping, moderately dissected, eolian deposits on discontinuous mesa tops and plateaus, for example in the Sand Flats region, along both the northeastern and southwestern flanks of the surrounding rim lands; 3) greatly dissected, connected and disconnected, continuous and discontinuous fractured bedrock features (trenches and fins) and hillslope fans and mass wasting features (particularly talus and debris flows along these rimlands); and 4) continuous alluvial valley bottoms associated with the principal drainage of Pack Creek (Figure 1, 5, and 6) and older alluvial terraces and pediment features in the southeastern part of Spanish Valley around South Mountain.

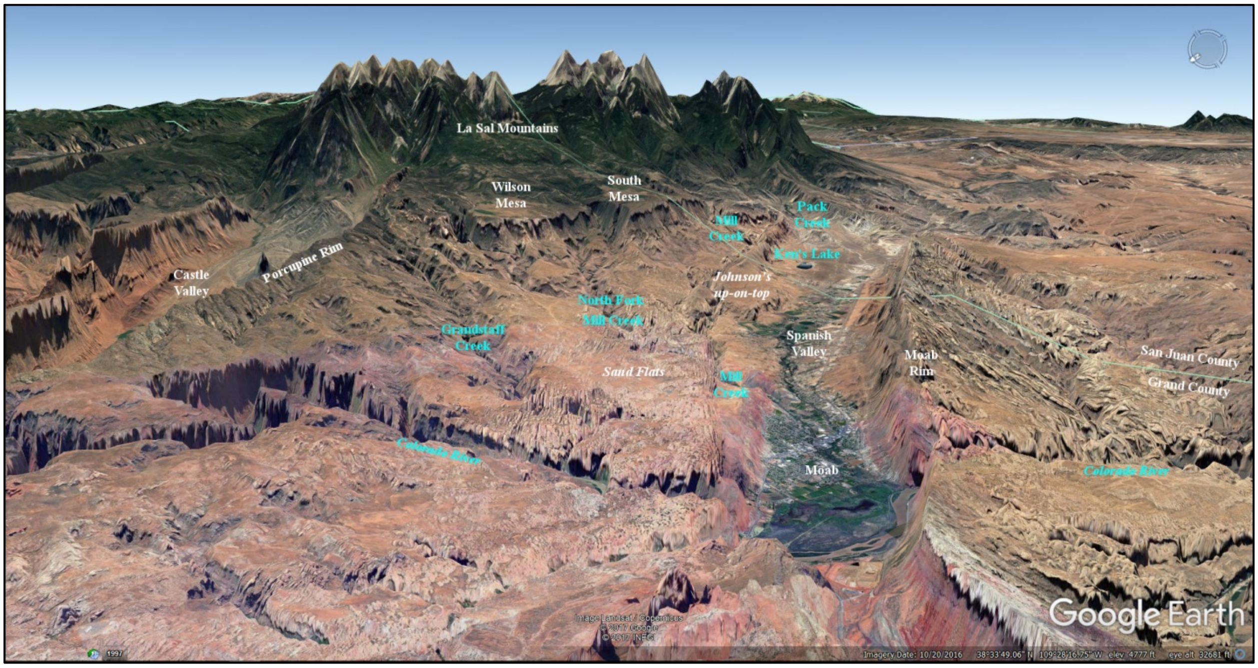

Figure 5. Topography in the MCWS Study Area Looking East.
(Source: Google Earth, Imagery May 2016).

The lower elevation sections of the MCSW study area --including the Pack Creek Alluvial Basin and the modern day talus, fans, and alluvial terraces in the Spanish Valley-- are separated topographically from other watersheds, specifically Mill Creek, Grandstaff Creek, and Kane Creek, regionally by the geologic structures and topography associated with the collapsed anticlines (Moab Rim, Sand Flats Rim, and Porcupine Rim) and the La Sal Mountain Tertiary intrusives (Ti), and locally by inter-fluvial bedrock uplands associated with features such as Johnson's up-on-top and the ridges associated with the La Sal Mountains. These bedrock features and associated geologic structures function as barriers to hydrologic connectivity across the features and, therefore, the hydrologic systems in the Spanish Valley are disconnected from adjacent fractured bedrock hydrologic systems. The effects of the bedrock impediments and geologic hydrostructures and the stream and valley dissection on the groundwater systems will be discussed in the Groundwater System Conceptual Site Models sections.

The deeper bedrock groundwater systems, if not topographically dissected by the surficial processes or affected by regional geologic structure and uplift activity, will be continuous and regional in nature. However, all of the deeper bedrock groundwater systems are affected by the regional geologic structure, and there is no continuity in the deeper bedrock systems across the region at this location (to be discussed in later sections of the report). Therefore, these deeper bedrock systems in the MCSW area do not receive regional groundwater recharge and are recharged by, or are discharging into, the local shallow groundwater systems depending on the geomorphic geometry. Most of the alluvial terraces, fans, and river bottoms in the study area are connected, but are isolated topographically from the rest of the region. This results in discrete and localized groundwater systems and can result in discrete and localized springs and connections to surface water systems. This concept is important in identifying various segments of the water budget.

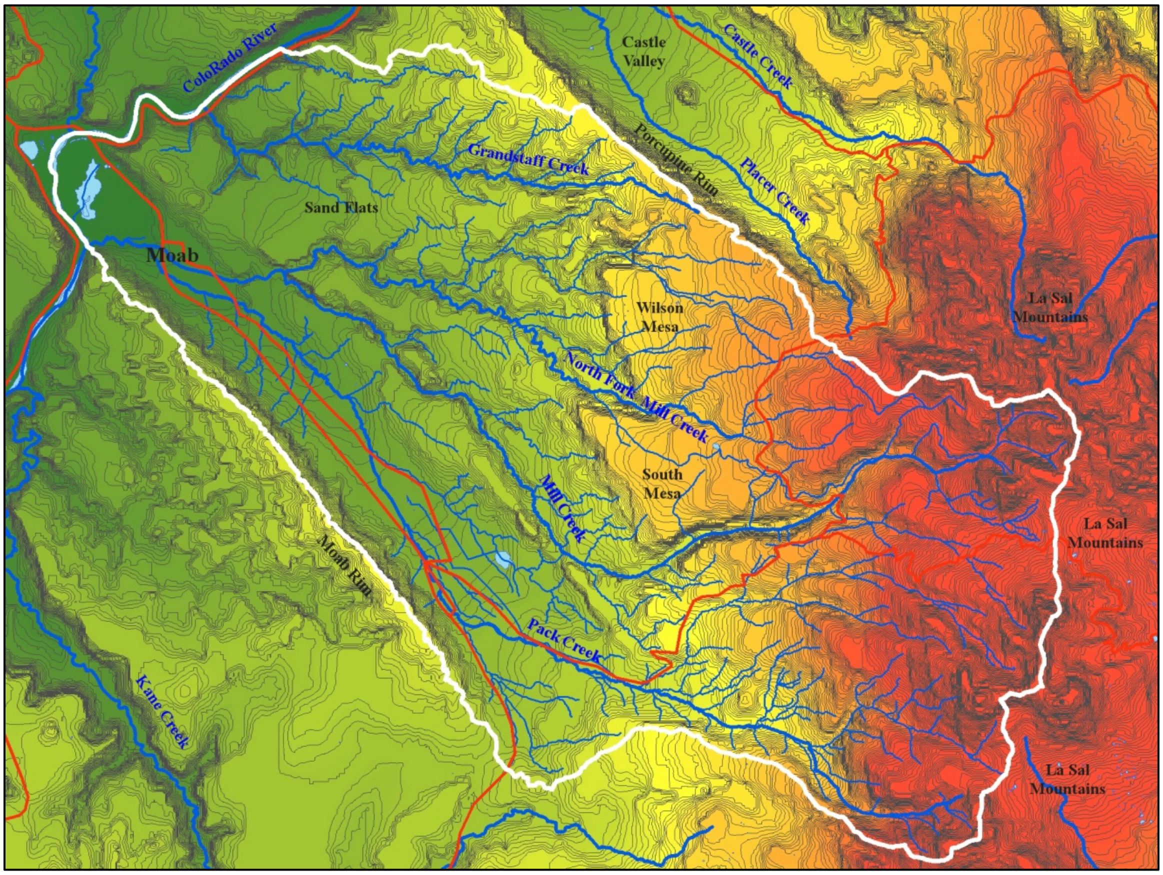

Figure 6. Topography (50ft Contours) and Streams in the MCWS Study Area. (Sources: Natural Resources Conservation Service, 2017.

The topographic gradients in the MCSW area can be divided into three types: 1) steep gradient bedrock slopes (greater than 2% slope) mostly in the dissected bedrock regions (dissected Sand Flats and La Sal Mountains region for example) and flanks of the surrounding rimlands of the collapsed anticlines; 2) steep gradient unconsolidated materials slopes (greater than 2%) including the talus and alluvial fans forming beneath the rimlands of Spanish Valley and along the exposed bedrock of the La Sal Mountains to the east; and 3) low gradient (less than 2% slope) fan, terrace levels, and alluvial valley bottoms associated with Pack Creek (Figures 5 and 6) and eolian and pedogenic soils atop undissected bedrock plateaus (Sand flats for example). The topographic gradient is useful in estimating the surface of the water table, for estimating the amounts of infiltration versus overland flow and interflow (rapid, shallow subsurface runoff), and for estimating residence times for subsurface water to be in contact with bedrock that may supply salt resulting in declining water quality.

2.3 Surface Water Characteristics

The MCWS study area contains three prominent local watersheds draining to the Colorado River via Grandstaff Creek, Mill Creek and Pack Creek (Figure 6). Streams can be gaining flow (from groundwater, rapid surface runoff, and interflow), or losing flow (to groundwater, diversions or evaporation through phreatophyte vegetation), dependent on local hydrology, hydrogeology, irrigation practices, and time of year. Grandstaff Creek, Mill Creek and Pack Creek are mostly dependent on groundwater interactions either as gaining or losing stream reaches.

The Grandstaff drainage originates near the top of Porcupine Rim, and does not have any surface water or groundwater originating from the La Sal Mountains. Grandstaff Creek has both ephemeral and perennial reaches. The upper Grandstaff drainage is ephemeral, and stream flows are observed after precipitation events and during snowmelt runoff. Groundwater infiltration from the stream bed occurs during these events resulting in channelized groundwater recharge into the stream alluvium and the underlying bedrock. The central and lower Grandstaff drainage is perennial where stream flow originates from spring flow and groundwater discharge from the stream bed and bedrock into the stream channel. Groundwater is also discharged by phreatophytes along these gaining stream reaches. Grandstaff Creek is not influenced by human diversions to date (Figure 7a).

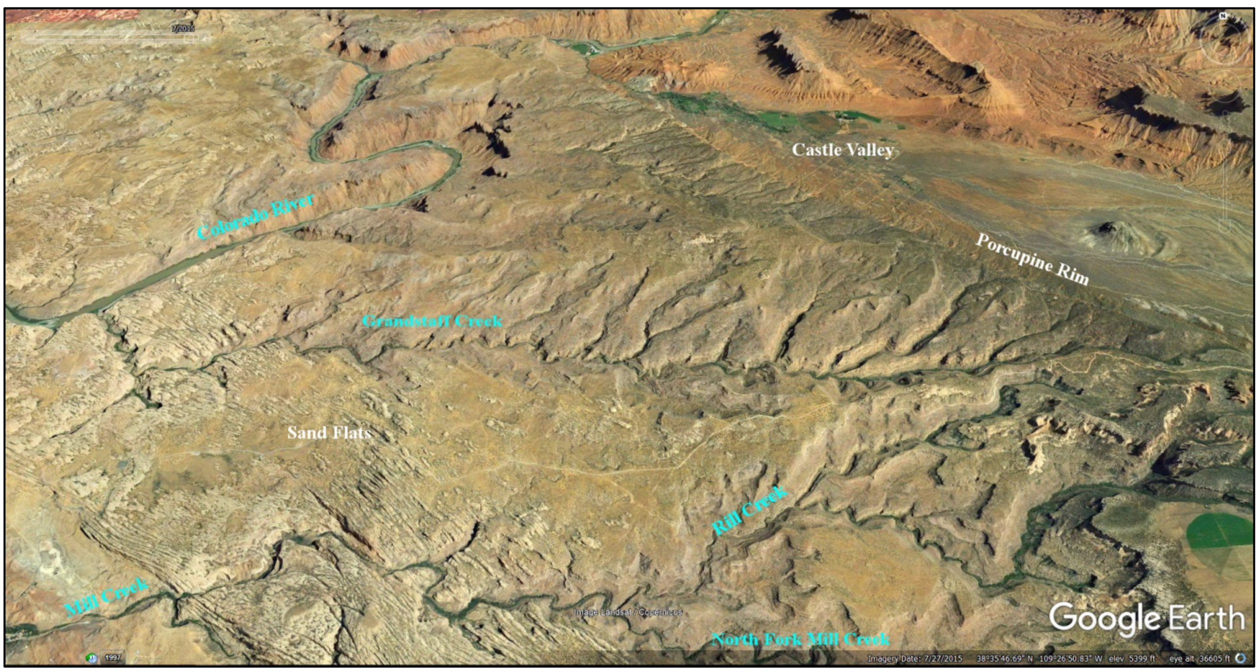

Figure 7a. Grandstaff Creek between Porcupine Rim and the Colorado River. (Source: Google Earth, Imagery July 2015).

The Mill Creek drainage originates in three regions: Sand Flats (Rill Creek, North Fork Mill Creek); Wilson Mesa (Burkholder Draw) and the La Sal Mountains (main Mill Creek channel), and, when not influenced by human diversions, the main Mill Creek channel remains perennial throughout its entire length (Sumsion, 1971; Blanchard, 1990; Lowe and others, 2007)

(Figures 7a, b, c, d). The Sand Flats and Wilson Mesa tributaries have both ephemeral and perennial reaches. The upper Rill Creek, North Fork Mill Creek, and Burkholder Draw drainages are ephemeral, and stream flows are observed after precipitation events and during snowmelt runoff. Groundwater infiltration from the stream bed occurs during these events resulting in channelized groundwater recharge into the stream alluvium and the underlying bedrock. The central and lower parts of these drainages are perennial where stream flow originates from spring flow and groundwater discharge from the stream bed and bedrock into the stream channel. Groundwater is also discharged by phreatophytes along these gaining stream reaches.

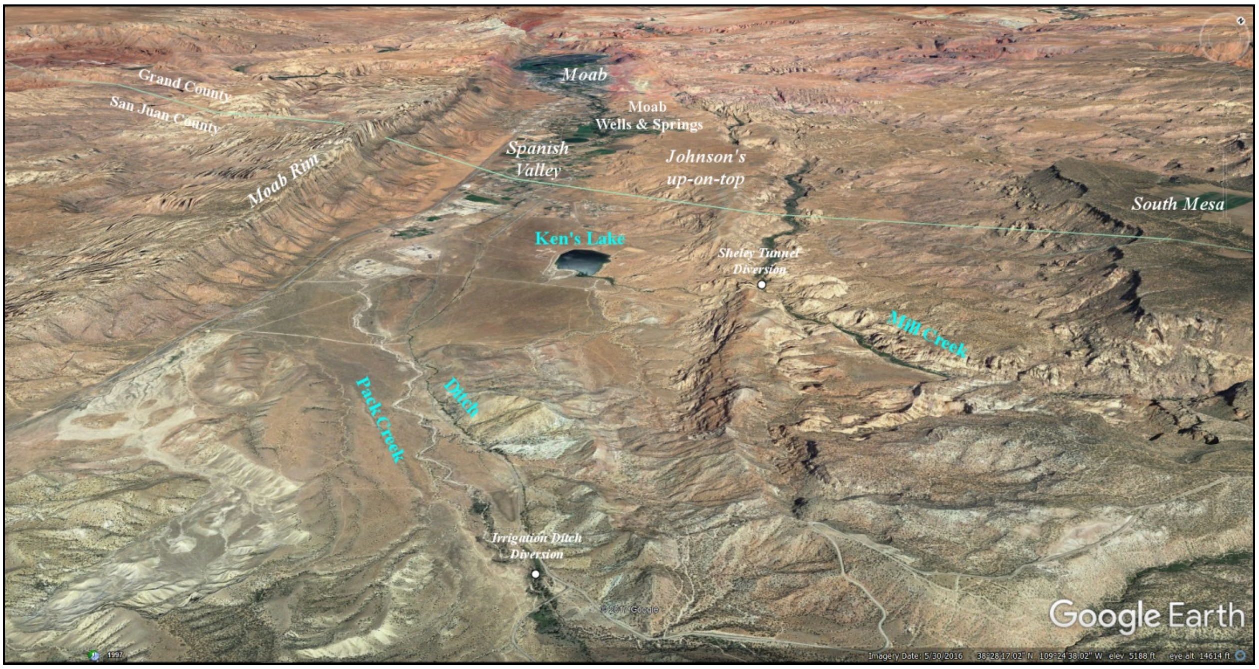

Figure 7b. Upper Reaches of Mill Creek and Pack Creek in the Southeastern Part of the MCWS Study Area. (Source: Google Earth, Imagery May 2016).

The La Sal Mountains tributaries of Mill Creek originate as ephemeral streams, but quickly become perennial as the channels have actively downcut through the glacial and alluvial deposits and bedrock units along its main channel. Mill Creek is a gaining stream from its headwaters to just above the Ken's Lake diversion at the Sheley Tunnel where it becomes a losing stream (Blanchard, 1990; Lowe and others, 2007) (Figure 7b and 8a). Mill Creek, from the Sheley Tunnel diversion to a point downgradient just above the Mill Creek/Unnamed Creek junction at the county line, is a gaining section to surface flow from groundwater (groundwater discharge to stream) (Data plotted and interpreted from Blanchard, 1990; Figures 7b and 8a). At a point where the Steel Bender Jeep Road reenters the Mill Creek Gorge from the east, Mill Creek becomes a losing stream along a reach extending north and downgradient to and beyond the junction with the "Middle" Fork of Mill Creek (east of the Moab City Springs and Wells) where a significant amount of the Mill Creek surface water recharges the fractured Glen Canyon Group bedrock (Data plotted and interpreted from Blanchard, 1990; Figures 7c and 8b and 8c). This losing reach of Mill Creek is critical for the Moab City Springs and Wells located at the City of Moab Golf Course. Below the confluence of the "Middle" Fork of Mill Creek with Mill

Creek, Mill Creek becomes a gaining stream again as evidenced by springs, increased surface water flow and phreatophytes along its channel, and remains a gaining stream until the confluence with the North Fork Mill Creek (which is also a gaining stream along its lower stretch) (Figures 7d and 8b and 8c). As Mill Creek takes a right angle bend and flows out to the Spanish Valley to the west, this channel is a significant losing reach where Mill Creek surface water recharges the ground water of the Kayenta Heights hydrostructure, which leads to Skakel Springs and other springs along the northeastern edge of City of Moab (Figures 7d and 8c). The reach continues to be losing as Mill Creek flows over the Mill Creek Delta in the Spanish Valley, recharging the Pack Creek aquifer system to the northwest (Figure 7d).

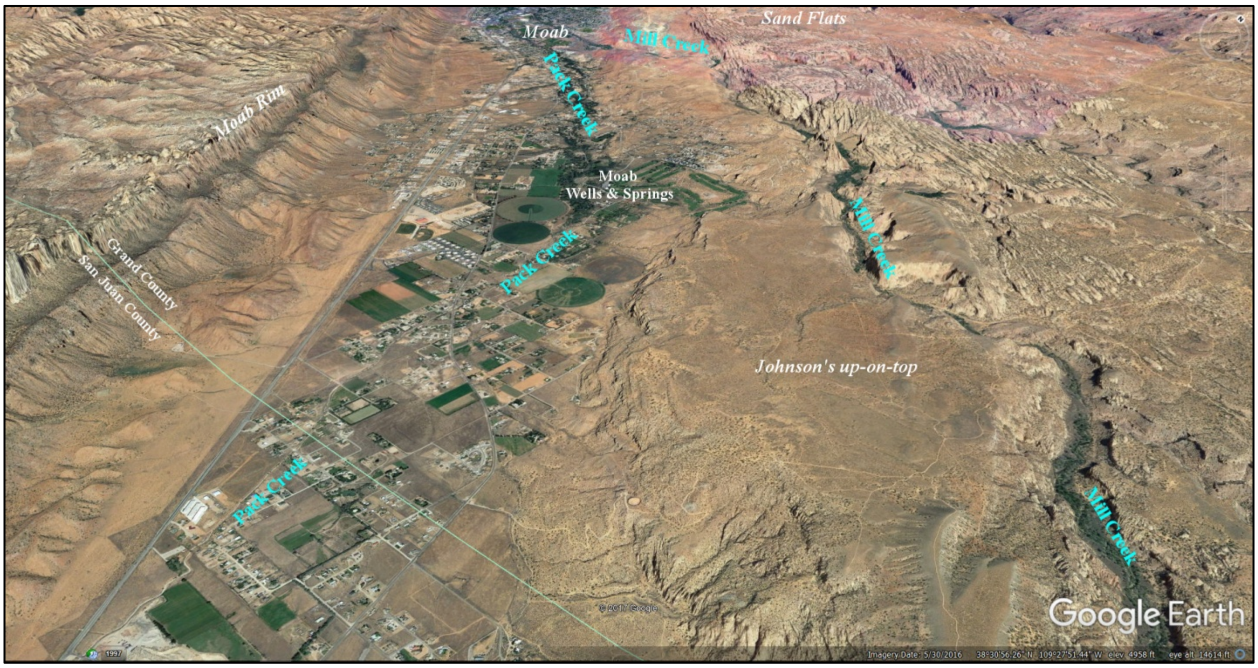

Figure 7c. Middle Reaches of Mill and Pack Creeks in the Central Part of the MCWS Study Area. (Source: Google Earth, Imagery May 2016).

The Pack Creek drainage originates in the southern La Sal Mountains. The La Sal Mountains tributaries and main channel of Pack Creek originate as ephemeral streams, but frequently become perennial as the channels have actively downcut through the glacial and alluvial deposits and bedrock units along its main channel, in the same way as upper Mill Creek. The upper part of Pack Creek, from its origin at Barber and Pack Springs, is a gaining stream to within a short distance of the diversion for irrigation (Sumsion, 1971). The entire surface water discharge is diverted into the irrigation ditch, where water infiltrates through the alluvium or is evapotranspired by phreatophytes and irrigated crops near the old airport area; there is no return flow to the ditch or channel (Sumsion, 1971). Pack Creek remains dry except during times of major precipitation and runoff events, and does not resume flow until the Moab City Park Springs area. The stream becomes a gaining stream from this location to the Colorado River (Sumsion, 1971).

The gaining and losing dynamics of these streams are influenced by seasonal events, with bank full conditions occurring during the spring runoff and summer irrigation season, and low water conditions occurring during the rest of the year. In addition, some storm events of various durations and amounts can affect the yearly and seasonal flows. A graph illustrating these daily, seasonal, and annual events is shown in Figure 8d.

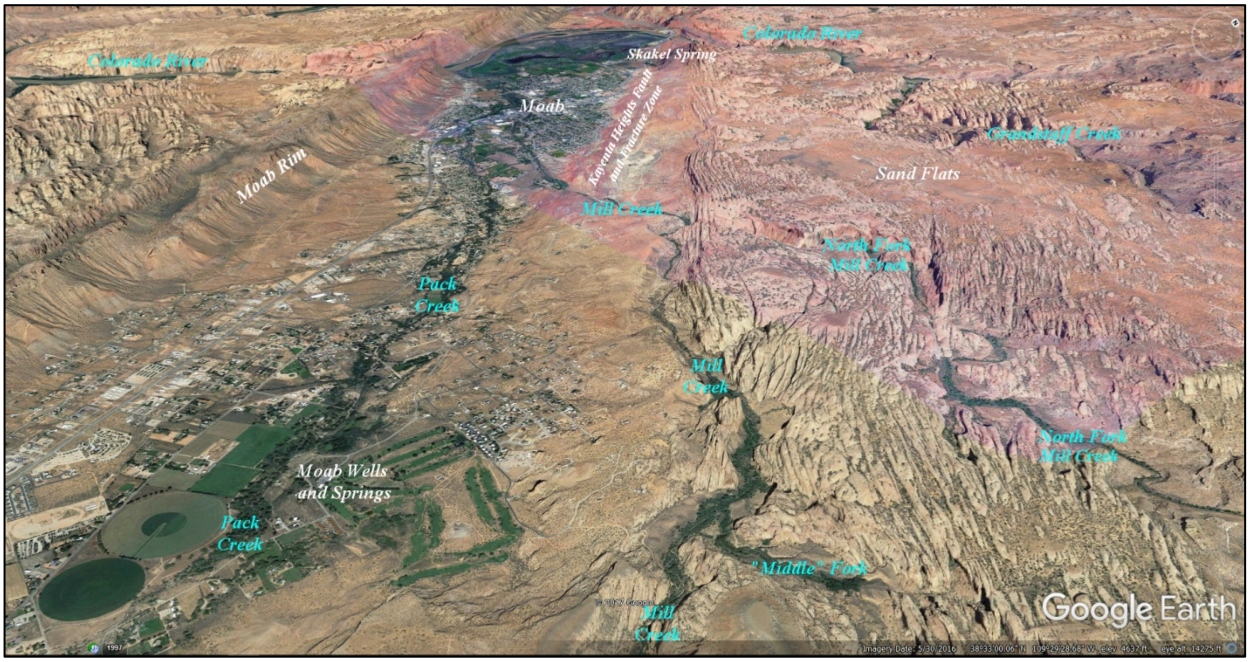

Figure 7d. Lower Reaches of Mill and Pack Creeks in the Northwestern Part of the MCWS Study Area. (Source: Google Earth, Imagery May 2016).

In the MCSW study area, water is delivered from diversion points to the irrigated fields primarily by means of pipes. In the absence of (unlined) ditches, as often encountered in areas with a long history of agricultural development, water leaking from such ditches into the subsurface is not a major concern in the MCSW study area and as such, does not have to be taken into account for the water balance of the groundwater system. The exceptions are the surface water features created by the Ken’s Lake diversion, which is a stream that delivers water from the diversion structure on Mill Creek to Ken’s Lake and Ken’s Lake itself, and by the Pack Creek Diversion ditch that carries surface water from near the Pack Creek bridge to the three lakes at the southeastern end of the Spanish Valley. These features are treated as losing streams, and Ken’s Lake as a losing (leaky) lake, that either recharge the underlying Pack Creek aquifer system, or have water losses due to evaporation and evapotranspiration (mostly by cottonwood trees and willows).

Where water is dispersed onto the crop field area, the excess water delivered to the soil drains down to the groundwater system and thus recharges the groundwater system. This water, called irrigation return flow, may have an altered water quality due to the agricultural chemicals used for the crops. Irrigation return flow is a source of groundwater recharge throughout the Spanish Valley to the Pack Creek bedrock and alluvial aquifer subsystem. Its significance for the water budget depends on the efficiencies of the agricultural practices applied.

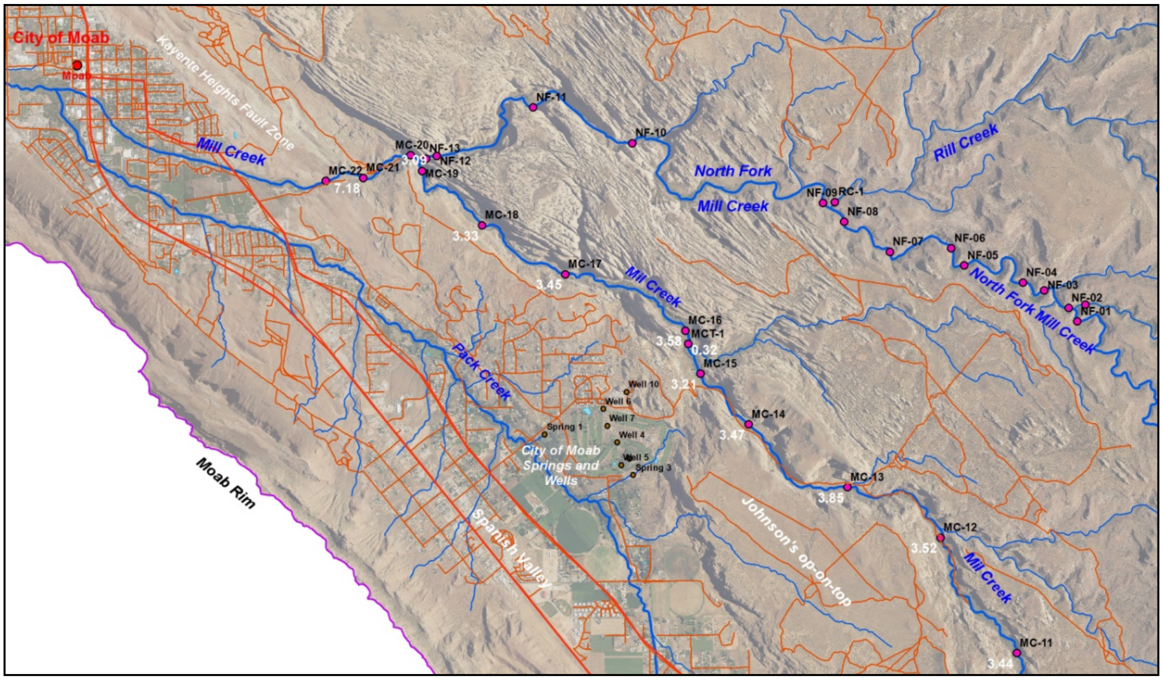

Figure 8a. Mill Creek Discharge Measurements (in ft^3/s or cfs) on October 21, 1985 (white) as published in Blanchard (1990) – Lower Section of Mill Creek.

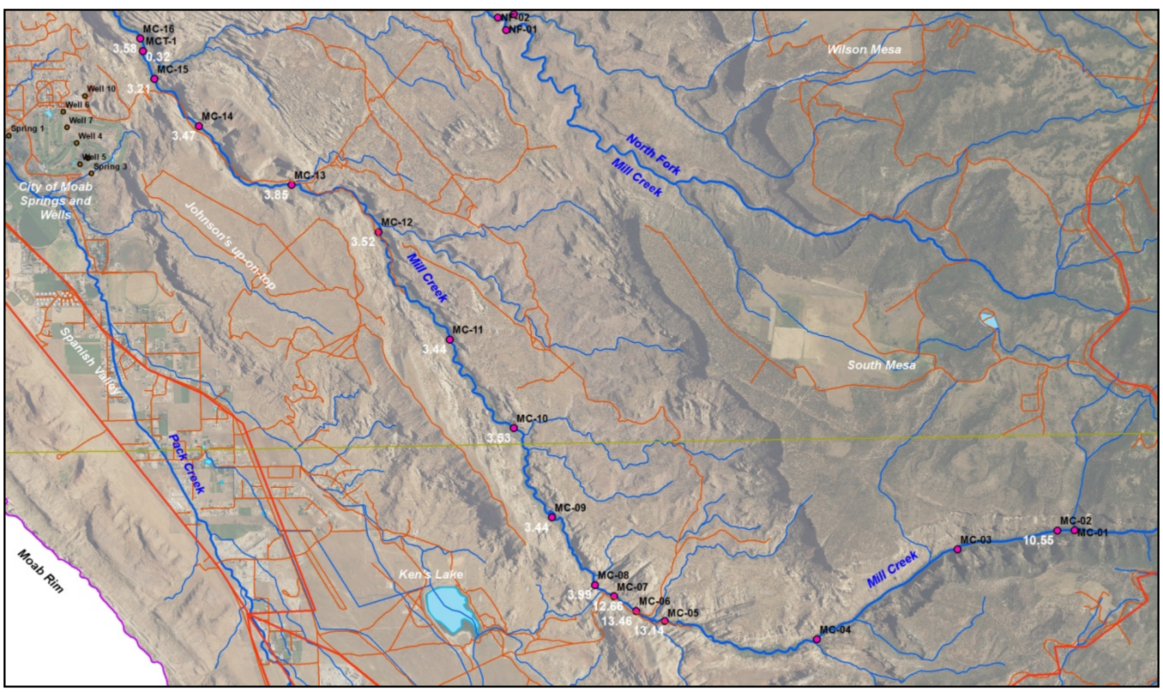

Figure 8b. Mill Creek Discharge Measurements (in ft^3/s in cfs) on October 21, 1985 (white) as published in Blanchard (1990) – Upper Section of Mill Creek.

Figure 8c. Mill Creek Discharge Measurements (in ft^3/s cfs) on October 21, 1985 (white) and on October 14, 1986 (red) as published in Blanchard (1990) – Lower Section of Mill Creek.

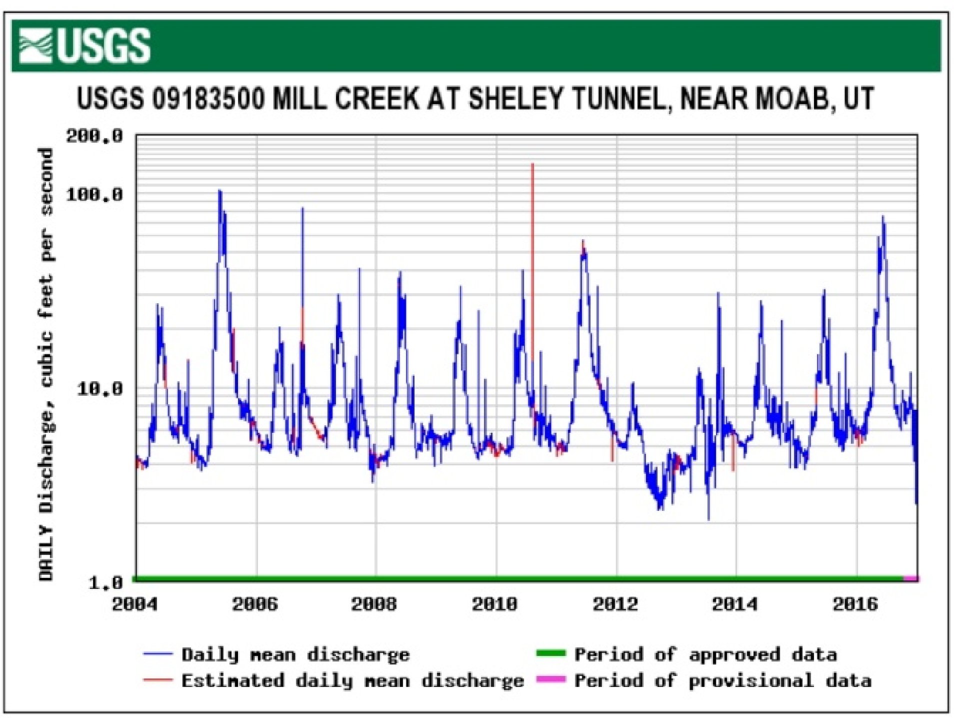

Figure 8d. Graph Showing the Daily Discharge of Mill Creek at Gage 09183500 at Sheley Tunnel, San Juan County, Utah for the Period January 2004-December 2016. (Source: USGS-NWIS, 2017).

According to the Utah state water right database, there are three major diversions in the MCSW study area. Two diversions directly affect the Mill Creek hydrologic systems: 1) the diversions in the La Sal Mountain tributaries below the high peaks that are used to irrigate South and Wilson Mesas that amounts to a net loss caused by evapotranspiration to the lower Mill Creek surface and groundwater systems, and 2) the Ken's Lake diversion that amounts to a net loss caused by direct removal of Mill Creek surface water flow from the Mill Creek surface and groundwater systems (Figure 7b). There are two diversions that directly affect the Pack Creek hydrologic systems: 1) the Ken's Lake diversion that amounts to a net gain caused by direct delivery of Mill Creek surface water flow to Ken's Lake, where surface water is recharged into the Pack Creek groundwater system by Ken's Lake subsurface leakage, and return flow from irrigation in the Spanish Valley, and ultimately by increased discharge from the Pack Creek aquifers to Pack Creek in the northwestern part of Spanish Valley, and 2) the Pack Creek diversion at the southeastern end of the Spanish Valley that amounts to a net loss of Pack Creek groundwater recharge due to evapotranspiration of ditch water directly, by phreatophytes, or by lake storage. The tradeoff of natural groundwater recharge due to Pack Creek channel delivery or ditch delivery would need to be calculated, but is assumed to be not significant.

As is indicated by the presence of wetlands, phreatophytes, and springs/seeps, some of these diversions and affiliated irrigation return flow move water into the groundwater systems of the Pack Creek Stream Alluvium (Qal). These groundwater systems may serve as aquifers used for irrigation and drinking water for landowners located topographically downgradient from the irrigated lands (see sections 2.5 and 2.6).

2.4 Springs and Seeps

Springs and seeps indicate places where water flows naturally from a rock or the soil onto the land surface or into a body of surface water. These features represent the contact between (saturated) groundwater and the land surface at that location. Springs usually emerge from a single point and result in a visible and measurable flow of water, or contribute measurably to the flow of a stream or the volume of a reservoir or pond. Seeps tend to be smaller than springs, have a more distributed character, and often show no visible runoff, especially in this semiarid climate where, in many cases, the water emerging in seeps is lost to evapotranspiration. In semiarid climates like the MCSW study area, springs and seeps may be identified by the presence of phreatophyte vegetation away from streams. Springs and seeps may be expressions of discharge of shallow groundwater from an unconfined aquifer, or of discharge from deeper aquifers at the contact between (more) permeable and (near) impermeable formations at or near the land surface, in fracture zones, or through karst conduits.

The MCSW study area contains a number of springs, seeps, and gaining reaches of streams as identified by previous publications, Google Earth analysis, field reconnaissance, and analysis of information from the State of Utah Water Rights Database (Figure 9). Most of the smaller springs and gaining reaches of streams are found in the upper reaches of Grandstaff Creek, Mill Creek and Pack Creek and their tributaries, and the larger springs are located in bedrock along the margins of the Spanish Valley (Figure 9). Of particular interest to this study are Skakel Spring (Figure 10a) and the City of Moab Springs (Figure 10b), which are located in bedrock above and near the Spanish Valley (Figure 9). A detailed discussion of springs and seeps in the MCSW area and their relationship with the local groundwater systems is presented in section 2.5.

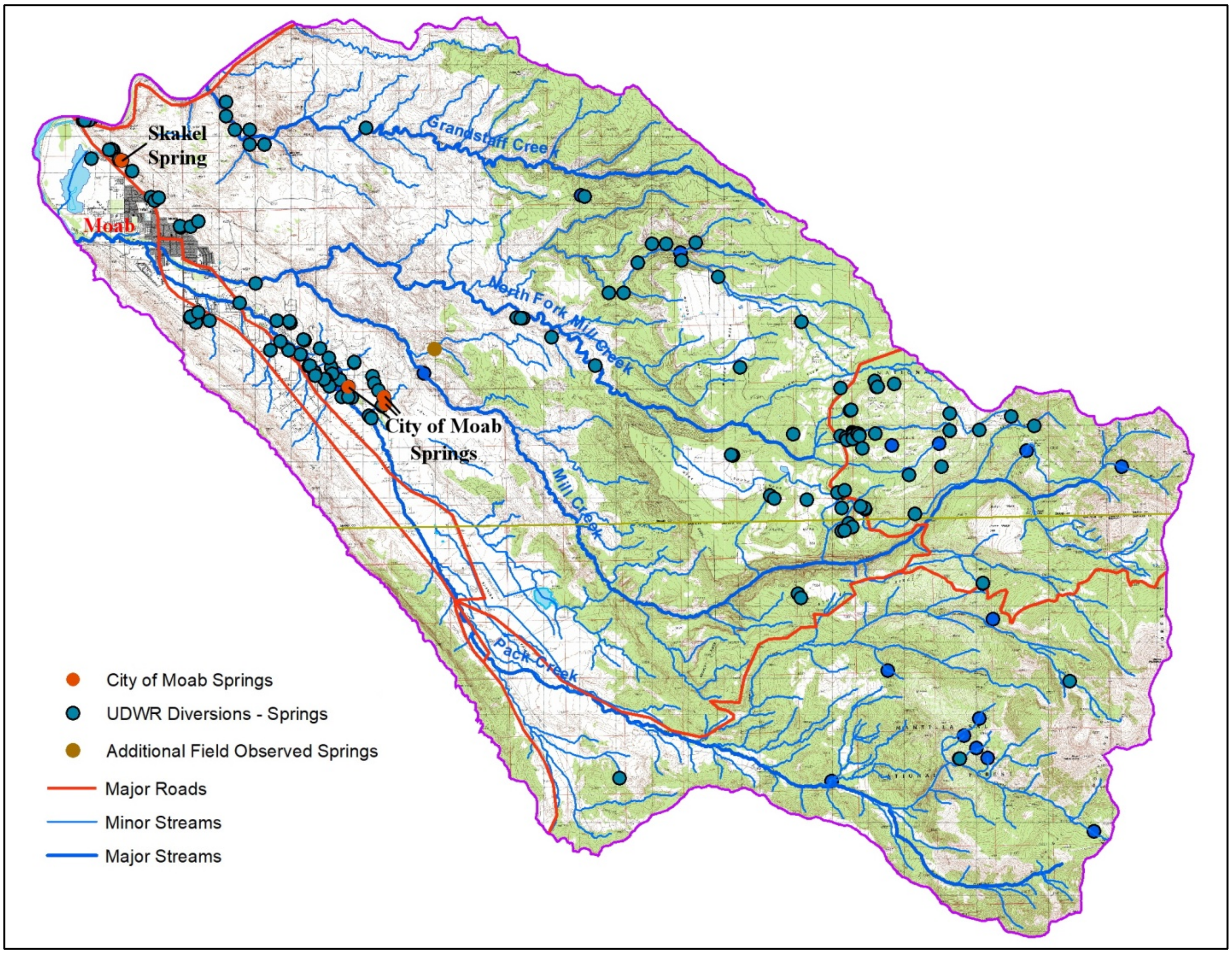

Figure 9. Location of Springs in the MCWS Study Area.
(Sources: Natural Resources Conservation Service, 2017; Utah AGRC 2017).

2.5 Hydrogeologic Framework

Bedrock and unconsolidated materials have traditionally been classified as either aquifers or aquitards based upon being able to provide sufficient water for irrigation and industrial and municipal consumption. In this context, an aquifer is a permeable body of rock that is saturated with water and is capable of yielding economically significant quantities of water to wells (human and agricultural use) and springs (human and ecological use). A low-permeability formation overlying an aquifer is often called an aquitard or confining unit. As the terms “aquifer” and “aquitard” are rather ambiguous (e.g., what are economically significant quantities? or how confining is a low-permeability unit with respect to the transport of contaminants?), the use of these terms is replaced by that of the term hydro-stratigraphic unit or hydrogeologic unit, in combination with terms qualifying the permeability and/or saturation of

Figure 10a. Location of the Skakel Spring in the MCWS Study Area Looking Northeast. (Source: Google Earth, Imagery May 2016).

Figure 10b. Location of Surface Water Diversions and Springs in the Central Part of the MCWS Area Looking Northeast. (Source: Google Earth, Imagery May 2016).

the unit (e.g., saturated, high-permeable hydrogeologic unit). A hydrogeologic unit is a geologic formation, part of a formation, or a group of formations with similar hydrologic characteristics (e.g., similar permeability characteristics and storage capacity). It should be noted that hydrogeologic units may not equate to geological units such as formations, formation members, and formation groups due to the frequently encountered variability of the flow characteristics of such geologic units. The term aquifer in this report is used to indicate a significant source of water supply from hydrogeologic units, and may include the qualifier potential (i.e., potential aquifer) when parameter uncertainty exists, especially with respect to average saturated thickness and water table fluctuations.

From a groundwater flow and water supply perspective, the most important property of rocks is the incorporated pore space and related permeability. The pore space, which defines the amount of water storage within a hydrogeologic unit, may be contemporaneous with the rock formation (primary or matrix porosity), or due to secondary geological processes, such as fracturing, faulting, chemical solution, and weathering (secondary porosity, fracture/karst porosity). The degree of connectivity and the size of the pore openings define the permeability of the rock, that is, the ease with which fluid can move through the rock. As with porosity, permeability may be primarily matrix based (matrix permeability), fracture and/or karst based (fracture/karst permeability), or may be a combination of both (Davis and DeWiest, 1966).

Unconsolidated sediments and clastic materials, as found in the MCSW study area, and observed on the pedogenic and eolian deposits, mass wasting colluvium and talus, pediment gravels and terraces, and alluvial floodplains in the Mill Creek, Pack Creek, and Grandstaff Creek drainages, and glacial till, moraines, and outwash plans, are geologically very young and consist primarily of clays, silts, sands, and gravels. They are generally very porous and permeable, but can be quite variable in their thickness, continuity, and hydraulic properties. For example, field observations revealed that the thickness of the unconsolidated sediments in the MCSW study area ranges from less than 1 ft to greater than 300 ft. (Lowe and others, 2007). Estimates of hydraulic conductivity (K) of these unconsolidated materials range from 29 to 174 ft per day (Sumsion, 1971). These hydrogeologic units most likely contain the greatest amount of groundwater.

Consolidated sedimentary rock and extrusive volcanic rock, by comparison, are often quite porous, but variable in permeability. Most fine-grained detrital rocks like shale, claystone, and siltstone may have relatively high matrix porosities, but very low permeabilities (Davis and DeWiest, 1966). These fine-grained bedrock hydrogeologic units are the dominant confining layers of sedimentary groundwater systems, with small hydraulic conductivity values typically less than 0.01 ft per day. Coarser-grained sedimentary rock, such as sandstone, and volcanic basalt, can pair relatively high matrix porosity with significant permeability, and may contain significant amounts of groundwater.

The hydraulic properties of sedimentary and extrusive igneous rock may be largely enhanced when fractures and faults are present (Davis and DeWiest, 1966). As a case in point, most of the sandstones and crystalline extrusive volcanic rocks in and near the MCWS study area have enhanced permeability due to fracture and fault density and connectivity. Significant secondary porosity and permeability are developed through faulting, fracturing, and weathering of the sedimentary and extrusive igneous rock, especially in association with active faults, fracture zones, and near-surface stress-release.

2.5.1 Regional Hydrogeologic Units

From a regional geologic perspective, the Moab/Spanish Valley area is part of the Paradox Subregion Section of the Colorado Plateau Physiographic Province, characterized structurally by northwest-southeast- trending salt anticlines (diapirs) with centrally collapsed areas or graben features due to salt dissolution by groundwater (Blanchard, 1990; Doelling, 1985, 1988; Doelling and Ross, 1993; Doelling and Others, 1995; Geldon, 2003) (Figures 11 and 12). Several faults related to this dissolution of salt and subsequent collapse structures have been mapped parallel to the Moab Rim on the southwest and the north east side of the Spanish Valley including the Kayenta Heights fault zone and extending faults bounding the Spanish Valley near the City of Moab Springs and Johnson's up-on-top (Lowe and others, 2007). As a result, the near-surface sedimentary bedrock stratum ranges from younger rock to the northeast and southwest, to older rock in the core of the anticlines, and the stratum shows a regional dipping trend to the northeast, northwest, and southwest (see Figures 13 and 14). The youngest bedrock units in the MCSW area are the Tertiary intrusive (granodiorite porphyry) units of the La Sal Mountains (Ti). These units form mountains in the eastern and southeastern part of the study area, and the older sedimentary rocks form the topographic rimlands and valley bottoms of the main Spanish Valley (Figures 13 and 14). It is in these sedimentary and volcanic units that regional and subregional groundwater flow systems are known to occur if the topographic, geomorphic, and geologic structure and continuity are favorable (Freethey and Cordy, 1991; Geldon, 2003).

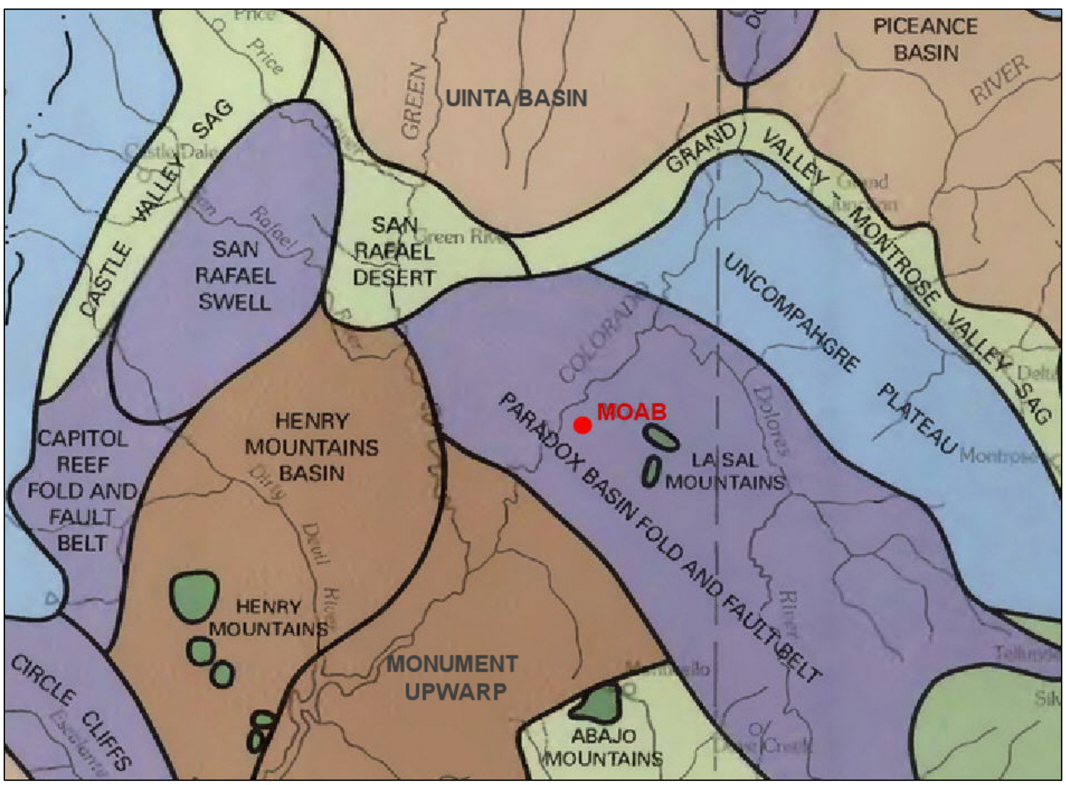

Figure 11. Regional Geologic Features in the Vicinity of the MCSW Study Area (From Geldon, 2003).

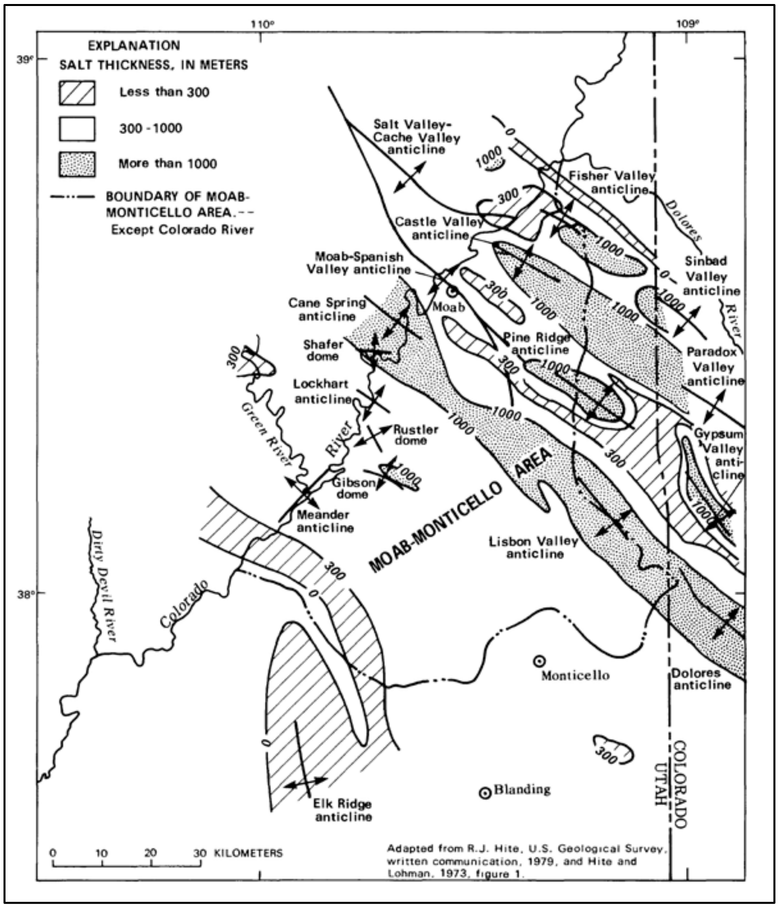

Figure 12. Generalized Salt Thickness and Major Structural Trends in the Vicinity of the MCSW Study Area (From Weir and Others, 1983).

Given the regional geology of the MCSW area, the hydrogeologic framework, including hydrostructures, present in the Moab City Springs and Wells Hydrologic System is very complex and is studied for the continuity and geometry of possible regional, subregional, and local hydrologic systems. Upon reviewing various groundwater reports for water budgets in the Mill Creek-Pack Creek drainages in Grand County (Sumsion, 1971); bedrock aquifer analysis in San Juan County (Avery, 1986); ground water conditions in Grand County (Blanchard, 1990; Esinger and Lowe, 1999); regional and subregional groundwater systems of the La Sal Mountains/Spanish Valley area (Geldon, 2003; Basye, 1994); recharge and water quality of the alluvial aquifer in Castle Valley (Snyder, 1996); and Castle Valley water studies and data (Ford and Grandy, 1997; Ford, 2006), the MCSW study area hydrological systems have multiple distinct hydrogeologic and hydro-structural units, including unconsolidated units consisting of various Quaternary- and Tertiary-aged, highly permeable deposits and weathered bedrock deposits, and several water-bearing bedrock units and significant confining bedrock units, and fault and fracture zones of untested, but very high vertical and lateral transmissivity. The major hydrogeologic unconsolidated and bedrock units are presented in Figures 15 and 16 and described in Tables 2a and 2b; the thickness of the unconsolidated valley-fill aquifer and the location of paleo-valleys are presented in figure 17; the major hydro-structural units are presented in Figure 18.

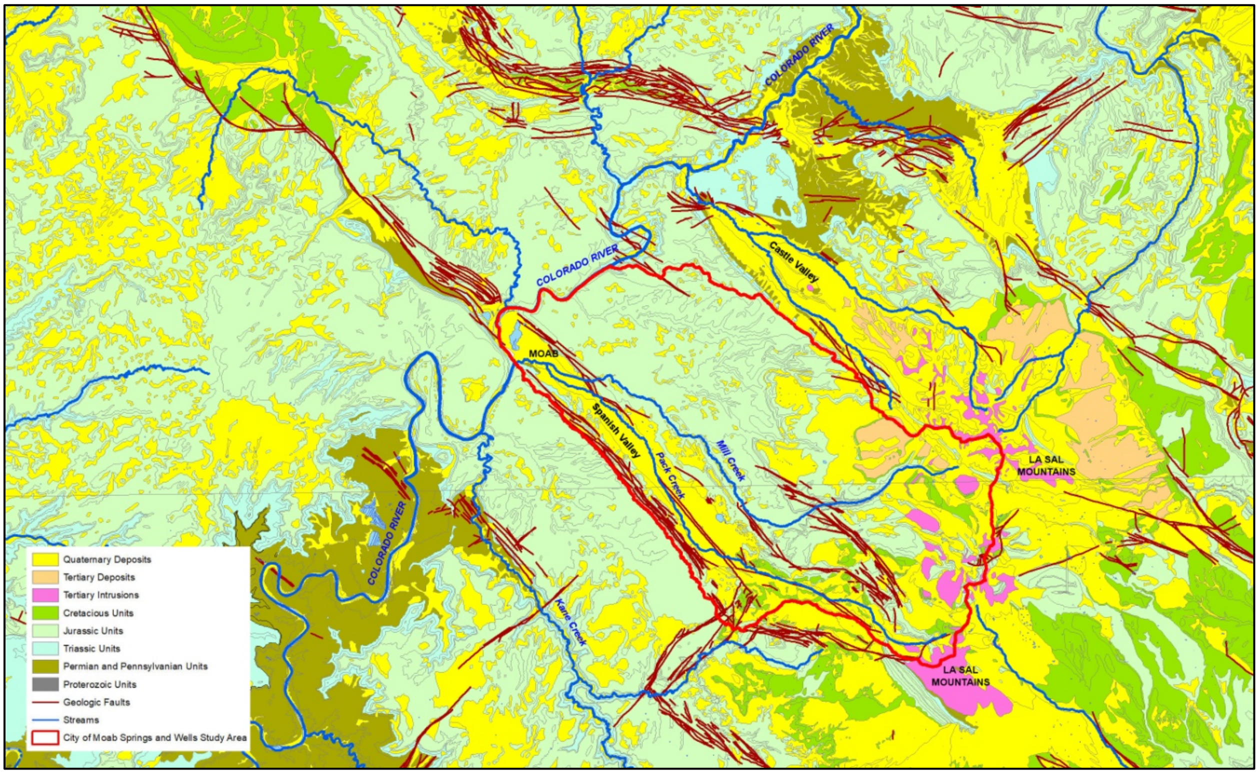

Figure 13. Generalized Map Showing Regional Geological Features in the Vicinity of the MCSW Study Area (Based on GIS Version of Utah Geological Survey Maps 180 and 205 (Doelling, 2002; Doelling, 2005).

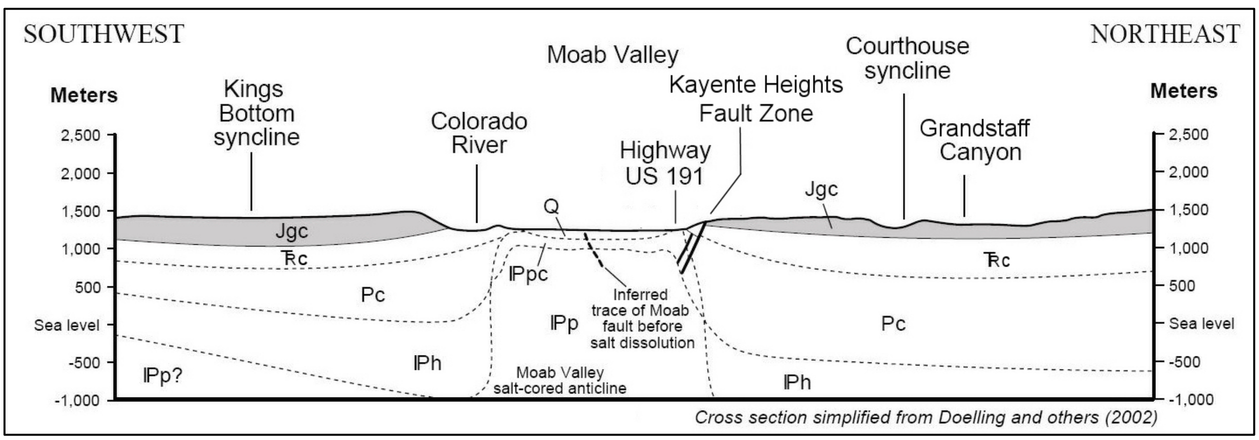

Figure 14. Generalized Northeast-Southwest Geological Cross Section Representative for Spanish Valley near Moab *(*Modified from Doelling and others, 2002*)*.

2.5.2 Hydrogeologic Units of the MCSW Area

There are two significant groups of hydrogeologic units in the MCSW study area: 1) Quaternary and Tertiary unconsolidated clastic materials (Figure 15, Table 2a), which are predominantly Stream Alluvium (Qal), Alluvial Fan deposits (Qaf), Glacial Till (Qgt), Older

Alluvial Fan/Slope Deposits (Qas), and Eolian Sand (Qes) overlying 2) Tertiary, Mesozoic and Paleozoic bedrock units (Figure 16; Table 2b), including the following potentially water-bearing units: fractured Tertiary Intrusive Granodiorite (Ti); fractured and matrix Dakota Sandstone and Burro Canyon Fm (Kdbc); fractured and matrix Salt Wash Member of the Morrison Fm (Jmsw); fractured and matrix Entrada Fm (Je); and fractured Glen Canyon Group (including fractured and matrix Navajo Fm (Jn), fractured Kayenta Fm (Jk), and fractured and matrix Windgate Fm (Jw). Tables 2a and 2b list the hydrologic characteristics of these units, and show that most of these units have low matrix hydrologic conductivity and have springs with low yields less than 1 gal per minute. By comparison, the Mancos Shale (Km), undivided Morrison Fm (Jm), Dewey Bridge Member of the Carmel Fm (Jcd), Triassic Chinle (TRc) and Moenkopi Fms (TRm), the unfractured Cutler Fm (Pc), and the Paradox Fm (IPpc and labeled “caprock” on some figures) may act as thick, poorly transmissive confining layers *(Blanchard, 1990; Ford, 2006*).

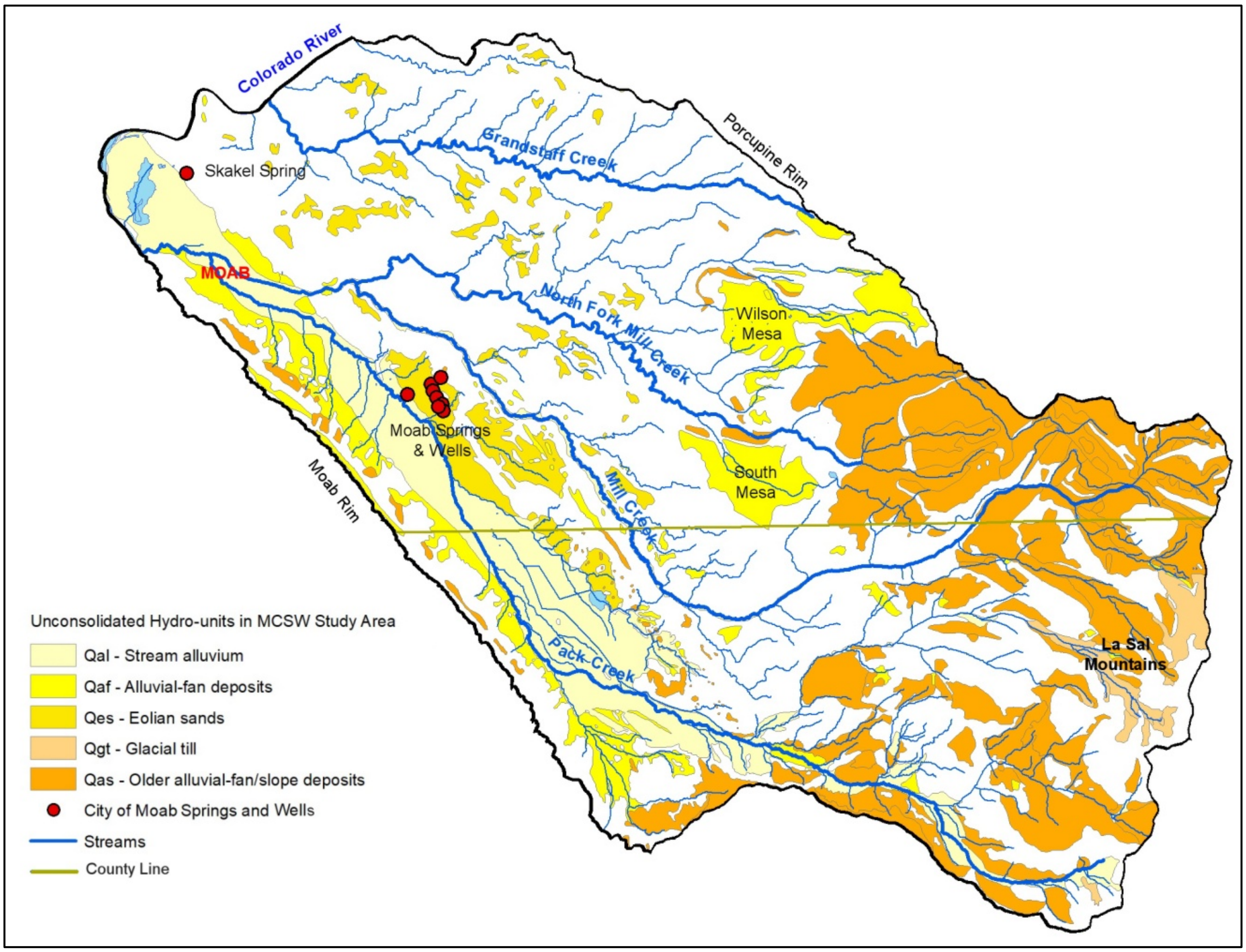

Figure 15. Map Showing the Main Unconsolidated Hydrogeologic Units in the MCWS Study Area.

From a water supply perspective, the unconsolidated clastic sediments, specifically when composed of larger size particles (>2.5 mm or 0.1 in) and observed to have sufficient saturated thickness and horizontal continuity, provide a significant and accessible water supply. The water supply function of bedrock units is largely dependent on rock type, large-scale structure and degree of fracturing, layer geometry and orientation, and the spatially variable hydrologic inputs and outputs, and may vary significantly dependent on location. The focus of this HESA was on both the shallow groundwater flow systems in the Quaternary and Tertiary unconsolidated clastic materials, which is the source of drinking and irrigation water for most households on wells, the deeper bedrock units that have been tapped for water supplies in areas where the shallow unconsolidated aquifers cannot supply adequate quantities of water for the landowners or are the source of major Springs for City of Moab water supplies, and the relations of these hydrologic systems to the surface water systems of Mill, Grandstaff and Pack Creeks and their tributaries. Additionally, water quality is also an issue that is addressed, both in discerning the nature of the shallow and deeper groundwater systems, the nature of the interactions between these two types of groundwater systems with Mill, Grandstaff, and Pack Creeks, and in the assessment of water protection of springs and water wells for the City of Moab water supply.

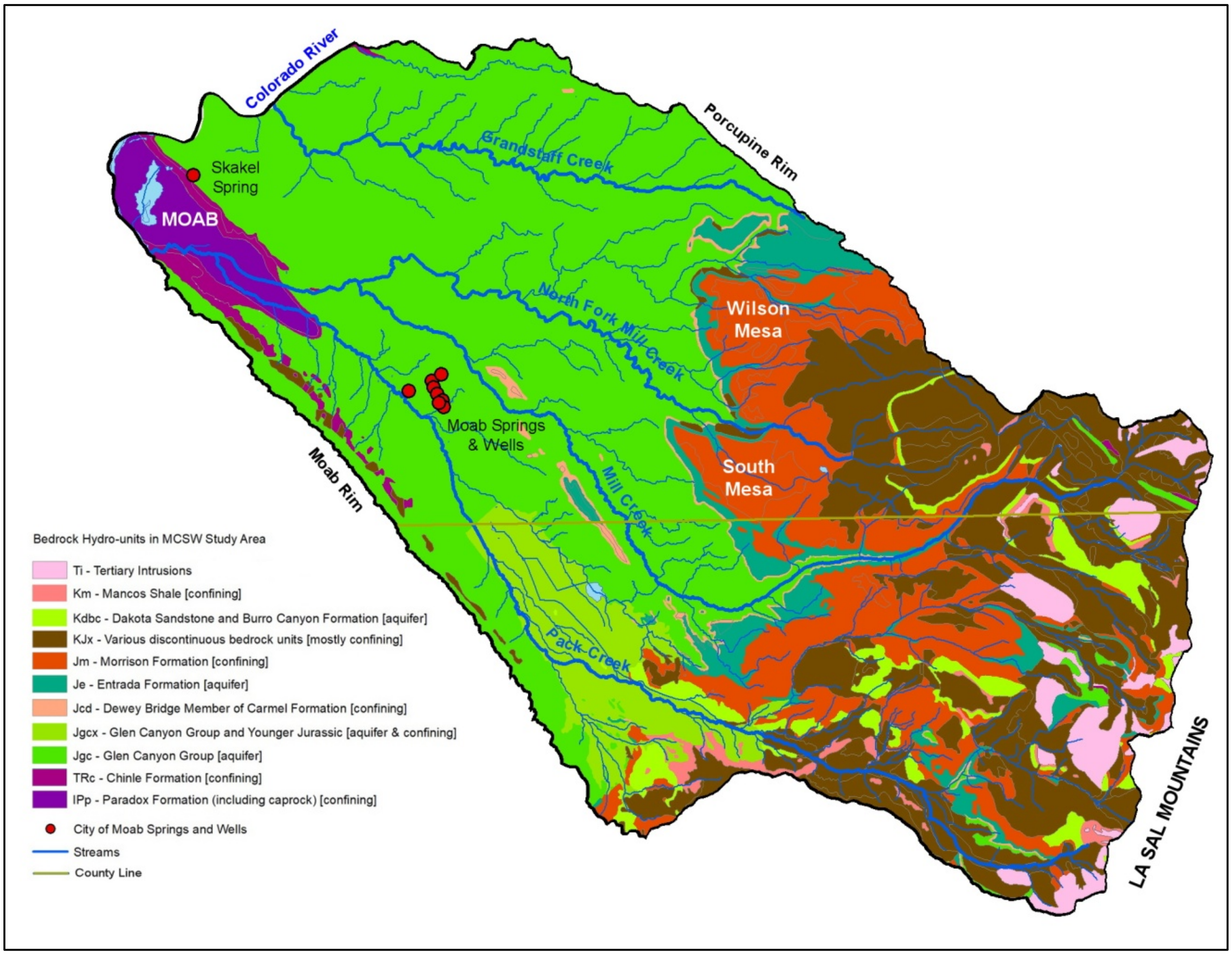

Figure 16. Map Showing the Main Bedrock Hydrogeologic Units in the MCWS Study Area.

Geological Unit	***Hydro-geological Unit***	***Hydro-geological Unit Symbol***	***Composition***	***Hydrogeological Characteristics***	***Permeability/Storativity***	***Depth to Water*** (small/ moderate/ large/ highly fluctuating)
Stream alluvium (Qal); Modern and older alluvium (Qa1, Qa2); Alluvial and colluvial deposits (Qac); Basin fill deposits (Qab/Qabf); Younger alluvial gravel deposits (Qagy)	Stream Alluvium	Qal	Unconsolidated deposits of poorly to moderately sorted riverine silt, sand, and gravel; Qa1 located in active larger channels and floodplains; Qa2 deposits form first surface 6-40 ft. above the active channels. Thickness up to more than 300ft.	Generally good local phreatic aquifer with matrix based permeability; limited variations in groundwater levels; often sustained by local and sub-regional discharge to adjacent stream or recharge directly from stream. Areas of alluvial fan deposits provide connectivity between adjacent aquifers but may not provide a sustainable source of water.	Stream deposits have high matrix-permeability and high storativity; alluvial fan areas have moderate to high permeability and high storativity	Small to highly fluctuating
(Older/younger) Alluvial-fan deposits (Qaf, Qafo, Qafy); Terrace deposits (Qaf); Mixed eolian and alluvial deposits (Qea)	Alluvial Fan Deposits	Qaf	Unconsolidated deposits of poorly sorted, muddy to sandy cobble gravel and boulders.	Potentially good, spatially continuous phreatic aquifer with high matrix based permeability.	High matrix-permeability; high storativity	Moderate to large
Glacial till (Qgt); Rock glacier deposits (Qmr)	Glacial Till	Qgt	Very poorly sorted, angular to sub-angular clasts of all sizes..	Potentially good local phreatic aquifer with variable matrix based permeability and high water table gradients.	High matrix-permeability; high storativity	Small on valley bottoms; moderate on ridges
Older Alluvial gravel deposits (Qago); Pediment-mantle deposits (Qap); Colluvium (Qc); Boulder colluvium (Qcb); Slumps and (land-)slides (Qms); Talus deposits/Talus and colluvium (Qmt); Older alluvial-fan deposits (Qtaf); Collapsed breccia (bx)	Older Alluvial Fan/Slope Deposits	Qas	Poorly to moderately sorted, locally derived gravel, sand, and soil, and rock-slope deposits of poorly sorted angular debris ranging from block to sand size of variable thickness. Thicknesses vary.	Potentially good, highly localized phreatic aquifer with high matrix based permeability and high water table gradients.	High matrix-permeability; high storativity	Highly fluctuating
Eolian and residual deposits (Qer); Eolian sand deposits (Qes)	Eolian Sand	Qes	Well-sorted, fine to medium grained sand with silt; deposited in sheets	Potentially good, spatially continuous phreatic aquifer with high matrix based permeability. Permeability may be anisotropic vertical to horizontal	High matrix-permeability; high storativity	Highly fluctuating

Table 2a. Correlation of Geological and Hydrogeologic Units in the Moab Study Area: Unconsolidated Units.

Geological Unit	***Hydrogeological Unit***	***Hydro-geological Unit Symbol***	***Composition***	***Hydrogeological Characteristics***
La Sal Mtn. Intrusive Rocks (Th, Ttp, Tpt, Trp, Tn)	Tertiary Intrusions	Ti	Alkaline silicic rocks (Granodiorite and quartz monzonite) intruded at shallow depths as laccoliths, plugs, dikes, and sills. (Subsurface) extent is variable.	Fractured crystalline system with very low matrix permeability; not a (sub-)regionale aquifer; may produce locally water in fracture zones and support adjacent unconsolidated aquifers. These characteristics may extend into adjacent rocks, methamorphosed during the Tertiary intrusion.
Mancos Shale (Km, Kmu, Kms, Kmf)	Mancos Shale	Km	Marine shale with localized, thin (shaly) sandstone or limestone beds.	Mostly very low permeability and layers with moderate matrix and fracture permeability; low to moderate storativity. Sandstone beds may feed some springs. Acts as confining unit.
Daota Sandstone (Kd); Burro Canyon Formation (Kbc); Dakota Sandstone and Burro Canyon Formation, undivided (Kdbc)	Dakota Sandstone and Burro Canyon Formation	Kdbc	Sandstone and conglomerate, interbedded with mudstone, shale, coal, and mudstone.	Low to moderate matrix permeability; higher permeability where fractured. Yields water to a few small springs. Acts as (local) aquifer.
Brushy Basin (Jmb), Salt Wash (Jms) and Tidwell (Jmt) members of Morrison Formation; and Summerville Formation undivided (Jsmt, Jsms)	Morrison Formation	Jm	Mudstone, claystone and siltstone with discontinuous beds of conglomerate and sandstone.	Mostly low permeability; sandstone beds may yield some water to wells, and may feed some springs and seeps. Acts as confining unit.
Moab Member of Curtis Formation (Jctm); Slick Rock Member of Entrada Sandstone (Jes); and Moab and Slick Rock Members (Ject).	Entrada Sandstone	Je	Fine-to medium grained, well sorted, cross-bedded eolian sandstone.	Moderate permeability, increased when fractured. May yield significant discharge to wells, springs and seeps. Acts as major aquifer.
Dewey Bridge Member of Carmel Formation (Jcd)	Dewey Bridge Member of Carmel Formation	Jcd	Poorly bedded, sandy siltstone.	Low permeability. Acts as confining unit.
Navajo Sandstone (Jn, Jnl); Kayenta Formation (Jk); Wingate Sandstone (Jw); Glen Canyon Group (Navajo, Kayenta, Wingate) undifferentiated (Jgc)	Glen Canyon Group	Jgc	Well-sorted, massive, fine- to medium-grained, eolian and fluvial sandstone, partially interbedded with siltstone and shale (Kayenta)	Moderate permeability, increased when fractured. Yields water to wells, springs and seeps. Acts as major aquifer.
Chinle Formation (TRc); Moenkopi Formation (TRm); Cutler Formation (Pc)	Chinle, Moenkopi and Cutler Formations	TRc	Silty and sandy mudstone and shale, interbedded with cross-bedded sandstone.	Mostly aquitard with very low permeability serving as a confining layer for overlying or embedded aquifers; however, locally moderate aquifer conditions when highly fractured.
Honaker Trail Formation (IPh)	Honaker Trail Formation	IPh	Thick- to thin-bedded limestone.	Low permeability except where fractured near surface. Acts as confining layer.
Paradox Formation Caprock (IPpc); Paradox Formation (IPp)	Paradox Formation	IPp	Caprock consists of light-gray to yellow-gray gypsum, gypsiferous claystone, silty shale, fine-grained sandstone, and thin-bedded carbonates. Paradox Formation consists of interbedded coarse, crystalline halite and other salts, massive anhydrite, gray dolomite, gray to black shale, and gray siltstone.	Mostly aquitard with very low permeability serving as a confining layer for embedded aquifers or impermeable base for overlying aquifers. Responsible for reduced water quality when wells are placed near the Paradox Formation, or shallow groundwater flows over it.

Table 2b. Correlation and Hydrogeologic Units in the Moab Study Area: Bedrock Units.

The Quaternary unconsolidated clastic units (Qal, Qaf, Qgt, Qas, and Qes in Table 2a and Figure 15) are locally heterogeneous, with predominantly a mix of coarser materials in the older alluvial deposits, and a mixture of coarser and finer materials in the younger deposits. These deposits, which are moderately to highly permeable, are recharged by infiltration from precipitation that is non-uniformly distributed due to the slope steepness, slope aspect, and to position in the landscape; by the incidental leaky irrigation ditch and irrigation return flow; and by flow in ephemeral stream channels and losing streams in perennial reaches where favorable. The unconsolidated units are variably to fully saturated, based on spatial location and seasonal precipitation events. There is lateral and vertical groundwater flow connection between the unconsolidated materials and the underlying bedrock formations that is critical for understanding the hydrologic systems and water quality of the Moab City Springs and Wells area.

The thickness and subsurface distribution of these unconsolidated sediments in the Spanish Valley may be estimated based upon the isopach maps produced in earlier studies (Plate 6 in Lowe and others, 2007). The thicknesses range from less than 50 ft in the southeastern part of Spanish Valley above Ken's Lake, to greater than 300 ft in the central part of Spanish Valley southwest of Johnson's up-on-top and south of the Moab City Springs and Golf Course, and in the northwest part of Spanish Valley (Figure 17). The thicknesses of the unconsolidated material in these collapsed parts of Spanish Valley commonly have ranges 100 – 200 ft.

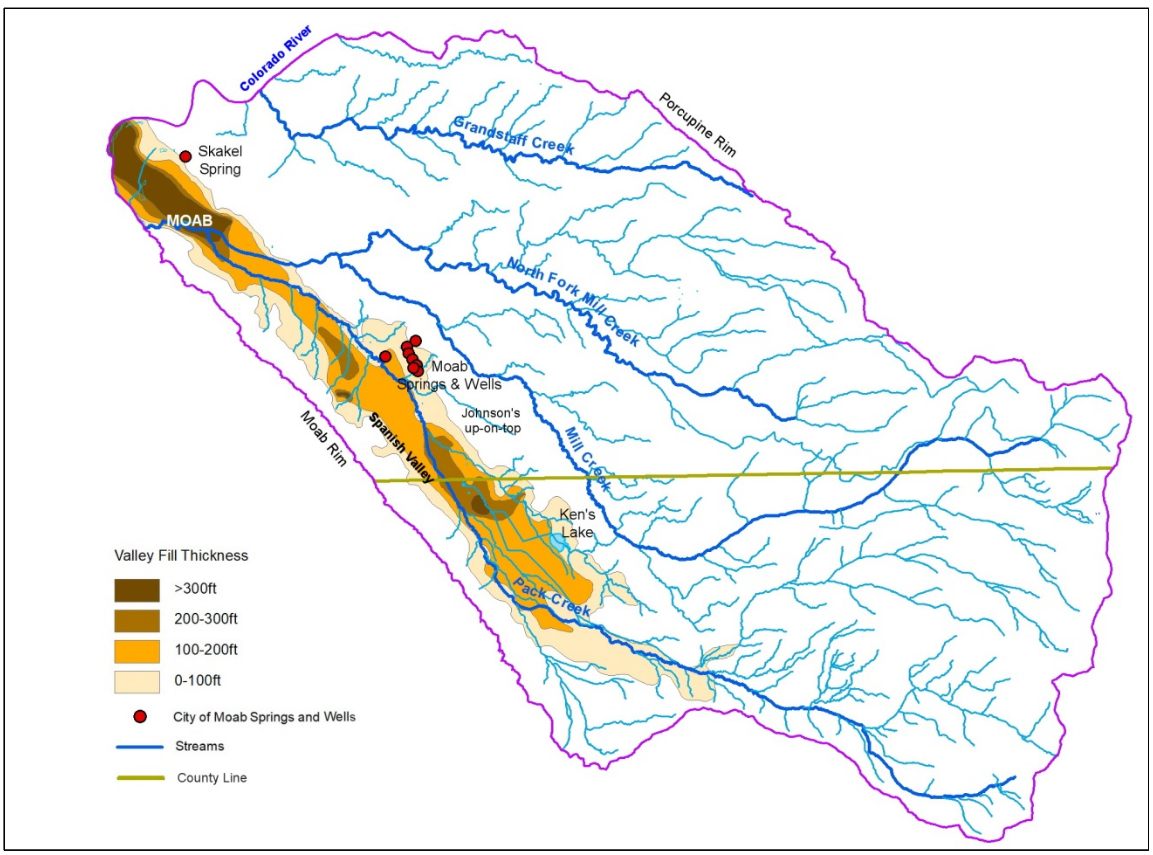

Figure 17. Isopach Map Showing Thickness of Valley Fill Deposits of the MCSW Study Area. The Valley Fill Deposits are the Shallow Unconsolidated Hydrogeologic Units in the Spanish Valley Section of the MCSW Study Area (modified from Lowe and Others, 2007).

The subsurface distribution of thickness is indicative of the structural collapse and faulting with subsequent erosion and filling of fault zones with gravels. Linear paleo-valleys and subsequent groundwater conduits are observed along the southwestern margin of the Moab Rim, and beneath the modern day Pack Creek along the entire length of the Spanish Valley (Figure 17). These groundwater conduits approximately overly possible bedrock conduits to be discussed in subsequent sections of this report.

2.5.3 Hydrostructural Units of the MCSW Area

Geologic faults and fracture zones, sometimes expressed at the surface as lineaments or linear drainage segments, may influence the hydrogeology and hydrologic systems of the Moab City Springs and Wells study area, including Mill, Grandstaff, and Pack Creeks (Figure 18). These hydrostructures underlie the drainages in the bedrock systems: Glen Canyon Group (Jgc) and Tertiary Intrusive Granodiorite (Ti), primarily; and are most likely associated with preferential groundwater flow along fault and fracture zones that are observed or hypothesized to transmit groundwater either vertically or laterally along the fault or fracture planes or zones. These structures may serve as distinct hydrogeologic units, may enhance the permeability of sections of bedrock hydrogeologic units, may connect multiple hydrogeologic units together, or may restrict the thickness and flow of overlying unconsolidated deposits resulting in springs and groundwater discharge areas. These hydrostructures, if “open”, may also result in connectivity between deeper groundwater systems and the streams, which may be a concern if future water well drilling or surface water diversion occurs. Each fault and fracture zone should be evaluated for the following characteristics: 1) fault and fracture plane geometry, including the vertical or horizontal nature of the fault/fracture plane and the relations of rock types and geometry on both sides of the structure; and 2) the transmissive nature of the fault/fracture plane or fault/fracture zone, including the nature of fault gouge, if any (clay, gravel), and tectonic setting of fault/fracture plane or zone (extension or compression). The fault/fracture plane geometry is important to evaluate if groundwater can move horizontally across the zone from one transmissive unit to another, or whether the groundwater is forced to move vertically upward to the surface, in many cases, or downward into a different hydrogeologic unit, or laterally parallel to the fault and fracture zone like a geotechnical French drain. The tectonic setting helps determine whether the fault/fracture plane is “open”—able to easily move water (extension), or “closed”—not able to easily move water (compression).

Hydrostructures, which are defined by folds, faults and fracture zones, control the location of Spanish Valley and the surrounding features, including the Moab Rim and the eastern Spanish Valley rimlands such as Johnson’s up-on-top, the location of Mill, Grandstaff, and Pack Creek, and major tributaries, the location of drainages that are part of the Sand Flats Plateau and Wilson and South Mesas, and the locations of streams draining the La Sal Mountains. These hydrostructures can exist subregionally and regionally if structural and topographic continuity exist (Figures 12, 13, and 18). The main subregional fold and fault structures are the Spanish Valley Salt Anticline with corresponding graben/collapse structure and Courthouse Syncline extending across the Sand Flats area, and the La Sal Mountain intrusions (Figures 12, 13, 14, and 18). The bounding faults of the collapse, located on the northeast and southwest sides of Spanish Valley, dip almost vertically and strike from the southeast to the northwest (Figures 14 and 18). The northeast fault zone, which is in the Glen Canyon Group Formation and labeled partially as the Kayenta Heights fault zone (Lowe and others, 2007), functions in part as a hydrogeologic conduit (high hydraulic conductivity zone or High "K" zone). This conduit is continuous from near the Mill Creek entry point into the Spanish Valley to the Colorado River and is a major spring line including Skakel Spring with high yields of groundwater with low TDS water quality (Figure 18).

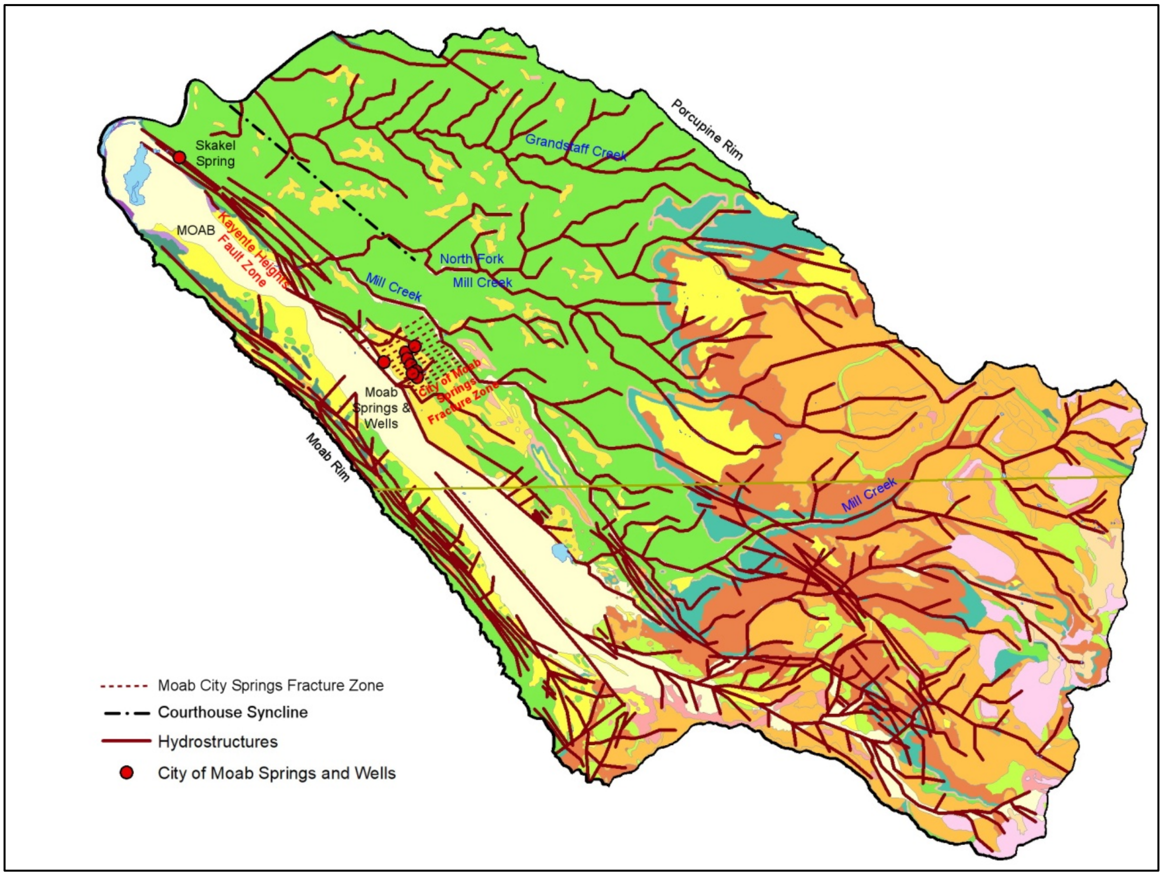

Figure 18. Map Showing Major Hydrostructures (Faults and Fracture Zones) in the MCSW Study Area on Top of Hydrogeologic Units.

These southeast/northwest hydrostructural units pinch out at either end of the valley and with depth keeping the groundwater system subregional and discontinuous beyond the Spanish Valley topographic feature. These hydrostructural units also inhibit lateral flow perpendicular to the fault zone. Therefore, no deep regional ground water is laterally entering or exiting Spanish Valley from the northeast or the southwest either through the entire Moab Rim, or from the upper part of the eastern Spanish Valley rimlands. The termination of these hydrostructural units to the southeast and northwest also blocks lateral flow, so no deep groundwater is laterally entering or exiting Spanish Valley from the southeast or the northwest. It is hydrologically important that the major part of the valley is underlain by a deep "flat lying" caprock of the Paradox Formation, which is a confining unit that, when interacting with groundwater, produces poor water quality due to dissolution of the salt bedrock. Effectively, these hydrogeologic/ hydrostructural units ensure that the Spanish Valley Bedrock groundwater flow system is entirely contained within the valley, and that the water quality derived from these units is not necessarily favorable (high TDS) (Figures 14 and 18).

The Spanish Valley Anticline/Graben also results in the younger bedrock hydrogeologic units being observed on the Moab Rim and eastern rimlands of Spanish Valley, in some locations, and dipping away to the northeast, northwest, and southwest (Figures 14 and18). This results in local and subregional groundwater and surface water systems that flow away from the Moab Rim into the Kane Creek hydrologic system, from the Eastern Spanish Valley rimlands into the Mill Creek hydrologic system, or towards the Colorado River and the Grandstaff Creek hydrologic system (Figures 14 and 18).

The fault and fracture zones have influenced the location of the main surface water drainages in the MCSW study area by providing zones of weakness whereby the streams have downcut into the bedrock of the Glen Canyon Group, observed in the Sand Flats area, and the Granodiorite Porphyry of the La Sal Mountains (Figures 16 and 18). As a result, the MCSW study area is dissected into three distinct watershed-based surface hydrologic subsystems: Mill Creek, Grandstaff Creek, and Pack Creek. Only Mill and Pack Creek become connected in the northwestern part of Spanish Valley at the confluence of the drainages (Figure 19).

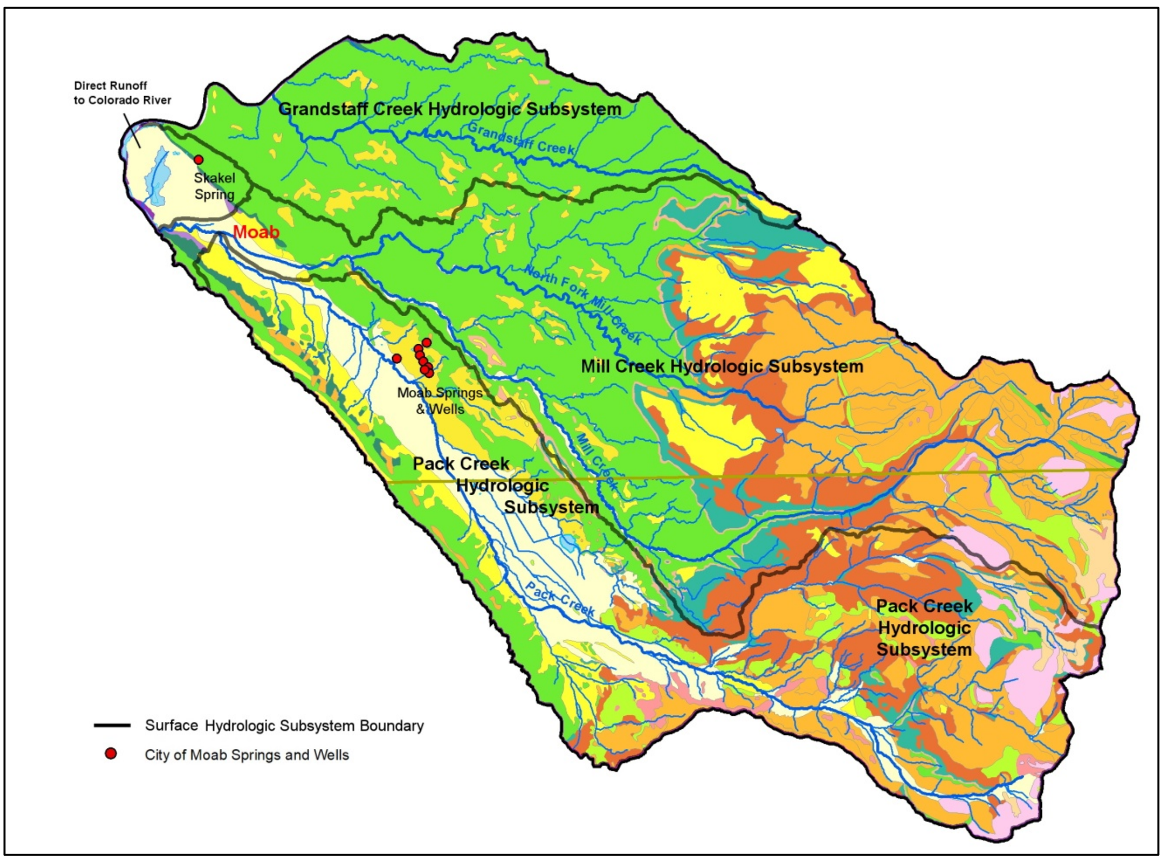

Figure 19. Map Showing the Three Major Surface Hydrologic Subsystems in the MCSW Study Area on Top of Hydrogeologic Units.

Two broad hydrostructure sets occur in the MCWS area: 1) the northwest-southeast and corresponding west-east trending faults and fractures that parallel the Spanish Valley fault and fracture zones and are parallel to the bounding faults of the Spanish Valley Anticline and collapse structures, including the Sand Flats part of Mill Creek canyon, Grandstaff Creek canyon, and the Kayenta Heights fault and fracture zone; 2) the northeast-southwest-trending cross mesa and valley fracture zones, including lower Mill Creek and Rill Creek by the Powerhouse, Grandstaff Creek, upper Mill Creek, and the Moab City Springs fracture zone (Figure 18). The northwest-trending and northeast-trending faults and fractures are relatively young, as the geomorphic systems of Mill Creek are responding with considerable downcutting, allowing for partial to full penetration of streams of the bedrock unit aquifers of the Glen Canyon Group, the geomorphic systems of Grandstaff and Mill Creeks, and the groundwater systems of the Moab City Springs fracture zone, which are diverting groundwater from the surface water systems to various springs. It is hypothesized that the northeast, east-west, and northwest fault and fracture zones are “open” and function like French drains. Groundwater moves laterally with the northwest trending Mill Creek parallel to the Spanish Valley and laterally from Mill Creek to Skakel Springs along the northwest trending Kayenta Heights fault and fracture zone. Groundwater moves laterally with the east-west, then northwest trending Grandstaff Creek towards the Colorado River. Groundwater also moves laterally from Mill Creek to the Moab City Springs along the northeast trending fracture zone labeled the Moab City Springs fracture zone (Figure 18). These groundwater recharge and flow zones are evidenced by losing reaches in streams and decreased groundwater head with depth in local wells.

The northeast-southwest trending drainages/fracture zones control most of the steep drainages on the flanks of the Moab Valley rimlands (Figure 18). These drainages are mostly ephemeral, and have the main hydrologic functions of delivering surface water down into the valley floor for groundwater recharge or surface water flooding and sediment transport into Pack Creek and associated tributaries.

The radial and concentric fracture pattern surrounding the La Sal Mountain intrusions (Ti) control the surface water drainages, and are open, therefore, supporting “French-drain” bedrock groundwater systems in the Tertiary intrusive (Ti) bedrock, and focusing groundwater towards drainages in the Older Alluvial Fan/Slope Deposits (Qas) locally (Figures 18 and 19). Examples of this are the minor drainages around Haystack Mountain, and the drainages in the eastern and southeastern part of the study area including the western flanks of the La Sal Mountain systems where Mill Creek and Pack Creek originate (Figures 18 and 19). In the Tertiary intrusive rocks (Ti), groundwater moves laterally down valley and vertically downward along these radial fault and fracture zone planes, and may move vertically up along the fault and fractures plane near the lower reaches of the various drainages as evidenced by gaining reaches in streams, increased groundwater head with depth in local wells, and by the springs that are the origin of various Mill and Pack Creek tributaries. The concentric fracture zones, which function as “French drains”, control the locations and origins of upper Mill Creek and Pack Creek (Figures 18 and 19).

2.5.4 Hydrochemical Units of the MCSW Study Area

The hydrochemistry of groundwater sampled from bedrock and unconsolidated materials can be commonly classified based on: 1) the relative amounts of common cationic (such as calcium, magnesium, sodium and potassium) and anionic (bicarbonate, sulfate, nitrate, chloride) chemical constituents; 2) the unique composition of a specific constituent or tracer (such as tritium or radionuclides); 3) a unique natural or human-caused contaminant (such as mercury or metals like lead, zinc, iron, copper); 4) a unique pH or Eh (such as acid rock drainage or oxy-redox conditions); or 5) a more general field and drinking water parameter such as Total Dissolved Solids (TDS). In this context, the use of the term *hydrochemical unit* is a classification of a hydrogeologic formation, part of a formation, or a group of formations with similar hydrochemical characteristics chosen for this HESA analysis (*e.g.*, similar chemistry, similar unique composition or unique contaminant, similar pH or Eh, or similar general field parameter).

Lowe and others (2007) summarized much of the previous work that has been conducted on the water quality analysis of the two primary hydrogeologic units discussed in Section 2.5.2: 1) Glen Canyon Group (Jgc) composed of the Wingate SS (Jw), the Kayenta Fm (Jk), and the Navajo Fm (Jn); and 2) Valley Fill (Qal, Qaf) in the Spanish Valley. Specifically, Rush and others (1982) reported the Wingate SS water samples had TDS values ranging from 164 – 680 mg/L averaging 260 mg/L. Blanchard (1990) sampled Wingate SS springs with TDS values ranging from 161-174 mg/L. The Wingate SS water quality type is classified as Ca-Mg-Bicarbonate (Lowe and others, 2007).

Weir and others (1983) reported the Navajo SS water samples had low TDS values ranging from 163 – 505 mg/L averaging 275 mg/L. Blanchard (1990) sampled Navajo SS springs with TDS values ranging from 102 -385 mg/L and wells with TDS values ranging from 210 – 360 mg/L. The Navajo SS water quality type is classified as Ca – Bicarbonate or Ca-Mg-Bicarbonate (Weir and others, 1983; Blanchard, 1990; and Lowe and others, 2007).

Steiger and Susong’s (1997) Grand County study on wells in the Glen Canyon hydrogeologic unit showed that water samples generally had values less than 500 mg/L with 83% of the samples having less than 250 mg/L. The low TDS of spring and well water, and the Ca-Mg Bicarbonate chemistry are attributed to the main source of groundwater being precipitation from the atmosphere, and the low chemical reactivity of the Glen Canyon hydrogeologic units to precipitation and groundwater flow.

The Valley Fill in the Spanish Valley is composed of unconsolidated deposits (Qal, Qaf) derived from the weathering, mass wasting, fluvial, glacial, and eolian processes of neighboring bedrock. Sumsion (1971) sampled 9 wells with TDS values ranging from 169 – 1020 mg/L, and Steiger and Susong (1997) sampled 20 wells with TDS values ranging from 260 -1818 mg/L. Lowe and others (2007), from groundwater samples and 63 well samples, found TDS values ranging from 140 – 1818 mg/L and overall average TDS value of 690 mg/L. In general, the Valley Fill hydrogeologic units have greater TDS values than the Glen Canyon hydrogeologic units, and are of Sulfate chemistry.

Lowe and others (2007) classified the spatial distribution of the water quality in the Glen Canyon and Valley Fill hydrogeologic units based on TDS: Class IA: Pristine Groundwater with TDS 140 – 454 mg/L; Class IB: Irreplaceable Groundwater (Sole Source Aquifer) with TDS less than 500 mg/L; and Class II: Drinking Water Quality Groundwater with TDS between 500 and 3,000 mg/L. Class IA and Class IB groundwater is mostly observed in samples derived from the Glen Canyon hydrogeologic unit (Jgc), and Class IIB groundwater is mostly observed in samples derived from the Valley Fill hydrogeologic units (Qal and Qaf) ranging from 516 – 1818 mg/L.

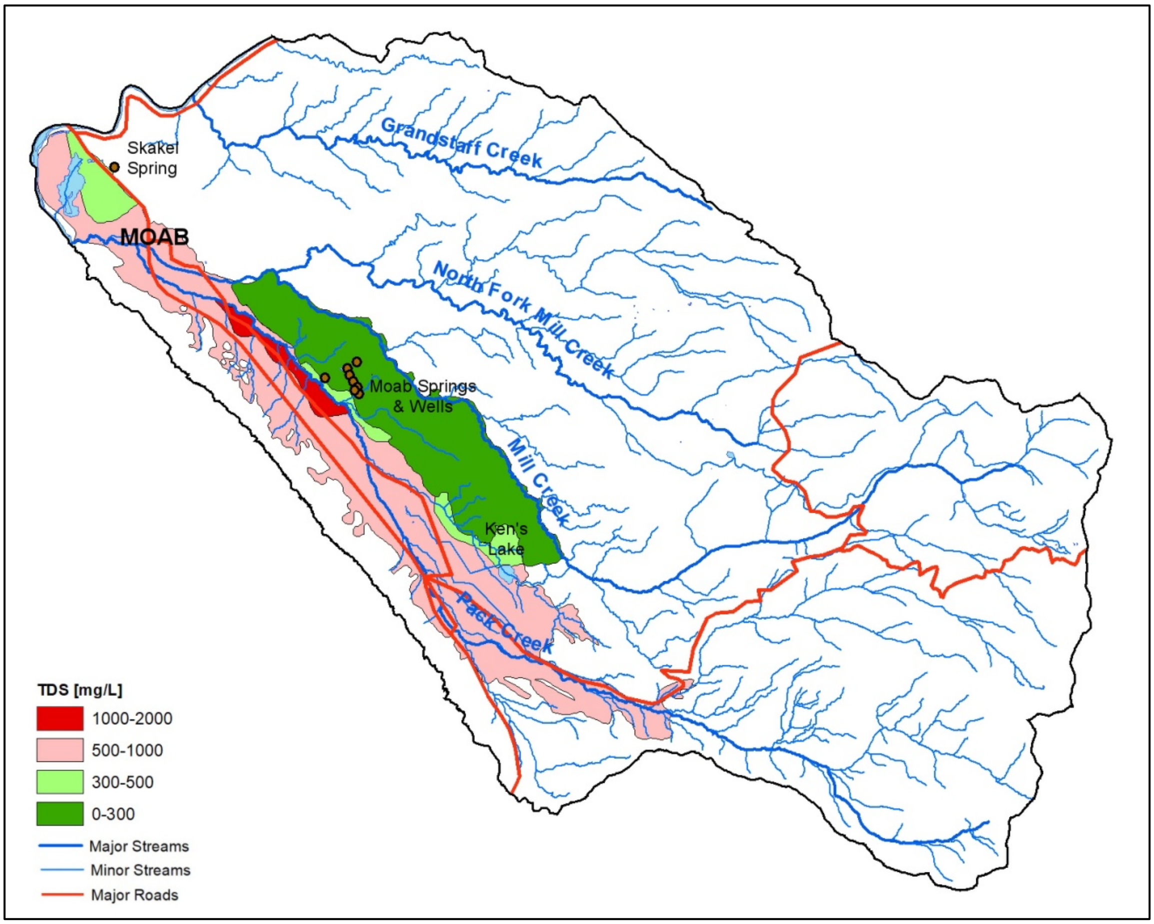

Figure 20. Total Dissolved Solids (TDS) of the Spanish Valley Groundwater System (Modified From Lowe and Others, 2007)

Lowe and others (2007) spatially plotted these sample values, and contoured the distribution of these TDS units (Figure 20). The categories that Lowe and others (2007) specified revealed that the low TDS (less than 250 mg/L) was exclusively found in wells and springs in the Glen Canyon Group bedrock above the Valley floor, and not in the Valley Fill alluvium or bedrock. The few TDS values ranging between 250 and 500 mg/L are found marginally in the Valley Fill next to areas where Glen Canyon springs are discharging to the surface on bedrock, and flow into the valley fill mixing groundwater types. The majority of the Valley Fill TDS values is in the 500 – 1000 mg/L range, and they define the Pack Creek groundwater system. There is a cluster of Valley Fill TDS values in the 1000 – 2000 mg/L range that may indicate a third source of water quality from the underlying Permian Paradox Formation (Figure 20).

2.6 Groundwater Flow Systems

Groundwater flow is the movement of water from the earth's surface into the subsurface (groundwater infiltration and recharge), through the subsurface materials (groundwater flow and storage), and from the subsurface back to the Earth's surface (groundwater discharge), expressed in terms of flow directions, patterns and velocities. The driving force for groundwater flow is a difference in piezometric "head" or groundwater levels, as expressed, for example, by the slope of the water table. The general Conceptual Site Model (CSM) of the groundwater flow system consists of 1) water inputs (recharge); 2) storage in and movement through subsurface hydrogeologic units (groundwater flow); and 3) water outputs (discharge). The general Conceptual Site Model (CSM) is helpful to determine the water balance of the groundwater flow system, which is the quantitative balance of the water inputs with the water outputs. Natural recharge is based on climate and soils resulting in infiltration of precipitation and snowmelt. Groundwater interaction with streams, vegetation (evapotranspiration), and human activity (irrigation, urbanization, wells and individual sewage disposal systems, reservoirs and ponds, oil and gas activity, mining, dewatering) will affect groundwater movement to varying degrees. The CSM also incorporates topography (steepness, slope aspect, degree of landscape dissection), geomorphology, and soil and rock properties. Because of the time-space variance of these inputs and outputs, a groundwater system often shows significant variations in water levels, water storage, flow velocities, and flow patterns. Some of the variations are seasonal; others may be related to multi-year periods of above-average or below-average precipitation. This results in variations in the availability of water from these hydrogeologic units.

Based on the HESA approach (*Kolm and others, 1996*), and previously collected supporting data, the regional, sub-regional, and local scale groundwater flow systems are delineated. The broad hydrologic system inputs include infiltration of precipitation as rain and snowmelt; areas of losing perennial and ephemeral streams (for example, reaches of the Mill and Pack Creek above the City of Moab, reaches of ephemeral streams on the sides of the Moab Rim and along the eastern Spanish Valley rimlands); infiltration and runoff from water bodies (Ken's Lake), upland irrigation areas (leaking ditches and irrigation return flow in upper Spanish Valley and on Wilson and South Mesas, lawn watering in the City of Moab and in Grand and San Juan Counties), and horizontal and/or vertical inter-aquifer transfer of groundwater between unconsolidated materials and bedrock systems, for example between the Tertiary Intrusive bedrock and the glacial till of the La Sal Mountains, or between the Pack Creek alluvium and the Glen Canyon Group bedrock. The general hydrologic flow subsystems, including the Mountain, Mesa Top, Hillslope, and Valley Bottom type subsystems, consist of the hydrologic processes of surface runoff (channel and/or overland flow) and rapid near-surface runoff (interflow or shallow through-flow); saturated groundwater flow in parts of the bedrock units, landslides, terraces, and valley bottoms; and discharge to springs and seeps, graining streams, by plants as evapo-transpiration, and by pumping wells. In general, shallow groundwater flow in these systems is with topography away from the mountain and ridge tops, along the axis of the mesa tops, and/or towards the valley bottoms, perpendicular to the major streams. Where permeable bedrock units underlie the mountains, mesa tops, hill slopes, and valley bottoms, recharge by groundwater moving from unconsolidated hydrogeologic units into the bedrock hydrogeologic units may force the groundwater into a more regional or subregional pattern determined by geological structure, independent from local topography and hydrography. However, the MCSW groundwater subsystems are a complex mix of bedrock aquifers, and predominantly shallow Mesa top, Hillslope and Valley Bottom aquifer systems underlain by either bedrock aquifers, or more confining hydrogeologic units, such as the Cretaceous Mancos Fm (Km), Jurassic Morrison Fm (Jm), the Triassic Chinle (TRc) and Moenkope Fms (TRm), the Permian Cutler Fm (Pc), and the Paradox Formation with caprock (IPpc). Locally and subregionally, various hydro-structures may influence interconnectivities of the shallow units with deeper bedrock systems, but in general, there are no regional systems due to a lack of hydrogeologic, structural, and geomorphologic (including topographic) connectivity.

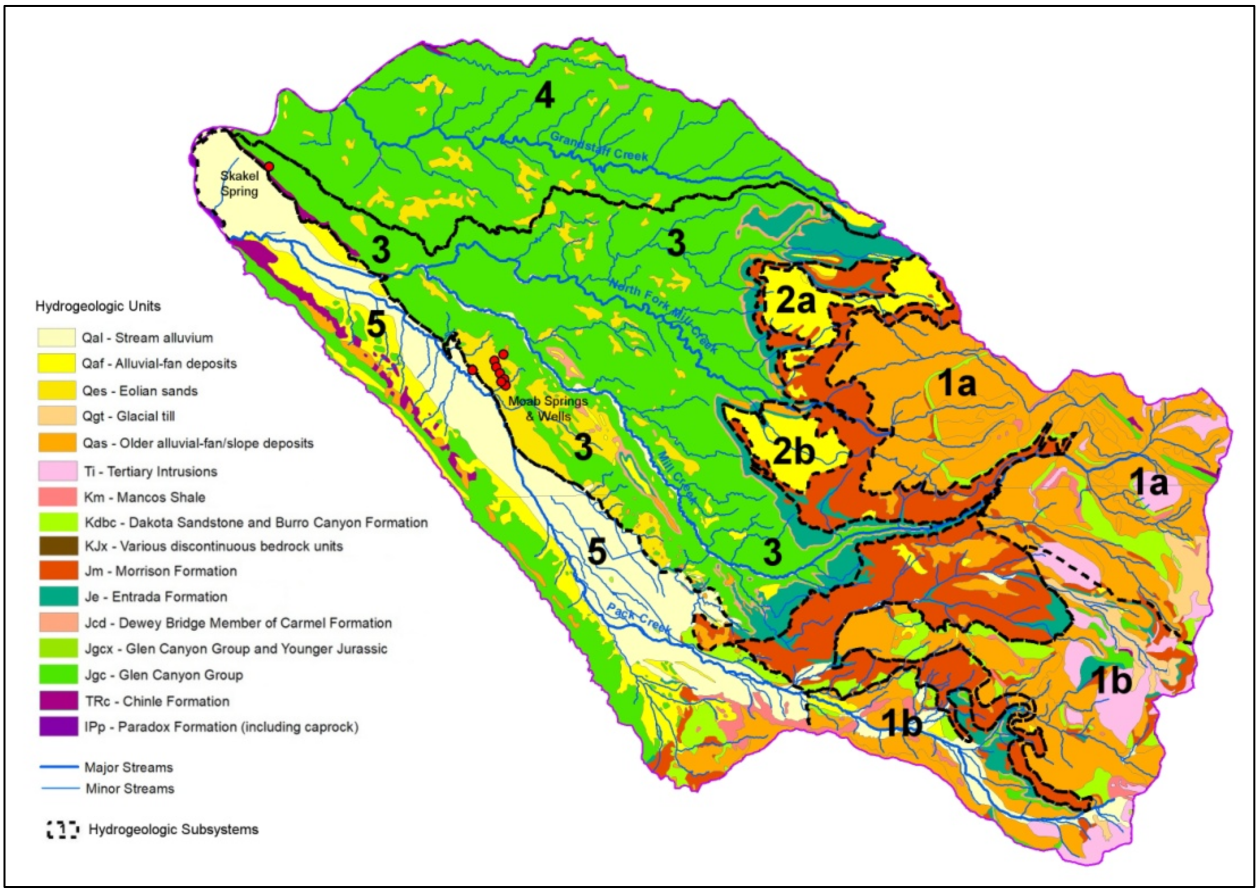

Figure 21. Plan View of the Conceptual Site Model Subsystems of the MCSW Study Area on Top of Hydrogeologic Units: 1a. La Sal Mountain Upper Alluvial Subsystem (LSMA-M) Mill Creek Headwaters; 1b. La Sal Mountain Upper Alluvial Subsystem (LSMA-P) Pack Creek Headwaters; 2a. Wilson Mesa Alluvial Fan Subsystem (WMAF); 2b. South Mesa Alluvial Fan Subsystem (SMAF); 3. Glen Canyon Group Mill Creek Subsystem (GCMC); 4. Glen Canyon Group Grandstaff Creek Subsystem (GCGC); and 5. Pack Creek Lower Alluvium Subsystem (PCLA).

The La Sal Mountain Upper Alluvial Subsystems (LSMA-M and LSMA-P), located in the southeastern part of the study area (CSMs 1a and 1b in Figure 21), is a complex mix of bedrock (Tertiary Igneous Intrusive rocks or Ti), Glacial Till (Qgt), and Older Alluvial Fan/Slope Deposits (Qas). These subsystems form several robust groundwater systems directly connected to the surface water systems that are the headwaters of Mill Creek (1a) and Pack Creek (1b) (Figures 21 and 22). These subsystems are hydraulically connected to the groundwater subsystems downgradient only by surface water streams and tributaries, and do not have significant direct groundwater connection through shallow or deep hydrogeologic units in the MCSW study area.

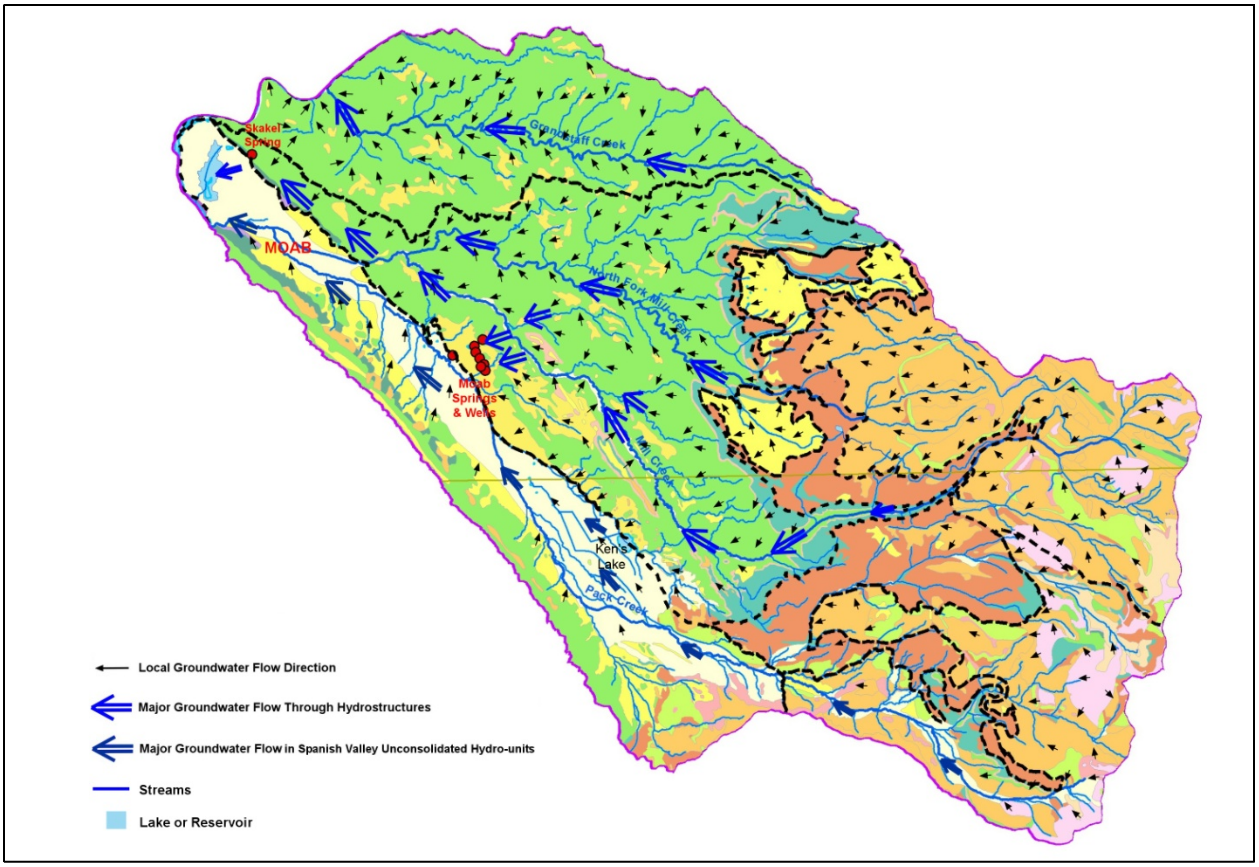

Figure 22. Plan View of the Groundwater Flow System Directions on Top of the Hydrogeologic Units of the MCSW Study Area. The small arrows are local groundwater flow directions. The larger blue arrows show groundwater flow direction along major hydrostructures and the major groundwater flow direction in the Spanish Valley area.

The Wilson Mesa and South Mesa Alluvial Fan Subsystems (WMAF and SMAF), located in the east central part of the study area (CSMs 2a and 2b in Figure 21), are predominately Alluvial Fan Deposits (Qaf), which form localized groundwater systems that are directly connected to the surface water systems forming the headwaters to tributaries of Mill Creek (Figures 21 and 22). These subsystems are hydraulically connected to the groundwater subsystems downgradient predominantly by surface water streams and tributaries, and do not significantly have direct groundwater connection through shallow or deep hydrogeologic units in the MCSW study area.

The Glen Canyon Group Mill Creek Subsystem (GCMC), located in the core of the study area (CSM 3 in Figure 21), is a complex mix of fractured and faulted Entrada Sandstone (Je) and Glen Canyon Group (Jgc), Eolian Sand (Qes), and hydrostructures (fault and fracture zones) which form the robust groundwater system and surface water system that is directly connected to the City of Moab springs and wells (Figures 21, 22, 23a and 23b). This subsystem is hydraulically connected to the Pack Creek Lower Alluvium subsystem (discussed in forthcoming paragraphs) downgradient predominantly by Mill Creek, outflow streams from the major springs like Skakel Spring, and by surface water diversions from Mill Creek (Sheley Tunnel diversion to Ken's Lake), and does not have significant direct groundwater connection through shallow or deep hydrogeologic units in the MCSW study area.

The Glen Canyon Group Grandstaff Creek Subsystem (GCGC), located to the north of the GCMC subsystem west of the Porcupine Rim of Castle Valley (CSM 4 in Figure 21), is a complex mix of fractured and faulted Glen Canyon Group (Jgc), Eolian Sand (Qes), and hydrostructures (fault and fracture zones) which form the robust groundwater system and surface water system, Grandstaff Creek, that is hydraulically connected directly to the Colorado River (Figures 21, 22 and 23a). This subsystem does not have significant direct groundwater connection through shallow or deep hydrogeologic units to any other subsystem in the MCSW study area, and has no direct connection to the snowmelt, surface water, or groundwater systems originating in the La Sal Mountains.

Finally, the Pack Creek Lower Alluvium Subsystem (PCLA), located in the southwestern and southern part of the study area (CSM 5 in Figure 21), is a complex mix of the main hydrogeologic bedrock units, including the fractured and faulted Entrada Sandstone (Je) and Glen Canyon Group (Jgc), complex hydrostructures (fault and fracture zones), Alluvial Fan Deposits (Qaf), Eolian Sand (Qes), and Stream Alluvium (Qal), which forms a robust groundwater system that is directly connected from the top of the La Sal Mountains near South Mountain, by both groundwater flow and surface water flow systems forming the headwaters of Pack Creek (LSMA-P in Figure 19 and Figure 21 Subsystem 1b), to the Colorado River northwest of Moab, Utah (Figures 21 and 22). The PCLA does not have significant direct groundwater connection through shallow or deep hydrogeologic units to other subsystems in the MCSW study area. The PCLA does have a connection to the LSMA (CSM 2b) and to GCMC (CSM 3) subsystems by surface water streams and stream diversions, including the tributaries of Pack Creek east of the La Sal Mountain Loop Road, the main channel of Mill Creek at the emergence below the Mill Creek Canyon into Spanish Valley, and diversions such as the Sheley Tunnel diversion to Ken's Lake.

As springs are discharge points of groundwater flow systems, their presence in the MCSW study area provide clues about these groundwater flow systems, including the role of the hydrogeological units, hydrostructures, and the effects of natural and anthropogenic recharge on flow and water quality. The location of springs and seeps in the MCSW area were identified using topographic maps and the Utah State water rights records, augmented by field reconnaissance. The locations of these springs are discussed in Section 2.4 (Figure 9). The springs are plotted with the distribution of the hydrogeologic units to determine the hydrologic systems relationships (Figure 24).

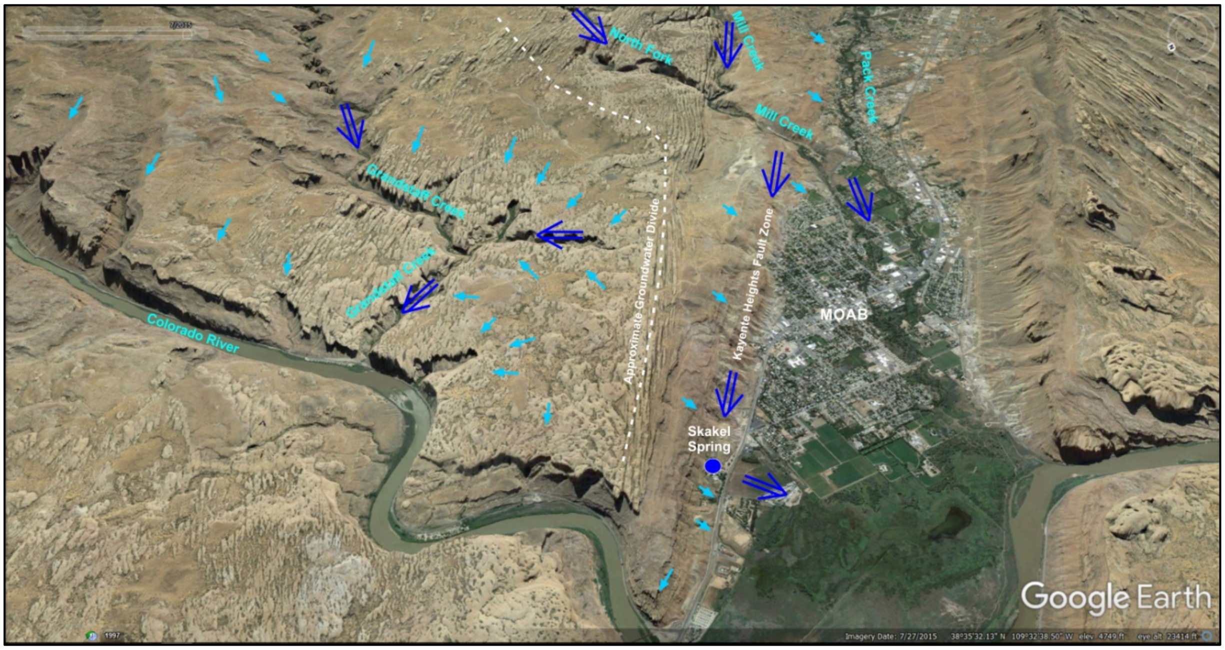

Figure 23a. Groundwater Flow in the Northwestern Part of the MCSW Study Area. Groundwater Flow Direction Is Shown with Blue Arrows (Google Earth, Imagery May 2016).

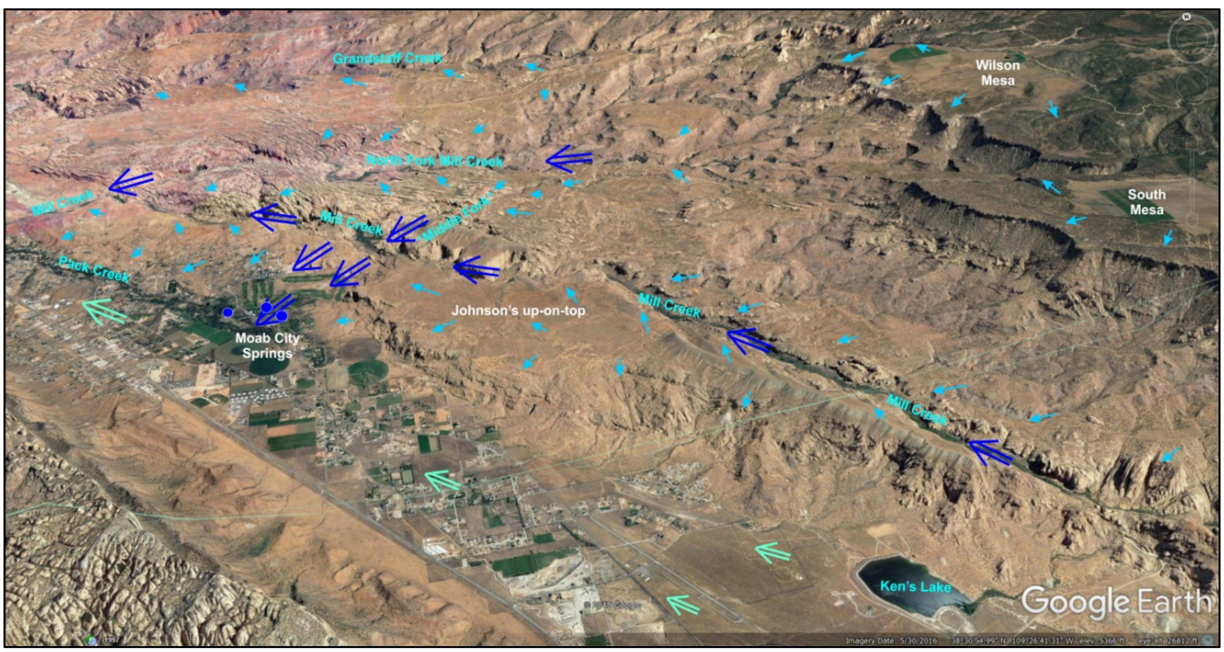

Figure 23b. Groundwater Flow in the Midsection of the MCSW Study Area. Groundwater Flow Direction Is Shown with Blue Arrows (Google Earth, Imagery May 2016).

There are five spatial distributions of springs, based on spring location with respect to hydrogeologic location, that are informative for the analysis of the surface water and groundwater systems in the MCSW study area. The highest elevation springs in the MCSW area are located in the La Sal Mountains and in the glacial and glacial/alluvial deposits surrounding the La Sal Mountains (Figures 9 and 24). These springs emanate from the Tertiary Bedrock (Ti) systems or the glacial (Qgt)/alluvial (Qas) deposits in the La Sal Mountains, and represent the culmination of the groundwater flow in the Tertiary Intrusive rocks and associated glacial gravels and alluvium of the La Sal Mountain Upper Alluvium subsystems (LSMA-M and LSMA-P shown in pink and orange, Figures 21, 22, and 24). These springs are the beginning of the tributaries of the Mill Creek and Pack Creek surface water systems, which will affect the entire MCSW hydrologic systems.

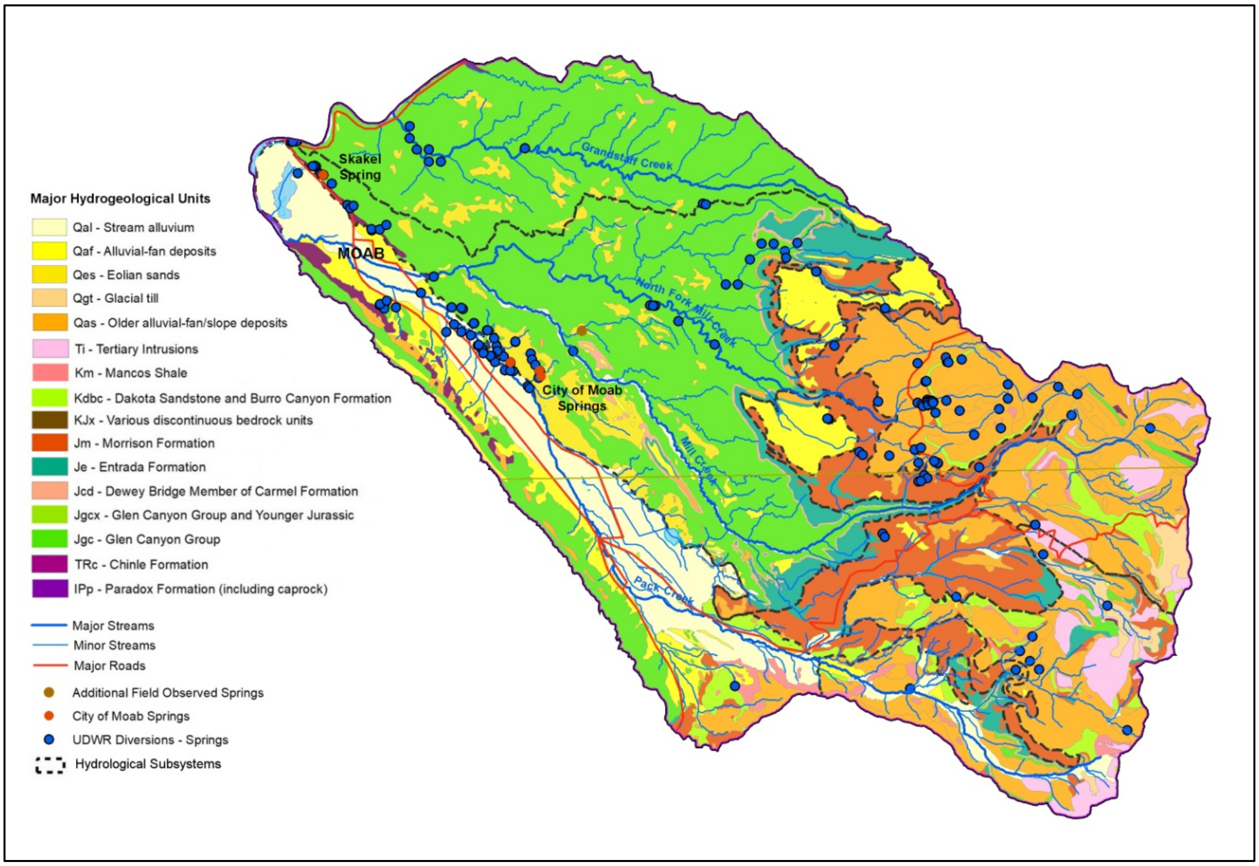

Figure 24. Plan View of the Location of Spring Areas, and the Conceptual Site Model Subsystems, Hydrogeologic Units and Streams of the MCSW Study Area.

The mid elevation springs at the edge of the Wilson Mesa and South Mesa emanate from the Quaternary alluvial fan (Qaf) subsystems (WMAF and SMAF) that are topographically below the La Sal Mountain Upper Alluvium (LSMA-M) subsystem, and represent the culmination of the groundwater flow in the South Mesa and Wilson Mesa Alluvial Fan subsystems (Figures 21, 22, and 24). These springs and associated streams are the beginning of the tributaries of Mill Creek that flow across the central Sand Flats area, which will affect the entire MCSW hydrologic system. These springs are discharge areas where the South Mesa and

Wilson Mesa Alluvial Fan Deposits (Qaf) overlying impermeable Morrison Fm bedrock (Jm) are thinning or terminating, forcing groundwater to daylight to the surface enhancing the surface water flow regimes. Downgradient of these features, the surface water eventually returns to a different groundwater system (GCMC) as recharge, evapotranspires in vegetation, or evaporates into the atmosphere.

The third group of springs are observed throughout the Sand Flats area in the Glen Canyon Group hydrologic units (Jgc), and are affiliated with the Grandstaff, North Fork Mill, Rill, and Mill Creeks and their associate subsystems (GCMC and GCGC) (Figures 21, 22, and 24). These springs are bedrock discharge areas where the Glen Canyon Units (Jgc) are deeply fractured or faulted and the groundwater finds a preferential flow path from the bedrock to the surface enhancing the surface water flow regimes (gaining streams). Downgradient of these springs, the surface water may eventually return to a different part of the groundwater system as recharge.

The fourth group of springs, which include the largest springs and Skakel and the Moab City Springs, are located in bedrock along and above the margins of the Spanish Valley (Figure 21, 22, 23a, 23b, and 24). These major springs are groundwater discharge areas where the Glen Canyon Group (Jgc) due to hydrostructures, such as the Kayenta Heights fault zone and the Moab City Springs fracture zone, force groundwater to daylight to the surface enhancing the surface water flow regimes of the GCMC subsystem (Figure 24). Downgradient of these major springs, the surface water quickly flows to a different groundwater system, the Pack Creek Lower Alluvium subsystem (PCLA), and becomes groundwater recharge, evapotranspires from vegetation, or evaporates into the atmosphere (Figures 22, 23a, 23b, and 24).

The fifth group of springs is located in the Pack Creek stream alluvium (Qal) in the Spanish Valley (PCLA subsystem; Figures 21, 22, 23a, 23b, and 24). These springs are groundwater discharge areas where the Quaternary Lower Alluvial Units (Qal) are thinning above a relatively impermeable bedrock (TRc, TRm, Pc, and IPpc) forcing the groundwater to the surface and enhancing the Pack Creek stream flow in some cases. This Pack Creek surface water reaches the Colorado River, evaporates, or is evapotranspired by phreatophytes.

2.7 Groundwater System Conceptual Site Models by Subsystem

Based on the presence and orientation of various hydrogeologic and hydro-structural units, hydrography and topography, five categories of Conceptual Site Models (CSMs) or Hydrogeologic Subsystems will be discussed in the MCSW study area:

1. The La Sal Mountain Upper Alluvium Subsystems (LSMA-M and LSMA-P), located in the southeastern part of the study area (CSM 1a and CSM 1b), is a complex mix of bedrock (Tertiary Igneous Intrusive rocks or Ti), Glacial Till (Qgt), and Older Alluvial Fan/Slope Deposits (Qas). These groundwater systems are directly connected to the surface water systems forming the headwaters of Mill Creek (CSM 1a) and Pack Creek (CSM 1b) (Figures 21 and 22);
2. The Wilson Mesa and South Mesa Alluvial Fan Subsystems (WMAF and SMAF), located in the east central part of the study area, are predominately Alluvial Fan

Deposits (Qaf). These localized groundwater systems (CSM 2a) and (CSM 2b) are directly connected to the surface water systems forming the headwaters to tributaries of North Fork Mill Creek, Rill Creek, and the main fork of Mill Creek (Figures 21 and 22);

3. The Glen Canyon Group Mill Creek Subsystem (GCMC), located in the core of the study area (CSM 3), is a complex mix of fractured and faulted Entrada Sandstone (Je) and Glen Canyon Group (Jgc), Eolian Sand (Qes), and high K hydrostructures (fault and fracture zones). This groundwater system and surface water system is directly connected to the City of Moab springs and wells (Figures 21, 22, 23a, 23b, and 24);
4. The Glen Canyon Group Grandstaff Creek Subsystem (GCGC), located to the north of the GCMC subsystem west of the Porcupine Rim of Castle Valley (CSM 4), is a complex mix of fractured and faulted Glen Canyon Group (Jgc), Eolian Sand (Qes), and high K hydrostructures (fault and fracture zones). This groundwater system and surface water system of Grandstaff Creek is hydraulically connected to the Colorado River (Figures 21 and 22); and
5. The Pack Creek Lower Alluvium Subsystem (PCLA), located in the southwestern and southern part of the study area (CSM 5), is a complex mix of the main hydrogeologic bedrock units, including the fractured and faulted Entrada Sandstone (Je) and Glen Canyon Group (Jgc), complex hydrostructures (fault and fracture zones), Alluvial Fan Deposits (Qaf), Eolian Sand (Qes), and Stream Alluvium (Qal). This groundwater system is directly connected from the top of the La Sal Mountains near South Mountain, by both groundwater flow (CSM 1b) and surface water flow systems forming the headwaters of Pack Creek (CSM 5), to the Colorado River northwest of Moab, Utah (Figures 21 and 22).

The La Sal Mountain-Glacial Till-Upper Alluvium Subsystems (LSMA) will be discussed first since they are located at the highest topographic level, and are the headwaters of the overall Mill and Pack Creek surface water systems, and directly influence the Pack Creek Lower Alluvium (PCLA) groundwater hydrologic system. In addition, the interface between the five subsystems will be discussed. The conceptual models are presented in forthcoming sections and illustrated by cross-sectional and plan view figures. Note that all of the subsystems have some interconnectedness with the surrounding subsystems, mostly by tributary or truck stream flow.

2.7.1 La Sal Mountain Upper Alluvium Subsystems (LSMA)

There are two separate LSMA subsystems that behave similarly, and differ only because the northern subsystem (LSMA-M; CSM 1a on Figure 21) is part of the greater Mill Creek Surface Watershed, and the southern subsystem (LSMA-P; CSM 1b on Figure 21) is part of the greater Pack Creek watershed. The surface water divide is indicated on Figure 21 by a dashed line approximating the delineation of the two LSMA surface watersheds. This may be significant as local surface water diversions may cross that divide, which could have a cascading effect on the surface water discharge and other groundwater systems downgradient in the two watersheds. However, the description of how the two separate LSMA subsystems are configured and function is nearly the same, so one description will be discussed pertaining to both systems.

As stated in Section 2.5.2, The La Sal Mountain Upper Alluvium Subsystems (LSMA) are a complex mix of bedrock (Tertiary Igneous Intrusive rocks or Ti) (Figures 16 and 21; Table 2b), and Glacial Till (Qgt) and Older Alluvial Fan/Slope Deposits (Qas) (Figures 15 and 21; Table 2a). In addition, there are two types of geological structures of significance to the hydrogeology in the LSMA Subsystems: 1) Northeast-southwest and east-west trending fault/fracture zone hydrostructures that are observed on the western flanks of the La Sal Mountains that control the major streams (Figures 13 and18); and 2) Radial and concentric fault/fracture zone hydrostructures that are observed radiating out from and surrounding the Tertiary intrusions (Figure 18).

The shallow Quaternary unconsolidated materials in the La Sal Mountain Subsystems are ubiquitous, and include alluvial, glacial-alluvial, glacial, and mass wasting deposits mostly derived from the Tertiary Intrusive rocks and underlying sedimentary rocks (Figure 15; Table 2a). These highly-permeable deposits are locally heterogeneous, with a mix of coarser and finer materials in all of the deposits. These deposits are underlain by a paleo-topographic surface carved out by paleo mass wasting and fluvial systems. The glacial, fluvial, and mass wasting processes continued to eventually deposit the Quaternary unconsolidated materials that are the shallow aquifers in Mill Creek and Pack Creek surface water systems (Figure 21). It should be noted that the paleo-alluvial and modern alluvial systems followed structural fault zone controlled valleys and account for increased aquifer thicknesses in these valleys (Figure 17).

The general aspects of groundwater flow in the Quaternary unconsolidated materials have been discussed in Section 2.5. Specifically, the shallow groundwater in the LSMA Subsystems is dominated by the Glacial Till (Qgt) and Older Alluvial Fan/Slope Deposits (Qas), which receive natural recharge by infiltration of precipitation (snow and rain); input from hillside (slope) deposits located upgradient from a given location; and input from predominantly the Tertiary Intrusive units (Figure 22).

Groundwater flow in the LSMA unconsolidated materials is with topography from hilltop and ridgetop down the hillslope to the valley bottom, and then parallel with the valley bottom streams (Figure 22). Groundwater in the valley bottom stream unit moves in the same direction as the stream with various stream reaches being gaining or losing depending on subsurface topography, saturated thickness of the alluvium, or the seasonal variations caused by snowpack runoff or storm events (Figure 22). These streams and tributaries are the headwaters of Mill Creek (CSM 1a in Figure 21) and Pack Creek (CSM 1b in Figure 21), and most reaches are gaining from the alluvial and bedrock aquifers (Figure 22). There is also groundwater discharge from the alluvium locally by groundwater wells and by phreatophytes.

The shallow groundwater in the LSMA Subsystems is sustained by and connected directly to the underlying bedrock groundwater systems, predominantly by the Tertiary Intrusive hydrogeologic unit (Ti) (Figures 21 and 22). The connection of these two units is further enhanced by the radial and concentric faults/fracture zones where preferential (high K zones) groundwater flow occurs in the bedrock (Figure 18).

Groundwater recharge occurs on the mountain tops and ridges where the Tertiary Intrusive units are frequently exposed (Figures 21 and 22). Groundwater then flows downgradient with topography along the radial faults and fractures to the radial and concentric valley bottoms, also preferred high K fault and fracture zones that serve as groundwater "French drains", where the groundwater discharges into the unconsolidated materials and streams (gaining streams) (Figure 22). These valley bottoms, with combined bedrock and unconsolidated deposits, have increased groundwater flow and storage, and connectivity between the two hydrologic systems. Given the granodiorite composition of bedrock, the natural water quality is good except where mining activity has been undertaken.

2.7.2 Wilson Mesa (WMAF) and South Mesa (SMAF) Alluvial Fan Subsystems

As stated in Section 2.5.2, The Wilson Mesa and South Mesa Alluvial Fan Subsystems (WMAF and SMAF) are predominately Alluvial Fan Deposits (Qaf) (Figure 15; Table 2a) overlying the mostly impermeable Morrison Fm bedrock unit (Figure 16; Table 2b). In addition, there are two types of geological structures of significance to the hydrogeology near these subsystems (Figure 18): 1) Northeast-southwest and east-west trending fault/fracture zone hydrostructures; and 2) Northwest-southeast trending fault/fracture zone hydrostructures influencing downcutting and stream erosion of nearby bedrock.

The shallow Quaternary unconsolidated materials (Qaf) in these two subsystems are isolated, and include Stream Alluvium and Alluvial Fan Deposits (Figure 15; Table 2a). These highly-permeable deposits are locally heterogeneous, with a mix of coarser and finer materials in all of the deposits. These deposits are underlain by a paleo-topographic surface carved out by paleo mass wasting and fluvial systems that eventually deposited the Quaternary unconsolidated materials that are the aquifers being evaluated.

The general aspects of groundwater flow in the Quaternary unconsolidated materials (Qaf) have been discussed in Section 2.5. Specifically, the shallow groundwater in the WMAF and SMAF subsystems is dominated by natural recharge by infiltration of precipitation (snow and rain), losing streams, and additional recharge from return flow from irrigation locally. Water leaking from the irrigated areas enters into the (connected) unconsolidated deposits underneath and flows downgradient towards the discharge zones (gaining streams, springs and seeps, and wetlands) (Figures 21, 22, 23b and 24).

Groundwater flow in these subsystems moves with topography towards the nearby bedrock drainages, and various nearby stream reaches may being gaining depending on subsurface topography, bedrock hydrogeology, hydrostructures, and saturated thickness of the alluvium, or the seasonal variations caused by snowpack runoff or storm events. There is also groundwater discharge from the alluvium locally by groundwater wells and by phreatophytes.

2.7.3 Glen Canyon Group Mill Creek Subsystem (GCMC)

The Glen Canyon Group Mill Creek Subsystem (GCMC), located in the core of the study area (CSM 3 in Figure 21), is a complex mix of fractured and faulted bedrock (Entrada Sandstone (Je) and the Glen Canyon Group (Jgc)), Eolian Sand (Qes), Stream Alluvium (Qal), and hydrostructures (high K fault and fracture zones) which form the robust groundwater system and surface water system that is directly connected to the City of Moab springs and wells in the vicinity of the golf course and Skakel Spring (Figures 21, 22, 23a, 23b, and 24). Compared with the other 4 subsystems, GCMC is the most important subsystem for the City of Moab springs and wells, and Skakel Spring sustainability and protection, although knowledge of the LSMA-M, WMAF, and SMAF subsystems is crucial in protecting these assets.

As stated in Section 2.5.2, there are two significant hydrogeologic groups in the GCMC Subsystems, which includes Mill Creek and its tributaries: 1) Quaternary unconsolidated clastic materials (Figure 15; Table 2a), which are predominantly Stream Alluvium (Qal) and Eolian Sand (Qes); partially overlying 2) Mesozoic bedrock units (Figure 16; Table 2b), including the following potentially water-bearing units: Entrada Sandstone (Je) and the Glen Canyon Group (Jgc), including the Navajo Sandstone (Jn), the Kayenta Sandstone when fractured (Jk), and the Wingate Sandstone (Jw).

In addition, there are two types of geological structures of significance to the hydrogeology in the GCMC Subsystem (Figures 13, 14, and 18): 1) Northeast-southwest and east-west trending fault/fracture zone hydrostructures; and 2) Northwest-southeast trending faults, and fault/fracture zone hydrostructures (bedrock high K units) that are observed on both the northeastern and southwestern sides of Spanish Valley dipping vertically. The most prominent northeast-southwest east-west trending fracture zones are observed in all of the Mill Creek tributaries such as Rill Creek, the North Fork Mill Creek, and the “Middle Fork” of Mill Creek (an unnamed, spring-fed tributary to Mill Creek east of the Moab Springs and wells). Several bends in the main Mill Creek drainage have this trend, as does the main Mill Creek gorges in two locations: 1) the reach from the La Sal Mountains to the upper Sand Flats region where the Ken’s Lake (Sheley Tunnel) diversion is located; and the reach where the North Fork Mill Creek joins the main fork of Mill Creek and exits to the Spanish Valley (Figure 18). In addition, the main fracture zone from the “Middle Fork” of Mill Creek to the City of Moab Springs and Wells has this same trend (Figure 18). These hydrofractures are “French drains” or High K zones in the Glen Canyon bedrock in the Mill Creek system, and are open with gaining tributary reaches (groundwater discharging to streams) (Figures 22, 23a, and 23b). In the case of the fracture zone at the junction of the “Middle Fork” of Mill Creek with the Main Fork, this East-West Fracture Zone transports Mill Creek surface water as groundwater through the Moab City Springs fracture zone to the City of Moab bedrock springs along the edge of Spanish Valley (Figures 22, 23b, and 24) and is quite important to the springs and well protection.

The entire Mill Creek gorge from the Ken’s Lake intake to the junction with the North Fork Mill Creek, and the upper part of the North Fork Mill Creek are along a northwest-southeast trending fault and fracture zone that is critical to understanding the GCMC hydrologic system (Figure 19). These zones serve as French Drains to the GCMC groundwater system, and for much of their reaches are gaining streams (Figure 22, 23b, and 24). The other major northwest-southeast fault zone of importance to the GCMC subsystem bounds the eastern Spanish Valley rimlands for their entire length, and has the name Kayenta Heights fault zone along the City of Moab (Figure 19). The Kayenta Heights fault zone is open and a groundwater conduit moving water from Mill Creek to various springs and discharge zones, including City of Moab’s Skakel Spring (Figure 22, 23a, and 24). The middle and southern part of this fault zone does not serve as a conduit, but as a block bringing the Glen Canyon Group next to the Permian shales and salts, as evidenced by the City of Moab Springs near the Moab golf course (Figures 14, 18, 22, 23b, and 24).

The shallow Quaternary unconsolidated materials in this subsystem are located in two strategic locations: directly along the main channels of the stream (Qal) and scattered on the mesa tops (Qes) (Figure 15 and Table 2a). These highly-permeable deposits are homogeneous, mostly fine to medium grained sand, and locally derived from the weathering of Glen Canyon Group (Jgc) bedrock.

The Glen Canyon Group bedrock has both matrix flow and fracture flow. The matrix flow has ranges estimated from 0.1 – 0.3 m/day (Jobin, 1962; Blanchard, 1990; Lowe and others, 2007); and the fracture flow can be as high as 25 m/day (88 ft/day) (Freethey and Cordy, 1991). Therefore, fracture flow will dominate travel times and will be most important for contaminant studies and well/spring protections, as well as estimating groundwater storage and recharge rates.

The general aspects of groundwater flow in the Quaternary unconsolidated materials have been discussed in Section 2.5. Specifically, the Eolian Sand (Qes) facilitates enhanced groundwater recharge by infiltration of precipitation (snow and rain) to the bedrock underneath. The Quaternary Stream Alluvium (Qal) in the Mill Creek channel and tributaries is closely aligned with the stream levels except where the stream is gaining, in which case the groundwater levels may be higher reflecting water moving from the bedrock into the stream.

Recharge to the Entrada Sandstone and Glen Canyon Group in the GCMC subsystem is by infiltration of precipitation (snow and rain) directly into bedrock, or through the eolian sand cover on the surface of the mesa and interfluve tops; by northeast-southwest and east-west trending fracture-controlled ephemeral stream channels, by northwest-southeast trending fracture controlled ephemeral stream channels, and by losing reaches of flowing streams (Figures 22 and 23b). These ephemeral channels are located mostly to the east along the Porcupine Rim, and along the Entrada Sandstone bluffs that are below Wilson Mesa and South Mesa (Figure 16). There may be a small amount of groundwater entering from under Wilson Mesa and South Mesa, but there is no evidence to date of this occurring or the amounts that may be entering the system by this mechanism.

Groundwater flow in the Entrada Sandstone and Glen Canyon Group is strongly fracture controlled, and moves from the drainage divides in the same direction as the stream with various stream reaches being gaining or losing depending on topography, bedrock hydrogeology, hydrostructures, and saturated thickness of the bedrock. Most of the streams are French drains where groundwater discharges into the gaining streams. There is also groundwater discharge from the bedrock locally mostly by phreatophytes.

The subregional groundwater flow direction is from southeast to northwest and east to west parallel to the Spanish Valley salt anticline collapse structures and both the North Fork Mill Creek and main fork Mill Creek canyons (Figures 22, 23a and 23b). The High K Zone flow systems of Mill Creek and the North Fork Mill Creek collect most of the groundwater flow system which ultimately ends in the Mill Creek main channel system (Figures 19 and 22).

The connectivity and interactions of Mill Creek with the groundwater flow paths of the GCMC subsystem along the eastern margins of the Spanish Valley area, from the Ken's Lake diversion to the emergence of Mill Creek into the Spanish Valley in the City of Moab, are extremely complex, and warrant detailed illustration. A map showing the locations of a series of detailed hydrogeologic and hydrologic system cross-sections illustrating the groundwater movement and discharge of the lower GCMC subsystem and the relationship to the both the PCLA and GCGC subsystems is shown in Figure 25. They are based on the modified geologic cross-sections presented in Lowe and Others (2007).

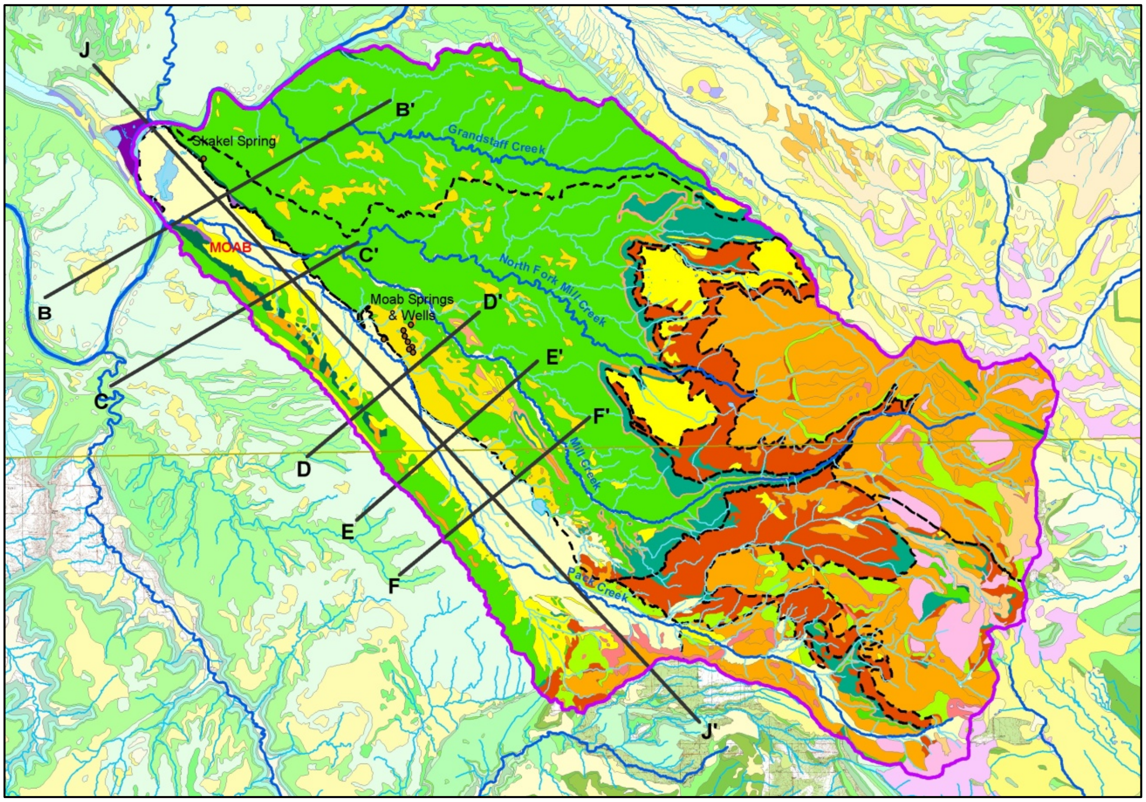

Figure 25. Map Showing the Locations of the Cross-sections Representative for the GCMC, GCGC, and PCLA Conceptual Site Models in the MCSW Study Area on Top of Hydrogeologic Units.

Groundwater discharges out of the GCMC subsystem in two places due to complex hydrostructures: 1) The Kayenta Heights fault zone that delivers groundwater to various springs and seeps along its path including Skakel Spring at the northwest end of Spanish Valley (Figures 26a and 26b; Figures 27a and 27b); and 2) The City of Moab Springs fracture zone that delivers groundwater to the City of Moab Springs (Figures 28a and 28b). At these locations, groundwater moves vertically upward onto the surface as discharge at springs, and the surface runoff from the springs flows over bedrock in channels down into the Pack Creek subsystem (Figures 26b and 28b). This results in increased water quality naturally in the PCLA subsystem that normally has higher TDS groundwater (Figure 20). Google Earth views of the GCMC subsystem and the Mill Creek drainage are shown in Figures 23a and 23b.

Figures 26a and 26b specifically illustrate that the Glen Canyon Group Grandstaff Creek Subsystem (GCGC; see Section 2.7.4) is a distinct groundwater system from the GCMC and

PCLA subsystems and that groundwater flows toward Grandstaff Creek to discharge as springs in the lower reaches near the Colorado River (Figures 22, 23a, and 24). The GCMC part of the system is the Kayenta Heights fault and fracture zone illustrated as a "drain like structure", and the out flow of the Skakel Spring and related springs is as surface water into the PCLA subsystem, which is primarily a valley fill groundwater system at that location (Figures 26a and 26b).

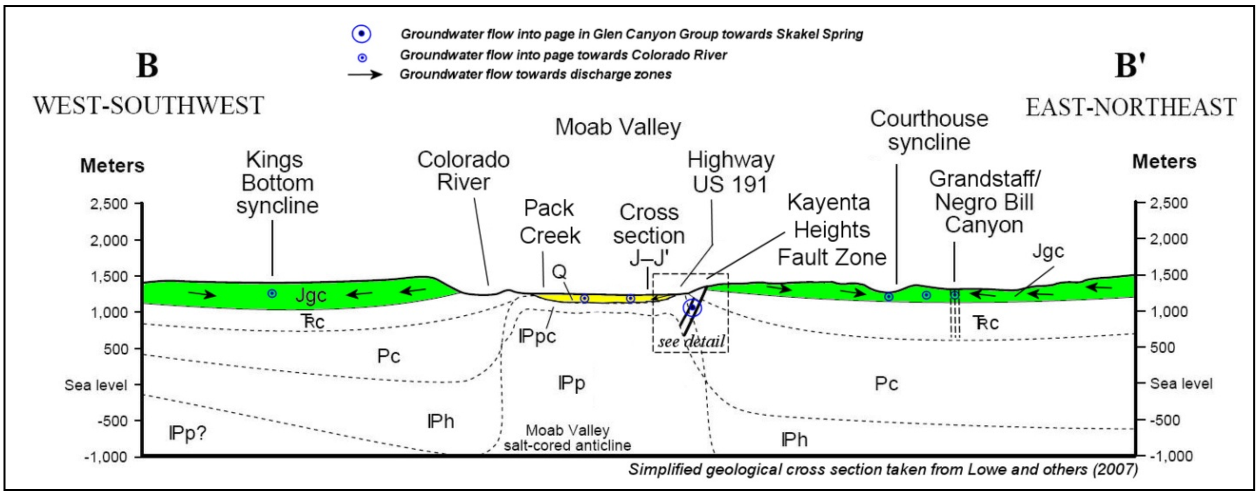

Figure 26a. Schematic Northeast-Southwest Cross-sectional View of Part of the Conceptual Site Models of the GCMC, GCGC, and PCLA Subsystems in the Vicinity of the City of Moab (B-B' in Figure 25).

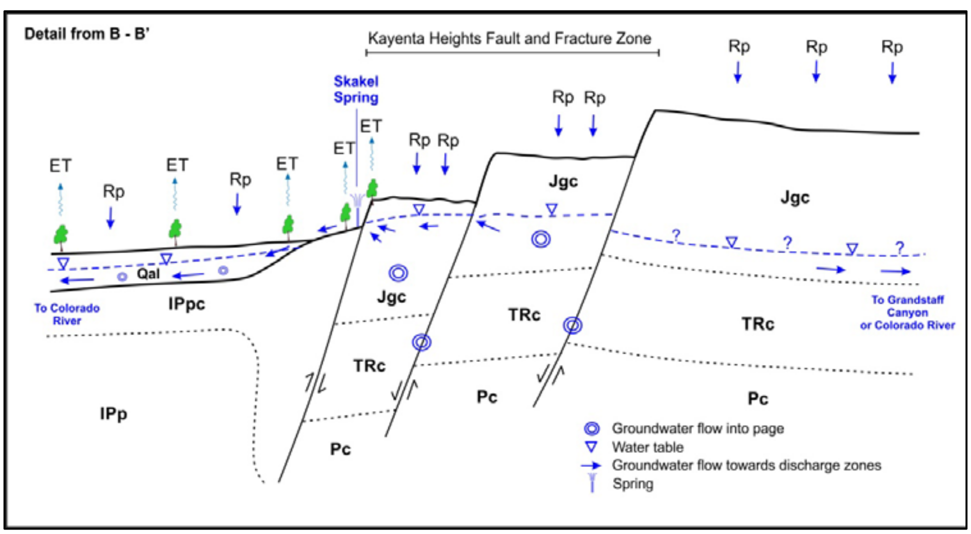

Figure 26b. Schematic Northeast-Southwest Cross-sectional View of Part of the Conceptual Site Models of the GCMC, GCGC, and PCLA Subsystems in the Vicinity of Skakel Spring in the City of Moab (Detail in Figure 26a).

Figures 27a and 27b specifically illustrate that the Glen Canyon Group Mill Creek subsystem (GCMC) is a separate groundwater flow system from the PCLA subsystem, and that as surface water flows over the Kayenta fault and fracture zone hydrostructure to discharge into the Spanish Valley, Mill Creek becomes a losing stream. The extension of the Kayenta fault and fracture

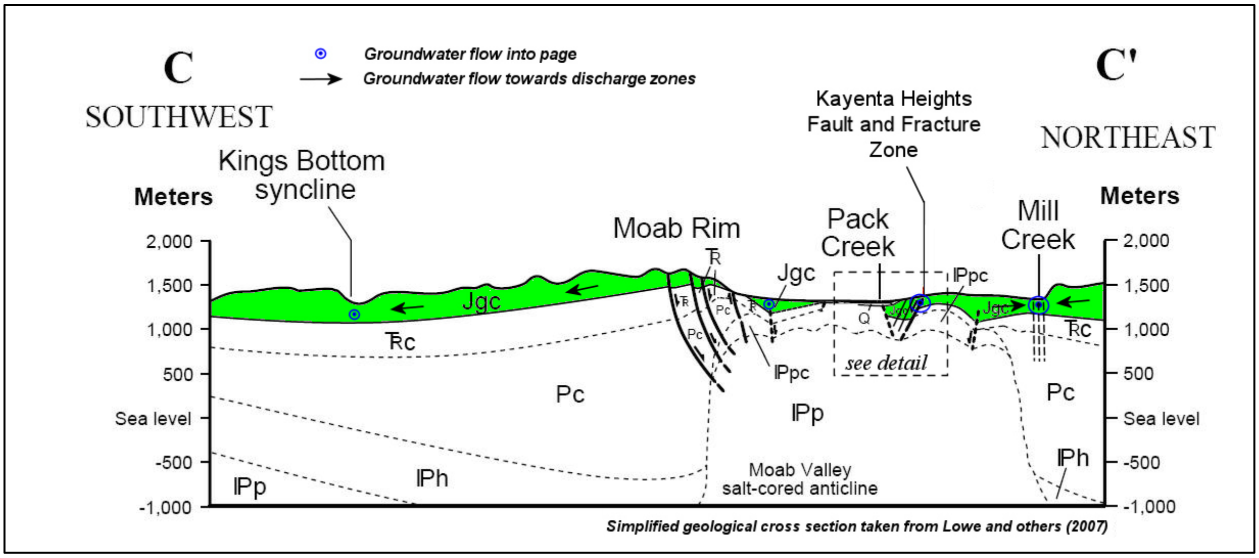

Figure 27a. Schematic Northeast-Southwest Cross-sectional View of Part of the Conceptual Site Models of the GCMC and PCLA Subsystems in the Vicinity of the Mill Creek Emergence to the Spanish Valley in the City of Moab (C-C' in Figure 25).

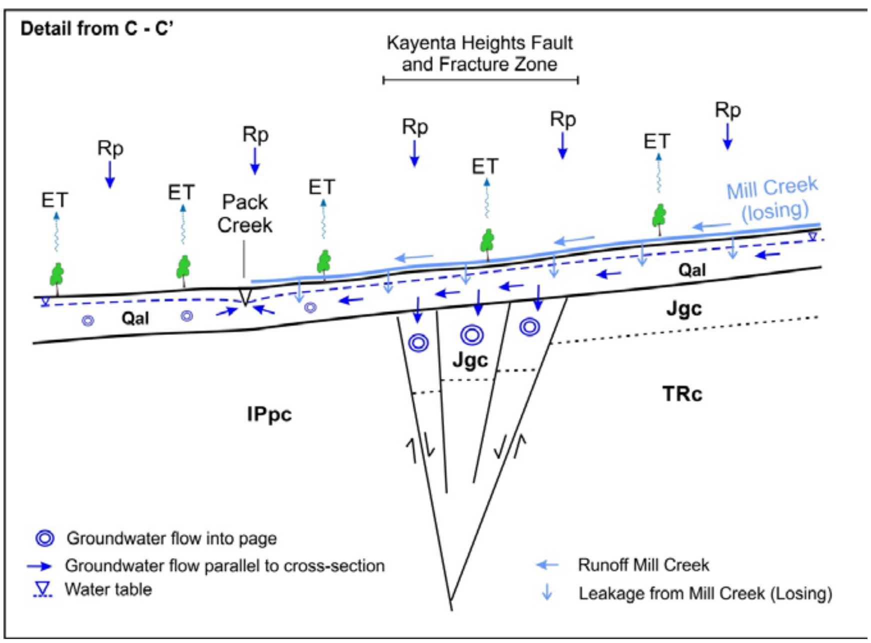

Figure 27b. Schematic Northeast-Southwest Cross-sectional View of Part of the Conceptual Site Models of the GCMC and PCLA Subsystems in the Vicinity of Kayenta Heights Fault and Fracture Zone in the City of Moab (Detail in Figure 27a).

zone provides the hydrostructure to allow groundwater to move from Mill Creek to the City of Moab Skakel Spring, and other springs along Highway 191 (Figure 27b).

Figures 28a and 28b specifically illustrate that the Glen Canyon Group Mill Creek subsystem (GCMC) is a separate groundwater flow system from the PCLA subsystem, and that groundwater flows from Mill Creek through the City of Moab Springs fracture zone

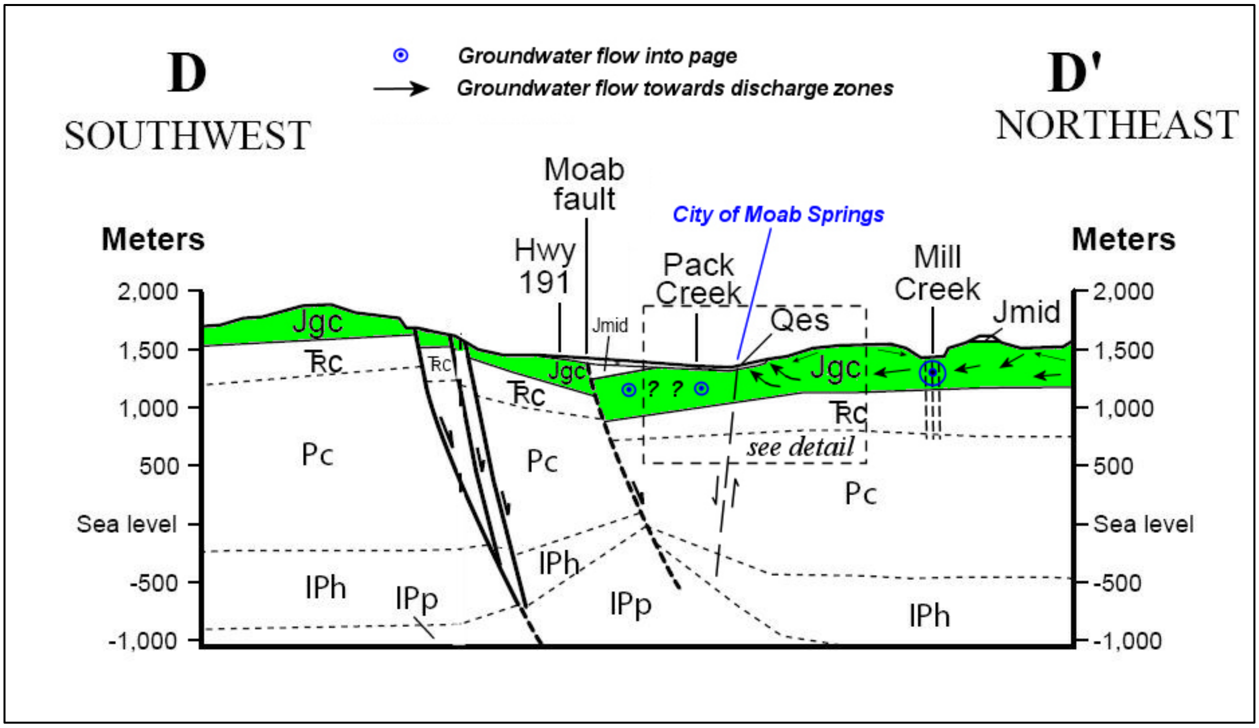

Figure 28a. Schematic Northeast-Southwest Cross-sectional View of Part of the Conceptual Site Models of the GCMC and PCLA Subsystems in the Vicinity of the City of Moab Springs (D-D' in Figure 25).

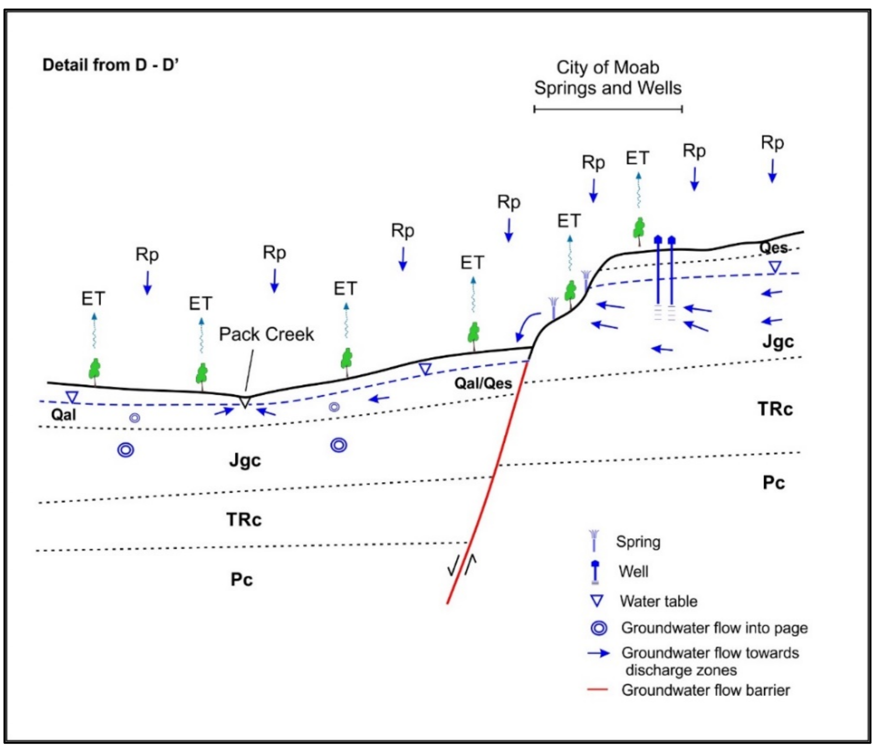

Figure 28b. Schematic Northeast-Southwest Cross-sectional View of Part of the Conceptual Site Models of the GCMC and PCLA Subsystems in the Vicinity of City of Moab Springs and Wells (Detail in Figure 28a).

hydrostructure to discharge into the City of Moab Springs. The extension of the Kayenta Heights fault and fracture zone provides the blocking structure to force groundwater to the surface as the City of Moab Springs (Figure 28b).

2.7.4 Glen Canyon Group Grandstaff Creek Subsystem (GCGC)

The Glen Canyon Group Grandstaff Creek Subsystem (GCGC), located to the north of the GCMC subsystem west of the Porcupine Rim of Castle Valley (Figure 21 Subsystem 4), is a complex mix of fractured and faulted bedrock (Glen Canyon Group (Jgc)), Eolian Sand (Qes), Stream Alluvium (Qal), and hydrostructures (high K fault and fracture zones) which form the robust groundwater system and surface water system that is directly connected to the Colorado River (Figures 21, 22 and 23a). As stated in Section 2.5.2, there are two significant hydrogeologic groups in the GCGC Subsystems, which includes Grandstaff Creek and its tributaries: 1) Quaternary unconsolidated clastic materials (Figure 15 and Table 2a), which are predominantly Stream Alluvium (Qal) and Eolian Sand (Qes); overlying 2) Mesozoic bedrock units (Figure 16; Table 2b), including the following potentially water-bearing units of the Glen Canyon Group (Jgc): Navajo Sandstone (Jn), the Kayenta Sandstone when fractured (Jk), and the Wingate Sandstone (Jw).

In addition, there are two types of geological structures of significance to the hydrogeology in the GCGC Subsystem (Figures 13 and 18): 1) Northeast-southwest and east-west trending fault/fracture zone hydrostructures; and 2) Northwest-southeast trending faults, and fault/fracture zone hydrostructures (bedrock high K units) that are observed in the Courthouse Syncline. The most prominent northeast-southwest east-west trending fracture zones are observed in all of the Grandstaff Creek tributaries such as Morning Glory Creek, and the main channel of Grandstaff Creek. These hydrofractures are “French drains” or High K zones in the Glen Canyon bedrock in the Grandstaff Creek system, and are open with gaining tributary reaches (groundwater discharging to streams) and springs (Figure 24).

The western end of the Grandstaff Creek gorge is along a northwest-southeast trending fault and fracture zone at the core of the Courthouse Syncline that is critical to understanding the GCGC hydrologic system (Figures 13 and 18). This zone serves as a French Drain, a gaining stream with many springs, in the GCGC groundwater system, and moves water from the groundwater and surface water system into the Colorado River (Figures 22, 23a, and 24).

The shallow Quaternary unconsolidated materials in this subsystem are located in two strategic locations: directly along the main channels of the stream (Qal) and scattered on the Mesa tops (Qes) (Figure 15; Table 2a). These highly-permeable deposits are homogeneous, mostly fine to medium grained sand, and locally derived from the weathering of Glen Canyon Group (Jgc) bedrock.

The Glen Canyon Group bedrock has both matrix flow and fracture flow. The matrix flow has ranges estimated from 0.1 – 0.3 m/day (Jobin, 1962; Blanchard, 1990; Lowe and others, 2007); and the fracture flow can be as high as 25 m/day (88 ft/day) (Freethey and Cordy, 1991). Therefore, fracture flow will dominate travel times and will be most important for contaminant studies and well/spring protections, as well as estimating groundwater storage and recharge rates.

The general aspects of groundwater flow in the Quaternary unconsolidated materials have been discussed in Section 2.5. Specifically, the Eolian Sand (Qes) facilitates enhanced groundwater recharge by infiltration of precipitation (snow and rain) to the bedrock underneath. The Quaternary Stream Alluvium (Qal) in the Grandstaff Creek channel and tributaries is closely aligned with the stream levels except where the stream is gaining, in which case the groundwater levels may be higher reflecting water moving from the bedrock into the stream.

Recharge to the Glen Canyon Group in the GCGC subsystem is by infiltration of precipitation (snow and rain) directly into fractured bedrock, or through the eolian sand cover on the surface of the mesa and interfluve tops; by northeast-southwest and east-west trending fracture-controlled ephemeral stream channels, by northwest-southeast trending fracture controlled ephemeral stream channels, and by losing reaches of the upper reaches of Grandstaff Creek. These ephemeral channels are located mostly to the north and east along the Colorado River and Porcupine Rims. There is absolutely no water with a La Sal Mountain source as there are no surface water or groundwater pathways linking the GCGC system to any of the other surrounding systems (Figures 19, 21, and 22).

Groundwater flow in the Glen Canyon Group is strongly fracture controlled, and moves from the drainage divides in the same direction as the stream with various stream reaches being gaining or losing depending on topography, bedrock hydrogeology, hydrostructures, and saturated thickness of the bedrock (Figures 21, 22 and 23a). Most of the streams are French drains where groundwater discharges into the gaining streams. There is also groundwater discharge from the bedrock locally mostly by phreatophytes.

The subregional groundwater flow direction is from northeast to southwest and east to west parallel to Grandstaff Creek until the Synclinal structure, then the groundwater flow direction is northwest towards the Colorado River (Figures 22 and 23a). This High K Zone groundwater flow system of Grandstaff Creek collects most of the groundwater flow system which ultimately ends in the Colorado River system. It should be noted that no water flows west or southwest into the Mill Creek system, or into the Kayenta Heights fault zone hydrofractures (Figures 22, 23a, 26a, and 26b).

2.7.5 Pack Creek Lower Alluvium Subsystem (PCLA)

As stated in Section 2.5.2, the Pack Creek Lower Alluvium Subsystem (PCLA) is a complex mix of the main hydrogeologic bedrock units, including the fractured and faulted bedrock of the Entrada Sandstone (Je) and the Glen Canyon Group (Jgc) (Figured 16; Table 2b), complex hydrostructures (fault and fracture zones), Alluvial Fan Deposits (Qaf), Eolian Sand (Qes), and Stream Alluvium (Qal) (Figure 15; Table 2a). The PCLA is a robust groundwater system that is directly connected from the top of the La Sal Mountains near South Mountain, by both groundwater flow and surface water flow systems forming the headwaters of Pack Creek (LSMA-P in Figure 19 and Figure 21 Subsystem 1b), to the Colorado River northwest of Moab, Utah (Figures 21 and 22). In addition, there are three types of geological structures of significance to the hydrogeology in the PCLA Subsystem: 1) Northeast-southwest trending fault/fracture zone hydrostructures that are observed on the northeastern side of the Moab Rim;

and 2) Northwest southeast trending fault and fracture zone hydrostructures that parallel and are part of the Spanish Valley collapse structure (Figures 13, 14, and18).

The shallow Quaternary unconsolidated materials in the PCLA Subsystem are ubiquitous, and include alluvial, glacial-alluvial, glacial, and mass wasting deposits mostly derived from the Tertiary Intrusive rocks at the top of the system and underlying sedimentary rocks of all types and ages underlying the majority of the subsystem (Figure 15 and Table 2a). These highly-permeable deposits are locally heterogeneous, with a mix of coarser and finer materials in all of the deposits. These deposits are underlain by a paleo-topographic surface carved out by paleo mass wasting and fluvial systems (Figure 17). The glacial, fluvial, and mass wasting processes continued to eventually deposit the Quaternary unconsolidated materials that are the shallow aquifers of the Pack Creek surface water system (Figure 21). It should be noted that the paleo-alluvial and modern alluvial systems followed structural fault zone controlled valleys and account for increased aquifer thicknesses in these valleys (Figure 17).

The general aspects of groundwater flow in the Quaternary unconsolidated materials have been discussed in Section 2.5. The shallow groundwater in the PCLA subsystem is dominated by the Alluvial Fan Deposits (Qaf) on the valley sides and the Stream Alluvium (Qal), which receive natural recharge by infiltration of precipitation (snow and rain); input from hillside (slope) deposits; and input from neighboring tributaries of stream flow located upgradient from a given location. The local stream flow and overland flow in the lower Pack Creek system is from the Cretaceous Mancos shale and Jurassic Morrison Formations (Jm), the Triassic Chinle and Moenkopi Fm (TRc and TRm labeled TRc on hydrogeologic maps and tables), and from the Permian Cutler (Pc), Pennsylvanian Honaker Trail (IPh) (both labeled TRc on the hydrogeologic maps) and Paradox (including caprock) Formations (IPpc), which adds considerable total dissolved solids (TDS) to the groundwater system.

Groundwater flow in the PCLA unconsolidated materials is with topography from hilltop and ridgetop down the hillslope to the valley bottom, and then parallel with the valley bottom streams (Figure 22). Groundwater in the valley bottom stream unit moves in the same direction as the stream with various stream reaches being gaining or losing depending on subsurface topography, saturated thickness of the alluvium, or the seasonal variations caused by snowpack runoff or storm events.

In the lower part of the PCLA subsystem, these deposits are underlain by a paleo-topographic surface carved out by paleo mass wasting and fluvial systems that eventually deposited the Quaternary unconsolidated materials that are the aquifers being evaluated. It is noted that the paleo-alluvial and modern alluvial systems followed structural fault zone controlled valleys and account for increased aquifer thicknesses in these paleo-valleys (Figure 17). Also in the lower PCLA subsystem, there is groundwater recharge from leaky irrigation ditches and return flow from irrigated lands. Throughout the subsystem, there is groundwater discharge from the alluvium by phreatophytes, and locally by groundwater wells.

In the upper part of the PCLA subsystem, the shallow groundwater is underlain by relatively impermeable bedrock units, such as the Mancos shale (Km) and the Morrison Fm (Jm). The shallow groundwater quality is affected by these units and the TDS increases, and the water has a different chemical signature (sulfate) then the LSMA-P water (bicarbonate) that flows into the upper PCLA system.

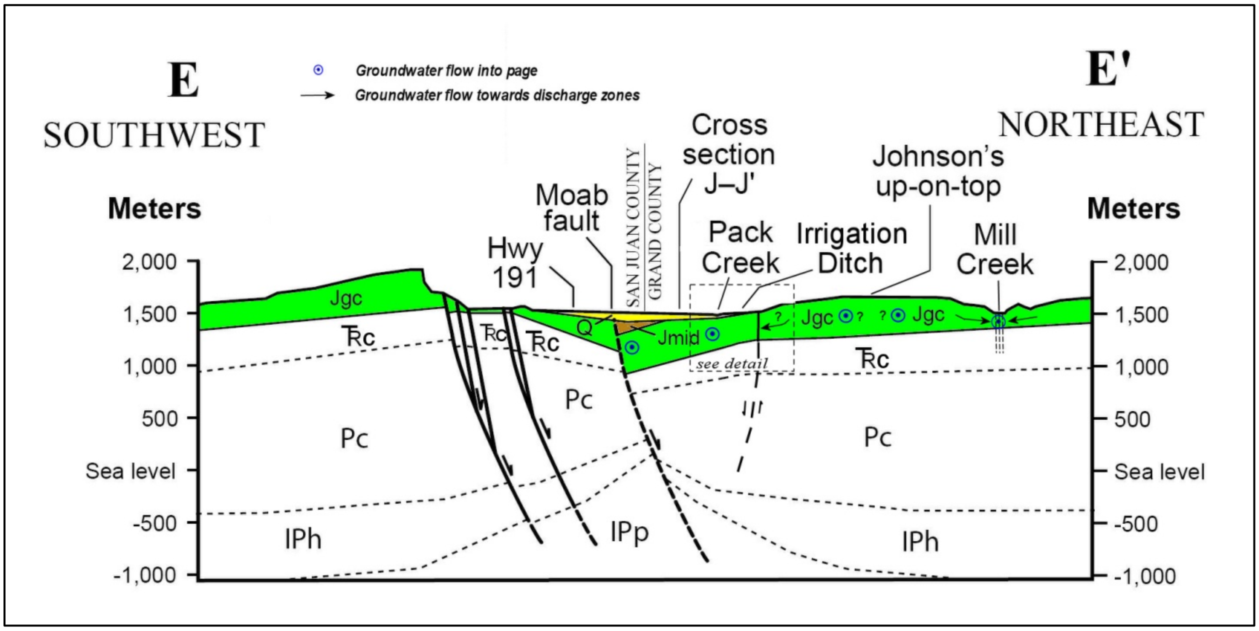

Figure 29a. Schematic Northeast-Southwest Cross-sectional View of Part of the Conceptual Site Models of the GCMC and PCLA Subsystems in the Vicinity of Johnson's up-on-top, Grand County, Utah (E-E' in Figure 25).

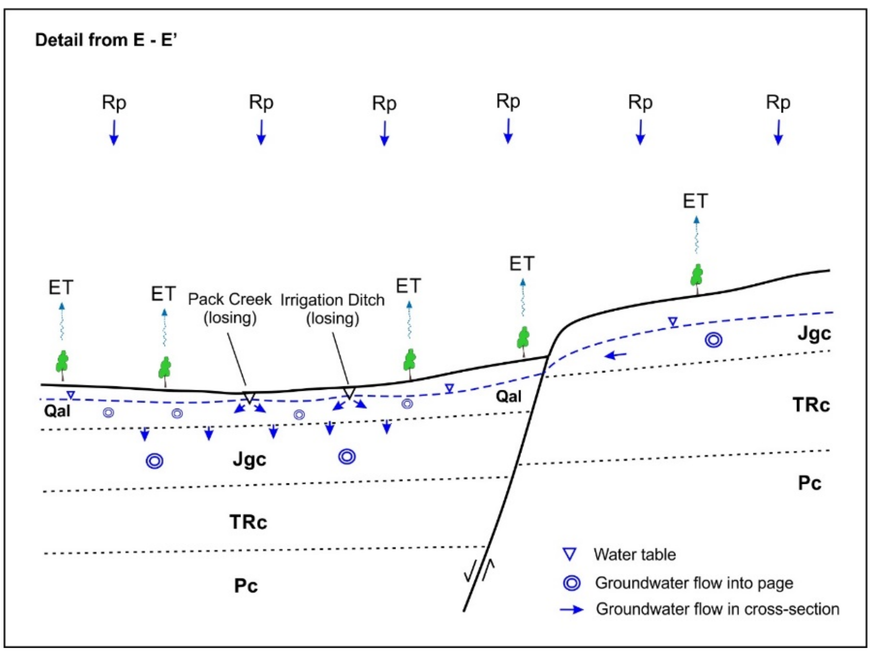

Figure 29b. Schematic Northeast-Southwest Cross-sectional View of Part of the Conceptual Site Models of the GCMC and PCLA Subsystems in the Vicinity of Johnson's Up-on-top, Grand County, Utah (Detail in Figure 29a).

In the San Juan County section of the Spanish Valley part of the PCLA subsystem, the shallow groundwater is underlain by the Glen Canyon Group (Figures 29a, 29b, 30, and 31). In this area, the shallow groundwater in the unconsolidated materials becomes influent (losing stream and ditches) and recharges the Glen Canyon Group, but retains the same water quality (high TDS and sulfate) (Figures 20 and 31). In the central and lower parts of the Spanish Valley (Grand County), the Glen Canyon Group discharges groundwater back into the unconsolidated materials, and then into Pack Creek (Figure 31). Ultimately the ground water flow is to the Colorado River.

Figures 29a and 29b specifically illustrate that the Pack Creek Lower Alluvium (PCLA) Subsystem is a distinct groundwater system from the GCMC and GCGC subsystems and that groundwater flows toward the northwest to discharge as springs and gaining reaches of lower Pack Creek near the City of Moab Springs and near the Colorado River (Figures 22, 23a, and 23b). The Pack Creek Lower Alluvium recharges the underlying Glen Canyon Group hydrogeologic units maintaining the same water quality as the Qal (Figure 29b and 31). Johnson's up-on-top is a groundwater divide with recharge going to both the PCLA and GCMC subsystems (Figures 29a and 29b).

Figure 30 specifically illustrates the Pack Creek Lower Alluvium Subsystem (PCLA) is a separate groundwater flow system from the GCMC subsystem, and as surface water leaks out of Ken's Lake, there may be preferential flow along the extension of the Kayenta Heights fault and fracture zone hydrostructure along the northeast side of the Spanish Valley. This results in better water quality along the east side of the valley (Figure 20), and suggests that wells located below Ken's Lake are actually tapping into the Ken's Lake leakage. Figure 30 also illustrates the groundwater divide on Johnson's up-on-top.

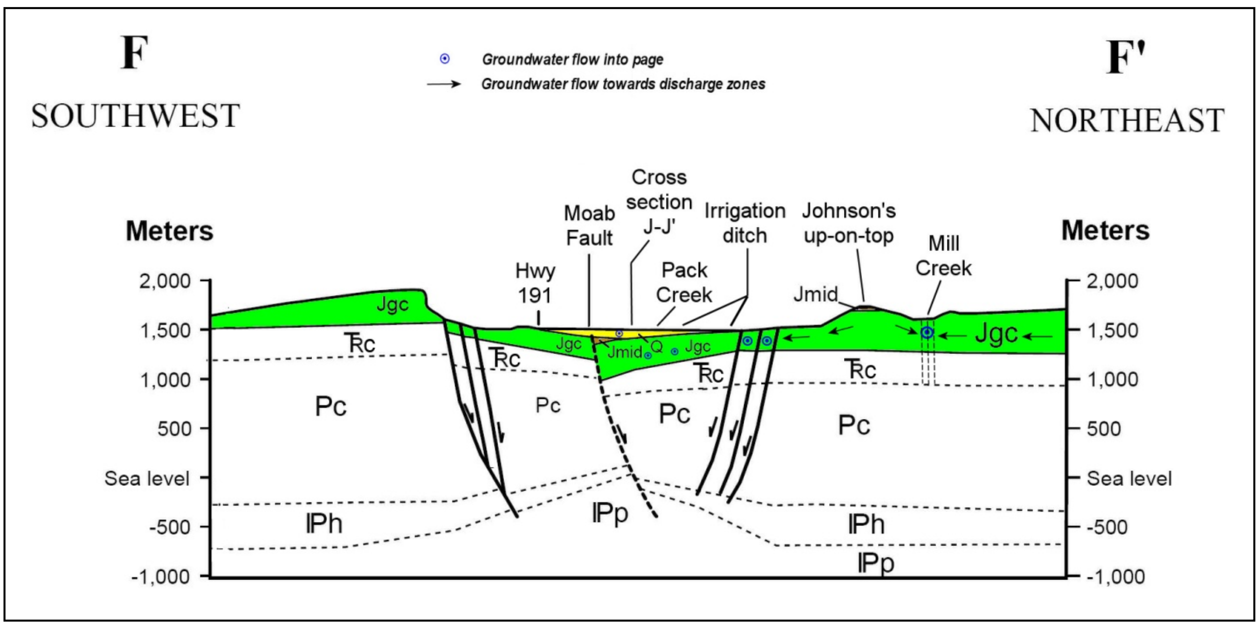

Figure 30. Schematic Northeast-Southwest Cross-sectional View of Part of the Conceptual Site Models of the GCMC and PCLA Subsystems in the Vicinity of Ken's Lake, San Juan County, Utah (F-F' in Figure 25).

Figure 31 specifically illustrates the groundwater flow paths along the longitudinal axis of the Spanish Valley. The PCLA shallow groundwater flow systems (Qal and Qaf) recharge the Glen Canyon Group hydrogeologic units beneath the upper Spanish Valley as is illustrated by the losing reaches of Pack Creek and the Pack Creek diversion ditch. The PCLA subsystem then discharges groundwater as gaining stream reaches and springs in the lower Spanish Valley (Figures 22 and 24).

In the lower Spanish Valley from the Moab City limits to the Colorado River, the shallow groundwater in the Pack Creek Lower Alluvial subsystem has little connection to the local bedrock or subregional groundwater systems, given the very low permeability Pennsylvanian Paradox Formation (IPpc) (Figure 31). As the shallow groundwater flows over this bedrock, a tremendous amount of salt is leached greatly reducing the water quality (Figure 20).

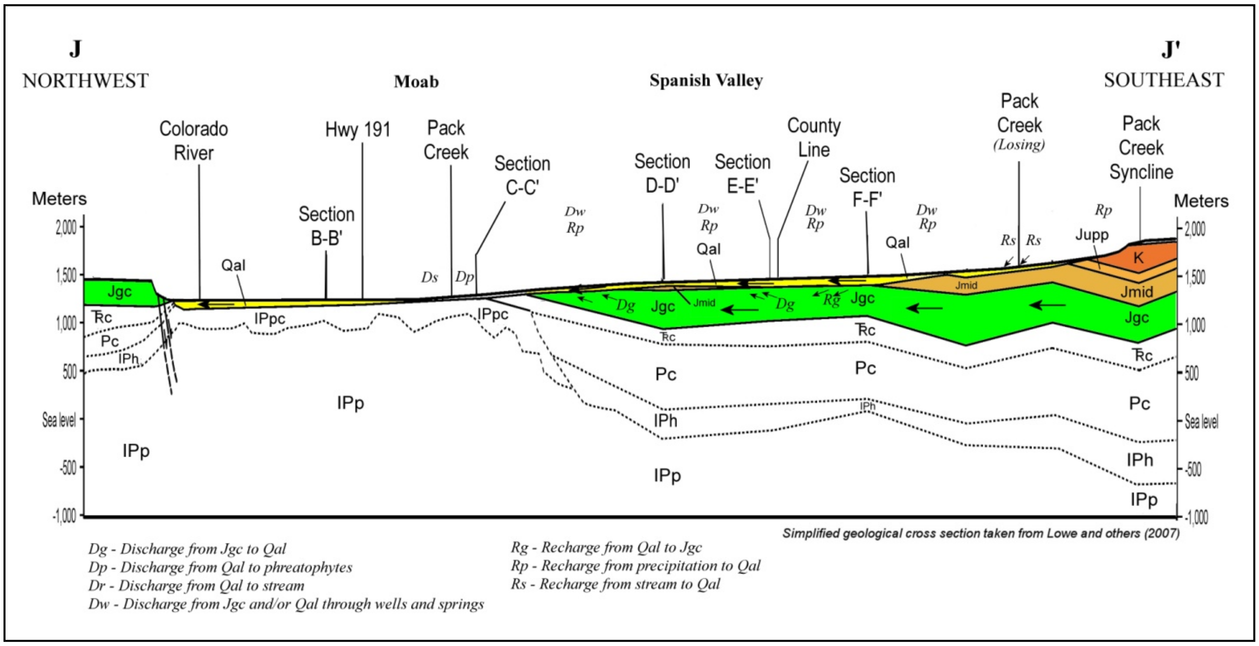

Figure 31. Schematic Northwest-Southeast Cross-sectional View of Part of the Conceptual Site Model of the PCLA Subsystem Along the Axis of the Spanish Valley, Utah (J-J' in Figure 25).

2.8 Anthropogenic Influences on the MCSW Hydrologic System

Human activity in the MCSW study area has affected both the surface and subsurface parts of the hydrologic systems. Past land use and human activity was mostly associated with cattle grazing, irrigation, and diversions of surface water to reservoirs with accompanying construction and operation, or subdivision of lands for domestic use. These activities have been accompanied by removal or selective reduction of native vegetation, introduction of irrigation and high-ET (evapotranspiration) crops or vegetation associated with homes, construction of (often leaking) irrigation ditches (now mostly piped), and the drilling of primarily domestic wells. This activity has resulted in localized changes of groundwater water levels and flow directions that are affected due to changes of recharge (return flow from primarily irrigation and, to a lesser extent, leaky irrigation ditches); and to changes in discharge such as new domestic wells, reduction of groundwater flow due to reduction of surface water flow that has been diverted in local, shallow aquifers of the Quaternary materials in the Stream Alluvium (Qal) of the Mill Creek and Pack Creek Subsystems, or to reservoirs such as Ken's Lake. In addition, this activity may result in increased mobility of various salts in the groundwater and surface water systems, particularly in the Pack Creek watershed below Ken's Lake.

Current land use and human activity changes are mostly associated with major development of tourist facilities and the subdivision of natural or agricultural lands, such as the expansion of the City of Moab or development in Grand and San Juan counties in the southeastern part of Spanish Valley, or the proposed SITLA developments for the eastern Spanish Valley rimlands (proposed Lions Back and Johnson's up-on-top). These changes may result in changes to surface water throughflow/interflow, overland flow, and channel flow, as well as changes in groundwater recharge, flow directions, and discharge. Water quality changes may result as well. Section 2.8 will focus on changes primarily on the Glen Canyon Group Mill Creek Subsystem (GCMC) as these will affect the future water balance, water quality, and water protection of the City of Moab Springs and wells to be accomplished in Phase 2 and 3 of this study.

2.8.1 Potential Effects of Surface Water Use on the GCMC Subsystem

The main agricultural and irrigation activities taking place upgradient of the GCMC subsystem is on the alluvial fans (Qaf) of the Wilson Mesa/South Mesa Alluvial Fan (WMAF/SMAF) subsystems. Currently there is grazing, and there are water diversions and irrigation of lands on the Alluvial Fan hydrogeologic units. Agricultural production of animal feed is supported by surface water irrigation, often delivered through pipes or ditches (Figure 32). The main irrigation method in use is flood irrigation, which tends to provide more water to the fields than can be consumed by vegetation. Excess water from irrigation results in infiltration to the water table and recharge of the groundwater system at the location of these fields (*i.e.*, irrigation return flow), or in direct runoff of surface water to Mill Creek or its tributaries (Figure 32). At this time, the WMAF/SMAF subsystems are not experiencing a major shift from agricultural to nonagricultural land use, and the return flow from irrigation and subsequent groundwater recharge is stable. However, changes in groundwater quality due to fertilization practices of home owners and ranches with irrigation should be monitored.

As discussed previously, irrigation return flow can be a significant recharge element in the local groundwater balance, and in the surface water balance within the lower part of the Mill Creek watershed. Taking irrigated fields out of production and re-allocating pipe-conveyed water reduces recharge of groundwater resulting in lowered local water tables, reduced groundwater discharges to nearby wetlands and streams, and decreased water supplies.

The main concern for impacting the GCMC subsystem water balance is the current reduction of Mill Creek flow into the GCMC subsystem by the Ken's Lake diversion, and the proposed future reduction of Mill Creek flow during the "off season". Any reduction of the Mill Creek surface inflow to the GCMC subsystem will directly impact groundwater recharge into the Glen Canyon Group Hydrogeologic units at the City of Moab Springs fault and fracture zone, and recharge into the Kayenta Heights fault zone. The City of Moab springs, wells, and Skakel spring will be impacted by both the water quantity, timing of delivery, and potentially the water quality will be impacted by any reduction of Mill Creek surface water flow at any time of year.

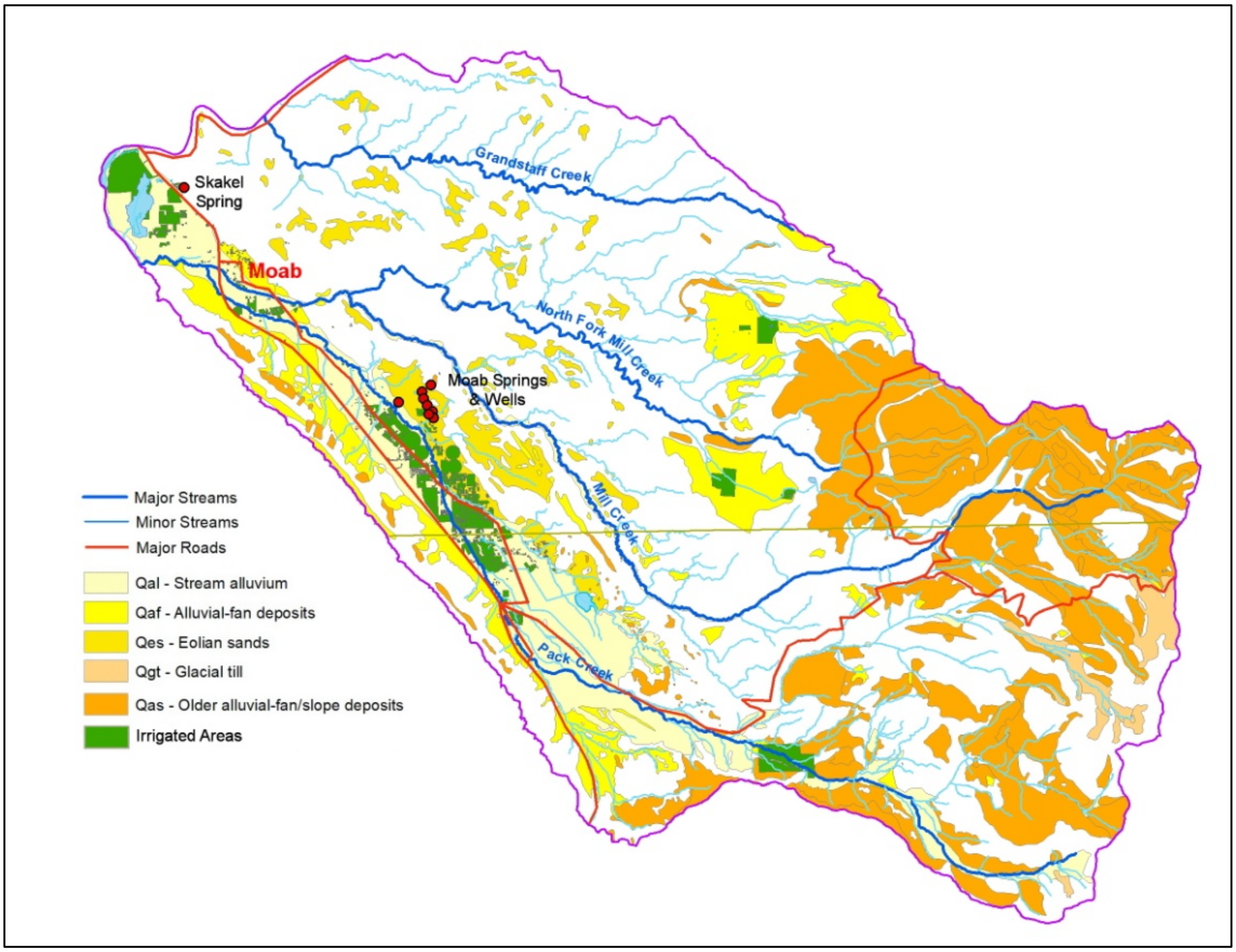

Figure 32. Anthropogenic Influences: Irrigated Parcels in MCSW Study Area (Utah AGRC, 2017). Note the irrigated lands located in Wilson and South Mesas (WMAF/SMAF subsystems) that could directly affect the GCMC subsystem downgradient.

2.8.2 Potential Effects of Groundwater Use through Wells on the GCMC Subsystem

Water wells are found in the GCMC subsystem, primarily in the unconsolidated Quaternary deposits (Qal) and consolidated bedrock of the Glen Canyon Group (Jgc) at valley bottoms in the High K Zone of Mill Creek, and in the High K Zone in the consolidated bedrock of the Glen Canyon Group called the City of Moab fracture zone that is the direct "pipeline" of the City of Moab springs and well fields (Figures 18, 22, 23b, and 33). Most of these wells serve domestic water supply or irrigation needs, and the effect on the groundwater system locally may be significant. However, if additional water is needed by urban or agricultural development, or water is displaced by urban and recreational activities, for example, the compound effect on the groundwater system could be more significant in the future, resulting in a possible lowering of the water table, changes in flow direction, decreasing discharge to streams or increasing stream loss to groundwater, draining of wetlands, or even depletion of local aquifers. It should be noted that areas with higher density of wells, such as around the City of Moab springs and wells also have a higher density of urban land use and runoff, which could affect the water quality of the City's water supply.

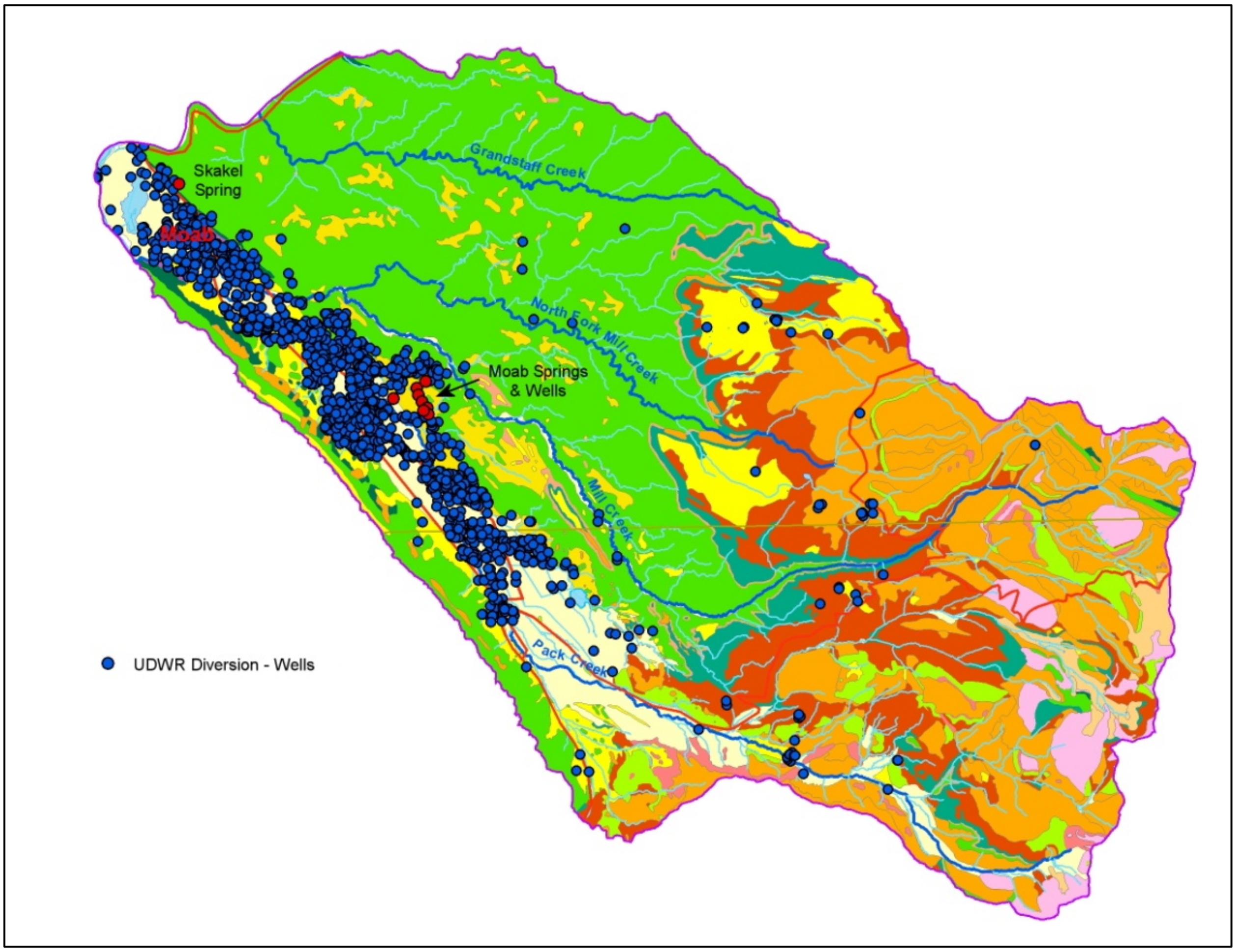

Figure 33. Anthropogenic Influences: Constructed Wells in the GCMC Subsystem. (Utah AGRC, 2017).

2.8.3 Potential Effects of Groundwater Use on Water Quality

The HESA evaluation of the MCSW hydrologic subsystems can also be used for assessing the vulnerability of groundwater and surface water to contaminants in both the natural and anthropogenic environment. Regionally, salt concentrations (Total Dissolved Solids or TDS) are known to frequently exceed drinking water and ecosystem standards, whether naturally or human-induced. Salts are very soluble and mobile in surface and groundwater environments, and tend to concentrate in surface water environments in arid and semi-arid climates. As applied to the GCGC and PCLA subsystems, the Mancos Fm (Km), Morrison Fm (Jm), Chinle (TRc), Moenkopi (TRm), Cutler (Pc), and Paradox (IPpc) hydrogeologic units, usually considered groundwater flow system confining layers, are the main source in the Pack Creek Lower Alluvium subsystem for naturally occurring salt in a chemically soluble form. If disturbed by grazing, timbering, or mining, the Morrison Fm outcropping in many of the areas around the LSMA-P and WMAF/SMAF Subsystems (Figures 16, 21, and 22), may allow large quantities of surface water to flow over these hydrogeologic units where large quantities of soluble salt could be incorporated into the surface water, and then groundwater flow systems downgradient. These salts are then transported in the groundwater and/or surface water to exposure sites such as wells, springs, and surface water bodies like Ken's Lake, where they may be measured in quantities unacceptable by drinking water and/or ecosystem regulatory standards. Many spatial (3-dimensional) and temporal (past, present, and future time frames) factors affect how the salt is being mobilized and transported including: 1) Salt source location with respect to hydrogeologic framework, specifically the hydrogeology of unweathered and weathered Morrison Formation bedrock and the hydro-geomorphology of overlying unconsolidated Quaternary deposits, such as alluvial gravels, soils and weathering profiles; 2) Groundwater flow pathways including exposure sites such as groundwater discharge zones to the surface water systems; and 3) Past, present, and future hydrologic "stresses" to the system, for example irrigation of weathered Morrison Formation bedrock, and irrigation on geomorphologic deposits on weathered Morrison or Mancos bedrock.

2.8.3.1 Glen Canyon Group Mill Creek (GCGC) Subsystem Water Quality

The hydrogeology of the GCGC Subsystem, as previously described in Section 2.6, is primarily Quaternary Stream Alluvium (Qal) and Eolian Sand (Qes), and Mesozoic bedrock units including the Glen Canyon Group (Jgc) and Entrada Sandstone (Je). A small weathered zone exists as the interface between the Quaternary unconsolidated hydrogeologic units and the bedrock hydrogeologic units. The hydrologic system of this GCGC Subsystem, as previously described in Section 2.6, is that surface water in fracture-controlled channels, and overland and interflow from precipitation rapidly infiltrates through the Quaternary alluvial and eolian hydrogeologic units, where the water quickly disappears into the fractured aquifer as groundwater recharge (Figure 22). In the process of channeled surface water, or overland and interflow, soluble salts in the bedrock are incorporated into the surface and near surface water to be transported into the unconsolidated deposits and bedrock aquifers. Given the chemistry of these unconsolidated and bedrock aquifers, the groundwater will have mostly the chemistry of rainwater and would have lower TDS than the aquifers in the four other subsystems (Figure 20).

The natural pollutants that are most likely occurring include salts (carbonates and sulfates, possibly nitrates), and the most likely source of these pollutants is rainwater from the atmosphere, or the input into GCMC subsystem groundwater by Mill Creek from upgradient sources. The natural system has very little TDS (less than 300 mg/L), and source of that has been rainwater from the atmosphere to date.

The anthropogenic pollutant sources to the GCGC subsystem are from the homes that are located on the unconsolidated materials and would include mostly fertilizers for grass (urban) or crops, or rural septic tank waste. Most of these are organics and nutrients, and would need to be monitored accordingly. Recreation by off road vehicles is also observed in the subsystem.

2.8.3.2 Pack Creek Lower Alluvium (PCLA) Subsystem Water Quality

In comparison to the GCMC Subsystem, the hydrogeology of the PCLA Subsystem, as previously described in Section 2.6, is primarily Quaternary unconsolidated clastic materials, which are predominantly Stream Alluvium (Qal), Alluvial Fan Deposits (Qaf), Older Alluvium Fan/Slope Deposits (Qas), and Glacial Till (Qgt) overlying Mesozoic and Paleozoic bedrock units, including the following potentially water-bearing units: Cretaceous Dakota/Burro Canyon (Kdbc); Entrada Sandstone (Je); and Glen Canyon Group (Jgc), and predominantly the following confining hydrogeologic units: Cretaceous Mancos Shale (Km); Jurassic Morison Fm (Jm); the Triassic Chinle (TRc) and Moenkopi (TRm) Fms; the Permian Cutler (Pc) Fm., and the Pennsylvanian Honaker Trail (IPh) and Paradox (IPpc) Formations. A major weathered zone called the “caprock” exists as the interface between the Quaternary unconsolidated units, and the bedrock hydrogeologic units of the lower Spanish Valley area. A weathered zone most likely exists as the interface between the two groups of hydrogeologic units in the central and upper Pack Creek Valley. The hydrologic system of the PCLA Subsystem is described previously in Section 2.6.

The natural pollutants that are most likely occurring includes salts (sulfates and high TDS), and the most likely source of these pollutants is the weathered zone at the interface between the hydrogeologic confining units and the Quaternary unconsolidated materials, and in the surrounding exposed bedrock of the Moab Rim and upper Pack Creek. It is hypothesized that the natural system has been flushing salts through this system since the deposition of the Quaternary glacial, mass wasting, and alluvial gravels (Qgt, Qas, Qaf, and Qal). Given the large water quantities being circulated, and long period of time of leaching, it is likely that large amounts of salts are being leached and transported directly from the bottom of these subsystems. In addition, it is hypothesized that a substantial amount of these natural pollutants enters the groundwater system as surface water flows over exposed Morrison, Mancos, Chinle, Moenkopi, Cutler, and Paradox bedrock areas to recharge the unconsolidated materials between the La Sal Mountains and the main Pack Creek drainage via tributaries (See Figure 22). In summary, the PCLA Subsystem has a distinctly different groundwater chemical signature (sulfate, high TDS) then the GCGC subsystem (bicarbonate, low TDS).

The anthropogenic pollutant sources in the PCLA subsystem are mostly fertilizers for grass (urban) or crops, industrial pollutants (local garages, for example), or rural septic tank waste. Most of these are organics and nutrients, and would need to be monitored accordingly.

3 SUMMARY AND CONCLUSIONS

Under an agreement with City of Moab, Utah, Hydrologic Systems Analysis LLC of Golden, Colorado, in conjunction with Heath Hydrology, Inc. of Boulder, Colorado, was tasked to: 1) Perform a Hydrologic and Environmental System Analysis (HESA) of the Moab City Springs and Wells (MCSW) area; 2) Develop a water budget for the area affecting the City's springs and wells at the golf course and Skakel Spring; and 3) Update the water source protection plans for all City springs and wells. Each of these tasks constitutes a phase of the project. This report contains the results of phase 1, Hydrologic and Environmental System Analysis (HESA).

There are two significant groups of hydrogeologic units in the MCSW study area: 1) Quaternary unconsolidated clastic materials, overlying 2) Tertiary, Mesozoic and Paleozoic bedrock units. The Quaternary unconsolidated units are generally moderately to highly permeable and include Stream Alluvium, Alluvial Fan Deposits, Older Alluvial Fan/Slope Deposits, Glacial Till, and Eolian Sand. Bedrock units are divided into: 1) Potentially water-bearing units including Tertiary Granodiorite, Dakota Sandstone and Burro Canyon Formation, Salt Wash Member of the Morrison Formation, Entrada Formation, and Glen Canyon Group; and 2) Very low-permeability, confining units including Mancos Shale, undivided Morrison Formation, Dewey Bridge Member of the Carmel Formation, and the Chinle, Moenkopi, Cutler, Honaker Trail, and Paradox (including caprock) Formations.

Geologic faults and fracture zones, sometimes expressed at the surface as lineaments or linear drainage segments, influence the hydrogeology and hydrologic systems of the MCSW study area. These features are most likely associated with preferential groundwater flow, either vertically or laterally along the fault or fracture planes, but may also function as a blockage to cross-structure groundwater flow.

The main subregional fold and fault structures are: 1) the Spanish Valley Salt Anticline, with corresponding graben/collapse structure, 2) the Courthouse Syncline extending across the Sand Flats area, and 3) the La Sal Mountain intrusions. The bounding faults of the collapse, located on the northeast and southwest sides of Spanish Valley, dip almost vertically and strike from the southeast to the northwest. These southeast/northwest hydrostructures pinch out at either end of the valley and with depth, keeping the groundwater system subregional and discontinuous beyond the Spanish Valley topographic feature. These hydrostructural units also inhibit lateral flow perpendicular to the fault zones. Therefore, no significant deep regional ground water is laterally entering or exiting Spanish Valley from the southwest through the Moab Rim or the northeast from the upper part of the eastern Spanish Valley rimlands. The termination of these hydrostructural units to the southeast and northwest also blocks lateral flow, so no deep groundwater is laterally entering or exiting Spanish Valley from the southeast or the northwest. As the major part of the valley is underlain by a deep "flat lying" caprock of the Paradox Formation, which is a confining unit, these hydrostructural units ensure that the Spanish Valley Bedrock groundwater flow system is entirely contained within the valley.

The Spanish Valley Anticline/Graben also results in the younger bedrock units, being observed on the Moab Rim and eastern rimlands of Spanish Valley, dipping away to the northeast, northwest, and southwest. This results in local and subregional groundwater and surface water systems that flow away from the Moab Rim into the Kane Creek Systems, and from the Eastern Spanish Valley rimlands into the Mill Creek hydrologic system, or towards the Grandstaff Creek hydrologic system and the Colorado River.

Two broad hydrostructure sets occur in the MCSW area: 1) the northwest-southeast and corresponding west-east trending faults and fractures that parallel the Spanish Valley fault and fracture zones, including the Sand Flats part of Mill Creek canyon, Grandstaff Creek canyon, and the Kayenta Heights fault and fracture zone; and 2) the northeast-southwest-trending cross mesa and valley fracture zones, including lower Mill Creek and Rill Creek by the Powerhouse, Grandstaff Creek, upper Mill Creek, and the Moab City Springs fracture zone. The northwest-trending and northeast-east-trending faults and fractures are relatively young, as the geomorphic systems of Mill Creek are responding with considerable downcutting, allowing for partial to full penetration by the streams into the bedrock aquifers of the Glen Canyon Group. The resulting geomorphic systems of Grandstaff and Mill Creeks, and the groundwater systems of the Moab City Springs fracture zone, use these conduits to divert water from the streams to various springs. It is hypothesized that the northeast, east-west, and northwest fault and fracture zones are "open" and function like French drains. Groundwater moves laterally with the northwest trending Mill Creek parallel to the Spanish Valley, and moves laterally from Mill Creek to Skakel Springs along the northwest trending Kayenta Heights fault and fracture zone. Groundwater moves laterally with the east-west, then northwest trending Grandstaff Creek towards the Colorado River. Groundwater also moves laterally from Mill Creek to the Moab City Springs fracture zone along the northeast-east-west trending fracture zone.

The radial and concentric fracture pattern surrounding the La Sal Mountain intrusions control the surface water drainages, and are open, therefore, supporting "French-drain" bedrock groundwater systems, and focusing groundwater locally towards drainages in the Older Alluvial Fan/Slope Deposits. In the Tertiary intrusive rocks, groundwater moves laterally down valley and vertically downward along these radial fault and fracture zone planes, and may move vertically up along the fault and fracture planes near the lower reaches of the various drainages as evidenced by gaining reaches in streams, and by the springs that are the origin of various Mill Creek and Pack Creek tributaries.

Using the HESA approach, and based on the presence and orientation of various hydrogeologic and hydrostructural units, hydrography and topography, five Conceptual Site Models (CSMs) are delineated in the MCSW study area: 1) La Sal Mountain Upper Alluvium Subsystems (LSMA-M; LSMA-P); 2) Wilson Mesa/South Mesa Alluvial Fan Subsystems (WMAF; SMAF); 3) Glen Canyon Group Mill Creek Subsystem (GCMC); 4) Glen Canyon Group Grandstaff Creek subsystem (GCGC); and 5) Pack Creek Lower Alluvium subsystem (PCLA). The La Sal Mountain Upper Alluvium Subsystems (LSMA-M; LSMA-P), located in the southeastern part of the study area, are a complex mix of bedrock (Tertiary igneous intrusive rocks), glacial till, and older alluvial fan and slope deposits, which form several robust, localized groundwater systems that are directly connected to the surface water systems forming the headwaters of Mill Creek and Pack Creek. These subsystems are vertically constricted by hydrogeologic confining units, such as the Mancos Fm and Morrison Fm, are hydraulically connected to the groundwater subsystems downgradient only by surface water streams and tributaries, and do not have direct groundwater connection through shallow or deep hydrogeologic units in the MCSW study area . Given the granodiorite composition of bedrock, the natural water quality is good except where mining activity has been undertaken.

The Wilson Mesa and South Mesa Alluvial Fan Subsystems (WMAF and SMAF), located in the east central part of the study area, are predominately alluvial fan deposits that form localized groundwater systems that are directly connected to the surface water systems forming the headwaters to tributaries of Mill Creek. These subsystems are hydraulically connected to the groundwater subsystems downgradient predominantly by surface water streams and tributaries. The shallow groundwater in the WMAF and SMAF subsystems is dominated by natural recharge from infiltration of precipitation, snow and rain, and losing streams, and by additional recharge from return flow from local irrigation. Recharging water enters into the alluvial fan deposits covering the mesas and flows downgradient towards the discharge zones (gaining streams, springs and seeps, and wetlands).

The Glen Canyon Group Mill Creek Subsystem (GCMC), located in the core of the study area, is a complex mix of fractured and faulted bedrock (Entrada Sandstone and Glen Canyon Group), eolian sands, and hydrostructures (fault and fracture zones) which form the robust groundwater system and surface water system that is directly connected to the City of Moab springs and wells. This subsystem is hydraulically connected to the PCLA groundwater subsystem downgradient in Spanish Valley predominantly by Mill Creek, outflow streams from the major springs like Skakel Spring, and by surface water diversions from Mill Creek (Sheley Tunnel diversion to Ken’s lake). There is no significant direct groundwater connection between the GCMC subsystem and surrounding subsystems through shallow or deep hydrogeologic units. Of the five hydrogeologic subsystems in the MCSW study area, the GCMC subsystem is the most important for the sustainability and protection of the City of Moab springs and wells (including Skakel Spring), although knowledge of the LSMA-M, WMAF, and SMAF subsystems will be vital in protecting these assets.

The most prominent northeast-southwest east-west trending fracture zones in the GCMC subsystem are observed in the main Mill Creek tributaries such as Rill Creek, North Fork Mill Creek, and the so-called “Middle Fork” of Mill Creek, a spring-fed tributary of Mill Creek straight east of the City of Moab springs and wells at the golf course. In addition, the main Moab City Springs fracture zone from the “Middle Fork” of Mill Creek to the Moab City Springs and Wells has this same trend. These hydrofractures are “French drains” or high-K zones in the Glen Canyon bedrock, and are open with gaining tributary reaches (groundwater discharging to streams). In the case of the fracture zone at the junction of the “Middle Fork” of Mill Creek with the Main Fork, this east-west trending fracture zone transports Mill Creek surface water as groundwater through the Moab City Springs fracture zone to the City of Moab bedrock springs along the edge of Spanish Valley and is quite important to the springs and well sustainability and protection.

The entire Mill Creek gorge from the Ken’s Lake intake to the junction with the North Fork Mill Creek, and the upper part of the North Fork Mill Creek are along northwest-southeast trending fault and fracture zones that serve as French Drains to the GCMC groundwater system, and for much of their reaches are gaining streams. The other major northwest-southeast fault zone of importance to the GCMC subsystem bounds the eastern Spanish Valley rimlands for their entire length, and has, along the City of Moab, the name Kayenta Heights fault zone. The Kayenta Heights fault zone is open and a groundwater conduit moving water from Mill Creek to various springs and discharge zones, including City of Moab's Skakel Spring. The middle and southern part of the Fault Zone does not serve as a conduit, but as a block bringing the Glen Canyon Group next to the Permian shales and salts, as evidenced by the City of Moab Springs near the Moab golf course.

Recharge to the Entrada Sandstone and Glen Canyon Group in the GCMC subsystem is by infiltration of precipitation (snow and rain) directly into bedrock, or through the eolian sand cover on the surface of the mesa and interfluve tops; recharge from losing reaches of perennial streams; and by recharge from ephemeral stream channels. These ephemeral channels are located mostly to the east along the Porcupine Rim, and along the Entrada Sandstone bluffs that are below Wilson and South Mesas.

Groundwater flow in the Entrada Sandstone and Glen Canyon Group is dominantly fracture controlled, and moves from the drainage divides in the same direction as the streams with various stream reaches being gaining or losing depending on topography, bedrock hydrogeology, hydrostructures, and saturated thickness of the bedrock. Most of the streams are French drains where groundwater discharges into the gaining streams. There is also groundwater discharge from the bedrock locally mostly by phreatophytes.

The subregional groundwater flow direction is from southeast to northwest and east to west parallel to the Spanish Valley salt anticline collapse structures and Mill Creek. The High K Zone flow systems of Mill Creek and the North Fork Mill Creek collect most of the groundwater flow system which ultimately ends in the Mill Creek main channel system. Groundwater then moves out of the Mill Creek system to discharge in two places: 1) the Moab City Springs fracture zone that delivers groundwater to the City of Moab Springs at the golf course; and 2) the Kayenta Heights fault zone that delivers groundwater to various springs and seeps along its path, including Skakel Spring at the northwest end of Spanish Valley. At both locations, groundwater moves vertically upward onto the surface and discharges as springs and seeps, and as phreatophytic losses; the resulting surface runoff flows over bedrock in channels down into the Pack Creek Lower Alluvium subsystem (PCLA).

The Glen Canyon Group Grandstaff Creek Subsystem (GCGC), located to the north of the GCMC subsystem and west of the Porcupine Rim of Castle Valley, is a complex mix of fractured and faulted bedrock (Glen Canyon Group), eolian sands, and hydrostructures (fault and fracture zones) which form the robust groundwater system and surface water system, Grandstaff Creek, that are directly hydraulically connected to the Colorado River. This subsystem does not have significant direct groundwater connection through shallow or deep hydrogeologic units to any other subsystem in the MCSW study area, and has no direct connection to the snowmelt, surface water, or groundwater systems originating in the La Sal Mountains.

The main channel of Grandstaff Creek, as well as its tributaries such as Morning Glory Creek, is aligned with the prominent northeast-southwest/east-west trending fracture zone, and these stream reaches are mostly gaining (groundwater discharging to streams). The western end of the Grandstaff Creek gorge is located along a northwest-southeast trending fault and fracture zone at the core of the Courthouse Syncline. Grandstaff Creek is a gaining stream with numerous springs, and channels water from the groundwater and surface water system into the Colorado River. Recharge to the Glen Canyon Group in the Grandstaff Creek watershed is by infiltration of precipitation (snow and rain) directly into fractured bedrock, or through the eolian sand cover on the surface of the mesa and interfluve tops; and by recharge from losing reaches of the upper section of Grandstaff Creek and its tributaries.

Groundwater flow in the Glen Canyon Group is strongly fracture controlled, and moves from the drainage divides in the same direction as the stream with various stream reaches being gaining or losing depending on topography, bedrock hydrogeology, hydrostructures, and saturated thickness of the bedrock. The subregional groundwater flow direction is from northeast to southwest and east to west parallel to Grandstaff Creek until the Synclinal structure, then the groundwater flow direction is northwest towards the Colorado River. No groundwater flows west or southwest into the Mill Creek system, or into the Kayenta Heights fault zone hydrostructure, and thus no groundwater in the GCGC Subsystem reaches Skakel Spring.

The Pack Creek Lower Alluvium Subsystem (PCLA), located in the southwestern and southern part of the study area, is a complex mix of the main hydrogeologic bedrock units, including the fractured and faulted Entrada Sandstone and Glen Canyon Group, complex hydrostructures (fault and fracture zones), alluvial fan and slope deposits, eolian deposits, and alluvium. This robust PCLA groundwater system is directly connected from the top of the La Sal Mountains near South Mountain by the LSMA-P Subsystem, to the Colorado River northwest of the City of Moab. The Pack Creek subsystems are hydraulically connected by both groundwater and surface water streams and tributaries. The PCLA does not have significant direct groundwater connection through shallow or deep hydrogeologic units to the WMAF, SMAF, GCMC, or GCGC subsystems in the MCSW study area. The PCLA does have a connection to the LSMA-P and to GCMC subsystems by surface water streams and stream diversions, including the tributaries of Pack Creek east of the La Sal Mountain Loop Road, the main channel of Mill Creek at the emergence below the Mill Creek Canyon into Spanish Valley, and diversions such as the diversion to Ken’s Lake.

Groundwater flow in the PCLA unconsolidated materials is with topography from hilltop and ridgetop down the hillslope to the valley bottom, and then parallel with the valley bottom streams with various stream reaches being gaining or losing. In the lower part of the PCLA subsystem, these deposits are underlain by a paleo-topographic surface carved out by paleo mass wasting and paleo fluvial systems that eventually deposited the Quaternary unconsolidated materials that are the aquifers being evaluated. It is noted that the paleo-alluvial and modern alluvial systems followed structural fault zone controlled valleys and account for increased aquifer thicknesses in these paleo-valleys. Also in the lower PCLA subsystem, there is groundwater recharge from leaky irrigation ditches, return flow from irrigated lands, and leakage from surface water bodies (most notably Ken’s Lake). Throughout the subsystem, there is groundwater discharge from the alluvium by phreatophytes, and locally by groundwater wells.

In the upper part of the PCLA subsystem, the shallow groundwater is underlain by relatively impermeable bedrock units, such as the Mancos shale and the Morrison Formation. The shallow groundwater quality is affected by these units and the TDS increases, and the water has a different chemical signature (sulfate) then the GCMC water (bicarbonate). In the San Juan County section of the Spanish Valley part of the PCLA subsystem, the shallow groundwater is underlain by the Glen Canyon Group. At this area, the shallow groundwater in the unconsolidated materials becomes influent (losing stream and ditches) and recharges the Glen Canyon Group, but retains the same water quality (sulfate). In the central and lower parts of the Spanish Valley (Grand County), the Glen Canyon Group discharges groundwater back into the unconsolidated materials, and then into Pack Creek, and ultimately the ground water flow is to the Colorado River. In the lower Spanish Valley from the Moab City limits to the Colorado River, the shallow groundwater in the Pack Creek Lower Alluvium subsystem has little connection to the local bedrock or the subregional groundwater systems, given the very low permeability Pennsylvanian Paradox Formation and caprock underlying the unconsolidated aquifer. As the shallow groundwater flows over this bedrock, a tremendous amount of salt is leached greatly increasing TDS and reducing the water quality.

There are five spatial distributions of springs, based on spring location with respect to hydrogeologic location identified on topographic maps, field excursions, and in the State water rights records, that are informative for the analysis of the surface water and groundwater systems in the MCSW study area: 1) The highest elevation springs, located in the La Sal Mountains and in the glacial and glacial/alluvial deposits surrounding the La Sal Mountains, emanate from the Tertiary bedrock systems or the glacial/alluvial deposits in the La Sal Mountains; 2) The mid elevation springs, located at the edge of the South Mesa and Wilson Mesa, emanate from the Quaternary alluvial deposits, and represent the culmination of the groundwater flow in the South Mesa and Wilson Mesa alluvial fan subsystems; 3) The third group of springs, observed throughout the Sand Flats area in the Glen Canyon Group hydrologic units, are bedrock discharge areas where the Glen Canyon units are deeply fractured or faulted and the groundwater finds a preferential flow path from the bedrock to the surface enhancing the surface water flow regimes; 4) The fourth group of springs, which include the largest springs and Skakel and the Moab City Springs 1,2, and 3 located in bedrock along and above the margins of the Spanish Valley, are ground water discharge areas in the Glen Canyon Group along hydrostructures, such as the Kayenta Heights fault zone and the Moab City Springs fracture zone, that force groundwater to daylight to the surface; and 5) The fifth group of springs, located in the Pack Creek alluvium of the Spanish Valley, are groundwater discharge areas where the Quaternary Lower Alluvial units are thinning above a relatively impermeable bedrock forcing the groundwater to the surface and enhancing the Pack Creek stream flow in some cases.

Human activity in the MCSW study area has affected both the surface and subsurface parts of the hydrologic systems. Past land use and human activity was mostly associated with cattle grazing, irrigation, and diversions of surface water to reservoirs with accompanying construction and operation, or subdivision of lands for domestic use. These activities have been accompanied by removal or selective reduction of native vegetation, introduction of irrigation and high-ET (evapotranspiration) crops or vegetation associated with homes, construction of (often leaking) irrigation ditches (now mostly piped), and the drilling of primarily domestic wells. This activity has resulted in localized changes of groundwater water levels and flow directions that are affected due to changes of recharge (return flow from primarily irrigation and, to a lesser extent, leaky irrigation ditches); to changes in discharge (new domestic wells); and to reduction of groundwater flow due to reduction of surface water flow that has been diverted in local, shallow aquifers of the Quaternary materials in the alluvium of the Mill Creek and Pack Creek Subsystems, or to reservoirs such as Ken's Lake.

Current land use and human activity changes are mostly associated with major development of tourist facilities and the subdivision of natural or agricultural lands. These changes may result in changes to surface water throughflow/interflow, overland flow, and channel flow, as well as changes in groundwater recharge, flow directions, and discharge. Water quality changes may result as well.

Water wells are found in the GCMC subsystem, primarily in the unconsolidated Quaternary deposits and consolidated bedrock of the Glen Canyon Group at valley bottoms in the High K Zone of Mill Creek, and in the High K Zone of the Moab City Springs fracture zone in the consolidated bedrock of the Glen Canyon Group that is the direct "pipeline" of the City of Moab springs and well fields. Most of these wells serve domestic water supply or irrigation needs, and the effect on the groundwater system locally may be significant. However, if additional water is needed by urban or agricultural development, or water is displaced by urban and recreational activities, for example, the compound effect on the groundwater system could be more significant in the future, resulting in a possible lowering of the water table, changes in flow direction, decreasing discharge to streams or increasing stream loss to groundwater, draining of wetlands, or even depletion of local aquifers. In areas with higher density of wells, such as around the City of Moab springs and wells, there is a higher density of urban land use and runoff, which could affect the water quality of the City water supply. The main concern for impacting the GCMC subsystem water balance is the current reduction of Mill Creek flow into the GCMC subsystem by the Ken's Lake diversion, and the proposed future reduction of Mill Creek flow during the "off season". Any reduction of the Mill Creek surface inflow to the GCMC subsystem will directly impact groundwater recharge into the Glen Canyon Group hydrogeologic units at the Moab City Springs fracture zone, and groundwater recharge into the Kayenta Heights fault zone at its intersection with Mill Creek. The City of Moab springs and wells, and Skakel spring will be impacted by both the water quantity and the timing of delivery, and, potentially, the water quality will be impacted by any reduction of Mill Creek surface water flow at any time of year.

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