HYDROLOGIC AND HYDROGEOLOGIC ASSESSMENT OF THE SURFACE WATER AND GROUNDWATER RESOURCES AFFECTING THE MOAB CITY SPRINGS AND WELLS, MOAB, UTAH: PHASE 2: PRELIMINARY HESA-BASED WATER BUDGET AND AQUIFER STORAGE EVALUATION

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FINAL REPORT

Prepared For:

City of Moab, Utah

August 13, 2019

Front Page: View of central Mill Creek and the Mill Creek Fracture Zone/French Drain in the southern area of the Glen Canyon Group Mill Creek Subsystem from Johnsons-Up-On-Top near Moab, Utah. Mill Creek is a perennial stream, downcut into the Glen Canyon Aquifer (Hydrogeologic Unit). (K.E. Kolm, September 2018).

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Report prepared for City of Moab, Utah, March 2019
by
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EXECUTIVE SUMMARY

This report presents the findings of Phase 2 of a 3-phase project focused on improving the understanding of the hydrogeological setting of the water supply sources for the City of Moab, the quantification of the water resources available to the City, and updating the City springs and wells protection against contamination. In Phase 1, a Hydrologic and Environmental System Analysis (HESA) of the Mill Creek and Pack Creek watersheds was performed to identify the hydrological systems of specific importance to the sustainability of the Moab City springs and wells as water supply for the City. It was concluded that the City's water supply was mainly dependent on the hydrologic system formed by the Mill Creek Watershed and the Glen Canyon aquifer underlying the Sand Flats region, including Johnsons-on-the-Top. This hydrologic system, referred to as the Glen Canyon Group - Mill Creek (GCMC) hydrologic system, was chosen in Phase 2 of the project as the setting for the quantification of the water resources available to the City, resulting in a preliminary global water budget of the entire GCMC hydrologic system. It should be noted that only a part of this global water budget is available to the City's springs and wells based on hydrologic, hydraulic and technical considerations, and may be further restricted by water rights considerations. It is a preliminary water budget as there are many uncertainties with respect to the determination of the individual components given the sparseness of relevant published data.

The Glen Canyon Group - Mill Creek (GCMC) hydrologic system is a complex mix of fractured and faulted Entrada Sandstone and Glen Canyon Group rock, Eolian (wind-deposited) Sand, Alluvium, and hydro-structures (fault and fracture zones that are either conductive or a barrier to groundwater flow). These hydrogeologic units form the robust integrated groundwater and surface water system that sustains the City of Moab springs and wells in the vicinity of the golf course and the Skakel Spring. The HESA completed in phase 1 showed that the GCMC hydrologic system is a well-defined system for which the boundary conditions and internal surface water–groundwater interactions are well-understood and quantifiable to various degrees of accuracy.

In order to estimate the upper bounds of the water resources present in the GCMC hydrologic system, a preliminary (global) water budget (PWB) has been developed for the

GCMC hydrologic system, focused on the external inputs (inflows) and outputs (outflows). In addition, an analysis was made of the storage capacity of the Glen Canyon aquifer in the PWB area. The delineation of the PWB area is based on the location of City of Moab springs and wells, the location of stream gages in Mill Creek, the location of the Sheley diversion, and the natural boundaries of the GCMC hydrologic system, and covers almost the entire GCMC hydrologic system as determined in the HESA of Phase 1. The PWB area is bounded by the Glen Canyon Group - Grandstaff Creek (GCGC) hydrologic system to the north; the low permeability Morrison Formation to the east and southeast; and the Pack Creek - Lower Alluvium (PCLA) hydrologic system to the west and southwest.

There are two distinct time periods of anthropogenic stresses in the GCMC hydrologic system: 1) pre-1980s; and 2) from early 1980s until present. During the pre-1980s, limited municipal, domestic and irrigation demand kept most of the hydrologic system of the Sand Flats region in its natural state, a period that in this report is referred to as the pre-development phase. In the early 1980s, the start of the Sheley diversion, together with the initiation of a steady increase in municipal and domestic water use, represented a significant increase in the anthropogenic withdrawals from the GCMC hydrologic system that continues to the present day. This latter period is referred to in this report as the post-development phase. A preliminary water budget has been developed for each of these two time periods.

The pre-development GCMC water budget has as inputs: 1) Groundwater recharge by infiltration of precipitation (rain and snowmelt) across the entire GCMC area; 2) Direct runoff of precipitation across the rock surface to streams within the PWB area; 3) Groundwater underflow along the Mill Creek fracture zone at the USGS streamflow gage in Mill Creek; and 4) Mill Creek inflow at the point of entry to the GCMC hydrologic system at the USGS streamflow gage. Pre-development GCMC water budget outputs are: 1) Consumptive use by riparian vegetation (cottonwoods, willows, tamarisk, and other riparian species) along Mill Creek and tributaries; 2) Springs on the Kayenta Fault Zone (including Skakel); 3) Municipal water use (City of Moab springs and wells at the golf course); 4) Domestic consumptive use (private wells); and 5) Mill Creek outflow into the northern end of Spanish Valley downstream from the Powerhouse. The post-development GCMC water budget has the same type of inputs as the pre-development water budget, but has an additional outflow term, the Sheley diversion.

The closing term or balancing term in the pre-development PWB is formed by direct runoff to streams from precipitation. That term, adjusted for changes in average precipitation, is then used as an input for the preliminary post-development water budget, in which the closing term is a deficit inflow assigned to water released from aquifer storage.

Using the precipitation data sets for the 1971-2000 and 1981-2010 for the GCMC area, a series of potential recharge and consumptive use by riparian vegetation scenarios have been evaluated based on detailed knowledge of the hydrogeology and landscape characteristics. Recharge rates vary between 10% and 30% of precipitation based on infiltration capacity (type of rock matrix, presence of fracture zones, sand and gravel on top of bedrock), resulting in about 5284-5509 ac-ft/yr of recharge across the entire PWB area, representing about 18% of total precipitation, while average consumptive use by riparian vegetation was estimated at 5101 ac-ft/yr. Direct runoff to streams was calculated at 4648-4842 ac-ft/yr.

Preliminary water budget terms for Mill Creek inflow and outflow were adjusted between pre-and post-development calculations in accordance with USGS stream gage data, while municipal use terms were based on data provided by the City of Moab. Domestic use and spring runoff terms were compiled from the Utah water rights data base.

The post-development scenario incorporates the Sheley diversion with an average annual outtake of 3665 ac-ft/yr, (as derived from USGS gage data) that is approximately 17% of the total yearly water budget of 21641 ac-ft. The preliminary post-development water budget calculations show a deficit of 3994 ac-ft/yr, representing the amount of water removed from groundwater storage in an average year. This release from storage may be compensated over time by increased recharge during above average precipitation years, or by recharge from Mill Creek (losing stretches) into the GCMC aquifer due to increased runoff in upgradient stretches of Mill Creek from larger than normal snowpack.

The PWB shows that there is a significant amount of water contributed to the GCMC hydrologic system from the La Sal Mountain hydrological systems as surface water through the upper reaches of Mill Creek, or in percentages of pre-development input into the GCMC hydrologic system: surface water (inflow into Mill Creek from La Sal Mountain system) counts for approximately 42%; local recharge from precipitation and direct runoff to streams counts for 53%; and groundwater underflow counts for about 5%. The PWB also shows a total multi-year annually averaged inflow into the GCMC hydrologic system of about 17647 ac-ft. Any decline in upstream total average flows in Mill Creek from natural or man-made causes will have an immediate and significant impact on the various outflows of the GCMC hydrologic system and poses a potential threat to the sustainability of the City of Moab's water supply.

Many of the components of the PWB calculations include large uncertainties. The most reliable data are the USGS stream flow data in Mill Creek at and below the Sheley diversion (although it contains a data gap between 1957 and 1988), the springs and wells production data from the City of Moab, and the precipitation data from NOAA used to develop various recharge scenarios. All other data sets provide a "snap shot" of a particular variable in time as they were gathered at various, non-comparable moments in time and should be considered a first estimate, subject to refining by further field studies. Climate data can be refined by limiting the pre-development climate data set from the period 1971-2000 to the period 1971-1980. This also provides more insight in the effects of climate change on the GCMC water budget. Another area where significant cost-effective improvements to the PWB can be made is more detailed and frequent monitoring of the Mill Creek surface water system, specifically in the vicinity of the Moab City wells and springs and above and below the area where the Skakel source protection zone intercedes Mill Creek. Finally, more detailed monitoring of selected, "representative" springs, both to the north and south of the Mill Creek delta, should be initiated to obtain an indication of the relationships over time between spring discharge, climate variations, and Mill Creek runoff, as well as an insight in the resilience of the GCMC hydrologic system to external stresses.

The Glen Canyon Group groundwater system is mostly unconfined, i.e., having a readily fluctuating water table, and the aquifer storativity is characterized by so-called specific yield. The Glen Canyon Group bedrock has both matrix specific yield (small) and fracture specific yield (large). The matrix specific yield estimates range from 1.0 – 10.0%; the fracture specific yield estimates range from 10.0 – 40.0%. As there is a significant presence of fracture zones in the GCMC system, fractures are the dominant feature in determining available groundwater storage. The results of GIS-based calculations show that the GCMC groundwater system has a storage minimum of about 153,000 ac-ft, and a storage maximum of about 306,000 ac-ft, indicating significant uncertainty in the actual storage available in the GCMC groundwater system. Areas along the groundwater flow paths that directly affect the yields and water quality of Skakel Spring, and the City of Moab springs and wells at the golf course, have the largest amount of storage. The current City of Moab source protection plans identify these hydro zones as critical, and an update to these plans will be completed in Phase 3 of this project.

Restated, only a part of this global water budget is available to the City's springs and wells based on hydrologic, hydraulic and technical considerations, and it may be further restricted by water rights considerations, such as those pertaining to the Sheley diversion to Ken's lake. For example, a significant part of the recharge and direct runoff in the North Fork Mill Creek area only benefits Skakel Spring and adjacent springs and is not available to the current City's wells and springs at the golf course. This may involve up to 30% of the recharge and direct runoff term in the entire PWB area. Therefore, a preliminary estimate of the amount of water in the GCMC hydrologic system accessible to the City of Moab is about 6,000 to 7,000 ac.ft/yr. There is little control on consumptive use by riparian vegetation apart from removing it. Spring flows are dependent primarily on groundwater flow gradients, which in turn are determined primarily by recharge from precipitation and losing stream reaches. As there is no control on the amount of precipitation, ensuring sufficient year round stream flows is crucial (esp. in Mill Creek). Production increase at the City wells is limited by permeability and drawdown constraints; additional water resources may be accessed by new wells in GCMC system or diversions from streams.

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, and develop an as-accurate-as-possible water budget for the segment of the MCSW area 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 2: Collect hydrological, hydrogeological and other data, and develop an as-accurate-as-possible water budget for that part of the MCSW area which affects the City's springs and wells. The results of the HESA of the MCSW area performed in Phase 1 are documented in Kolm and van der Heijde (2018).

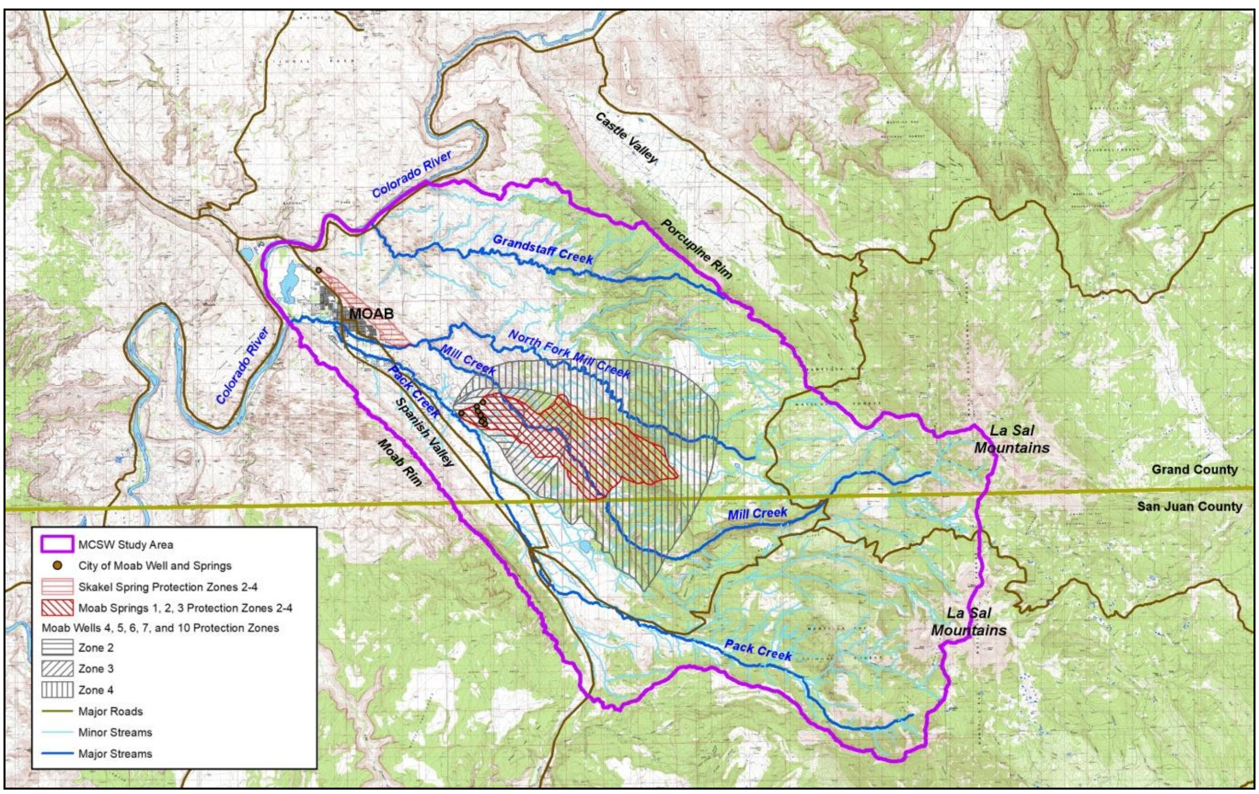

Figure 1. Topographic map showing the Phase 1 Moab City Springs and Wells (MCSW) Study Area, and the location of the City of Moab springs and wells and related Drinking Water Source Protection (DWSP) zones.

The Phase 1 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 (Figure 1). Based on the results of Phase 1, the combined Mill Creek Watershed and Glen Canyon aquifer underlying the Sand Flats region is chosen as the setting for the water budget developed in Phase 2 of this project, and for the updating of the Water Protection Plans for the springs and wells of the City of Moab planned for Phase 3 (Figure 2).

The HESA of the surface water and groundwater systems in the MCSW study area made 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 prepared to illustrate the HESA – particularly with respect to the hydrogeological characteristics of the rock types present and the significance of hydrostructures (i.e., hydrogeologically significant faults and fracture zones). The results of the HESA provide the conceptual basis for the development of the hydrological water budget for the City wells and springs in this second project phase. The HESA included a few scoping site visits to the study area; additional field surveys have been conducted as the project progressed.

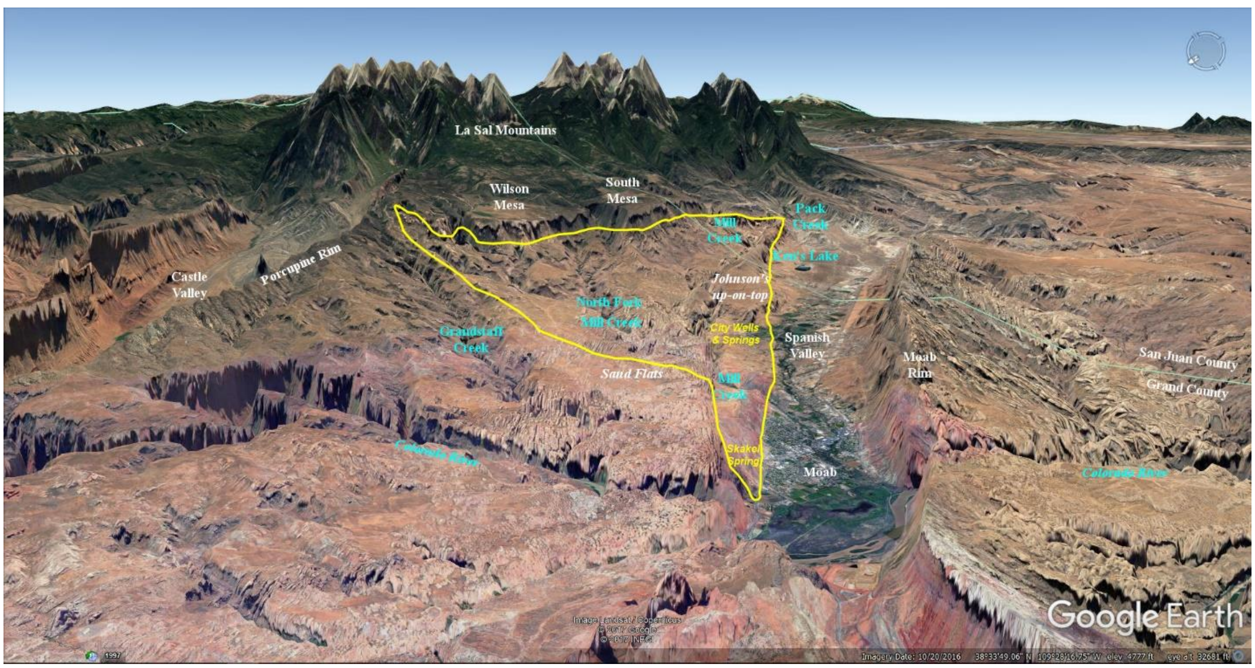

Figure 2. View of the regional setting of the Moab City springs and wells and the approximate Phase 2 Water Budget (WB) area outlined in yellow (Source: Google Earth, Imagery May 2016).

Various information sources have been consulted in preparation of the Phase 2 analysis of the hydrological water budget for the area affecting the City wells and springs, including Federal, State and City reports and data bases. When applicable, data were organized 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 or water management decision-making process, and to provide a starting point for further study of the City's surface water and groundwater resources.

2 HESA-BASED CONCEPTUAL MODEL OF GLEN CANYON GROUP MILL CREEK HYDROLOGIC SUBSYSTEM OF THE MCSW STUDY AREA

Hydrologic and Environmental System Analysis (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 surface water subsystems (Figure 3) and hydrogeologic subsystems (Figure 4) were identified within the MCSW study area in Phase 1 of this project (Kolm and van der Heijde, 2018). Each of these subsystems is characterized by a unique combination of surface water system, hydrogeologic setting, and groundwater flow system (Figure 5) and is described in detail in the Phase 1 report. Section 2 of the Phase 2 report summarizes the HESA-based conceptual model of the Glen Canyon Group Mill Creek Hydrologic Subsystem of the MCSW study area presented in the Phase 1 report as the City's wells and springs are entirely supported by this subsystem . This subsystem is the focal point of the preliminary water budget analysis presented in later sections of this report.

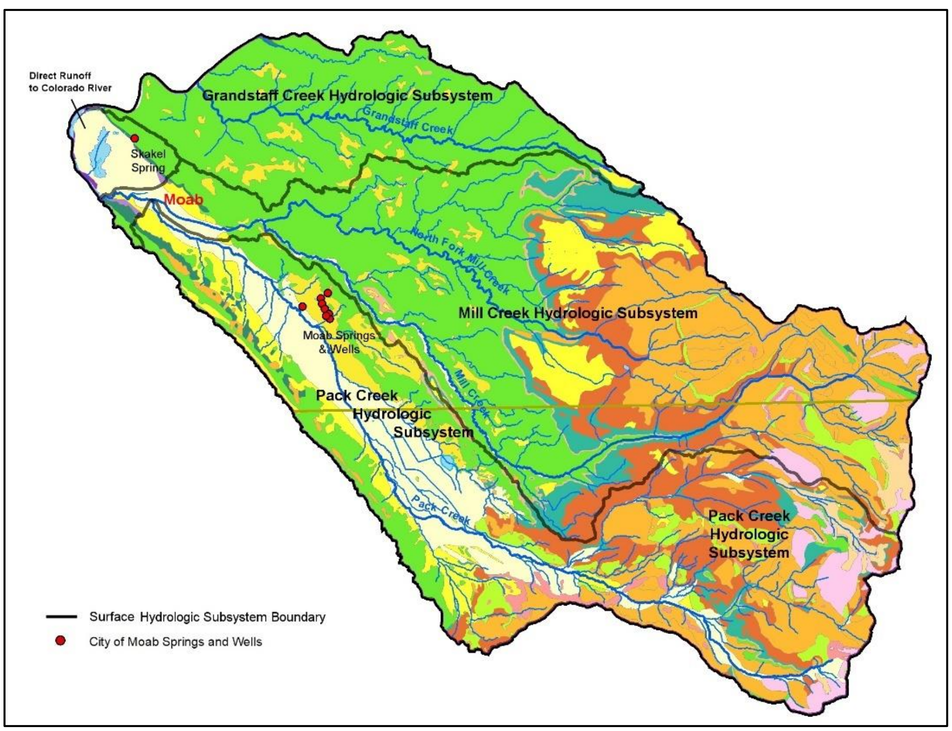

Figure 3. Map showing the three surface hydrologic systems in the MCSW study area on top of hydrogeologic units (see legend in Figure 4). Modified from Figure 19 in Kolm and van der Heijde (2018).

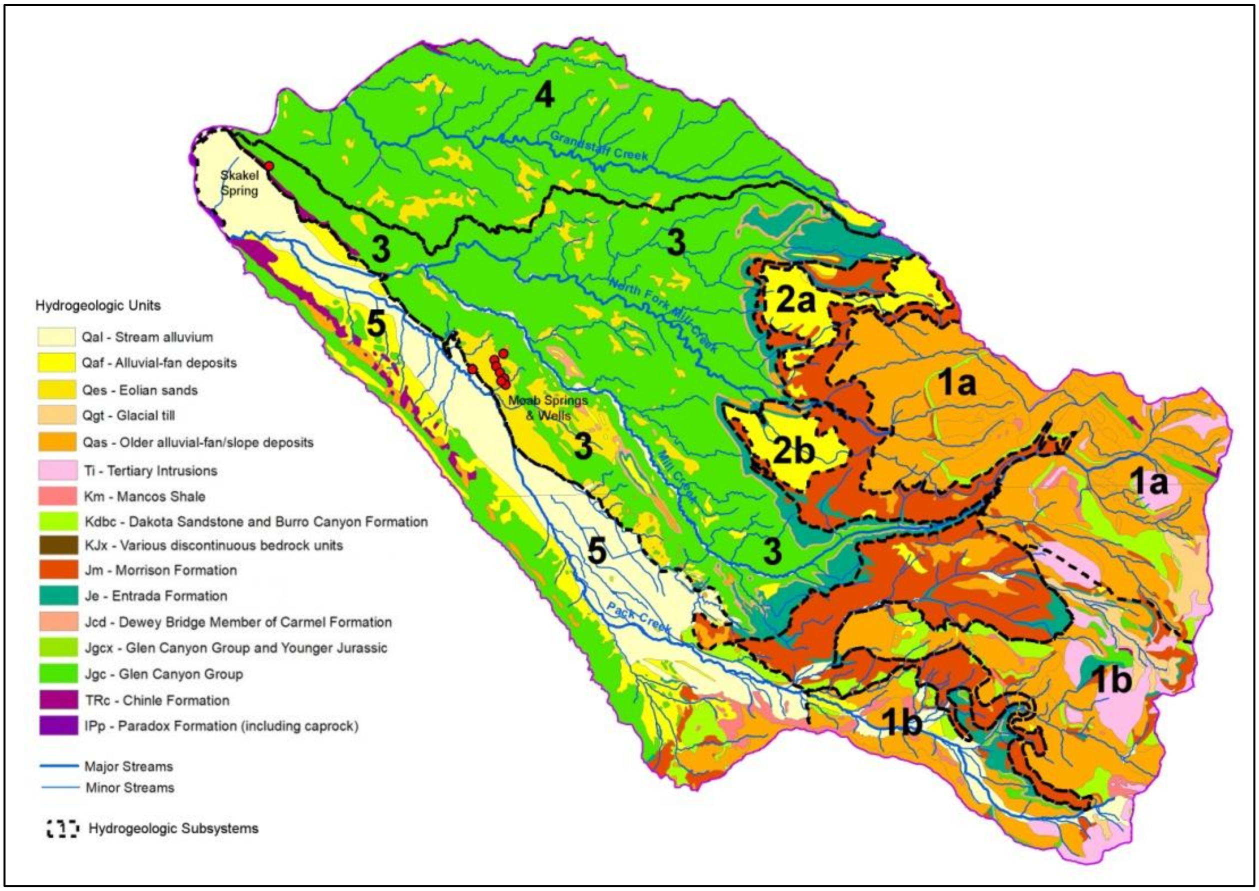

Figure 4. Plan view of the Conceptual Site Model (CSM) subsystems of the MCSW study area on top of hydrogeologic units: 1a. La Sal Mountain Upper Alluvial Subsystem (LSMA-M) Mill Creek Headwaters; 1b. La Sal Mountain Upper Alluvial Subsystem (LSMA-P) Pack Creek Headwaters; 2a. Wilson Mesa Alluvial Fan 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). Modified from Figure 21 in Kolm and van der Heijde (2018).

The Glen Canyon Group Mill Creek Subsystem (GCMC), located in the core of the study area (CSM 3 in Figure 4), 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 in the vicinity of the golf course and Skakel Spring (Figures 4, 5 and 6). 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. This subsystem is hydraulically connected to the Pack Creek Lower Alluvium subsystem 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.

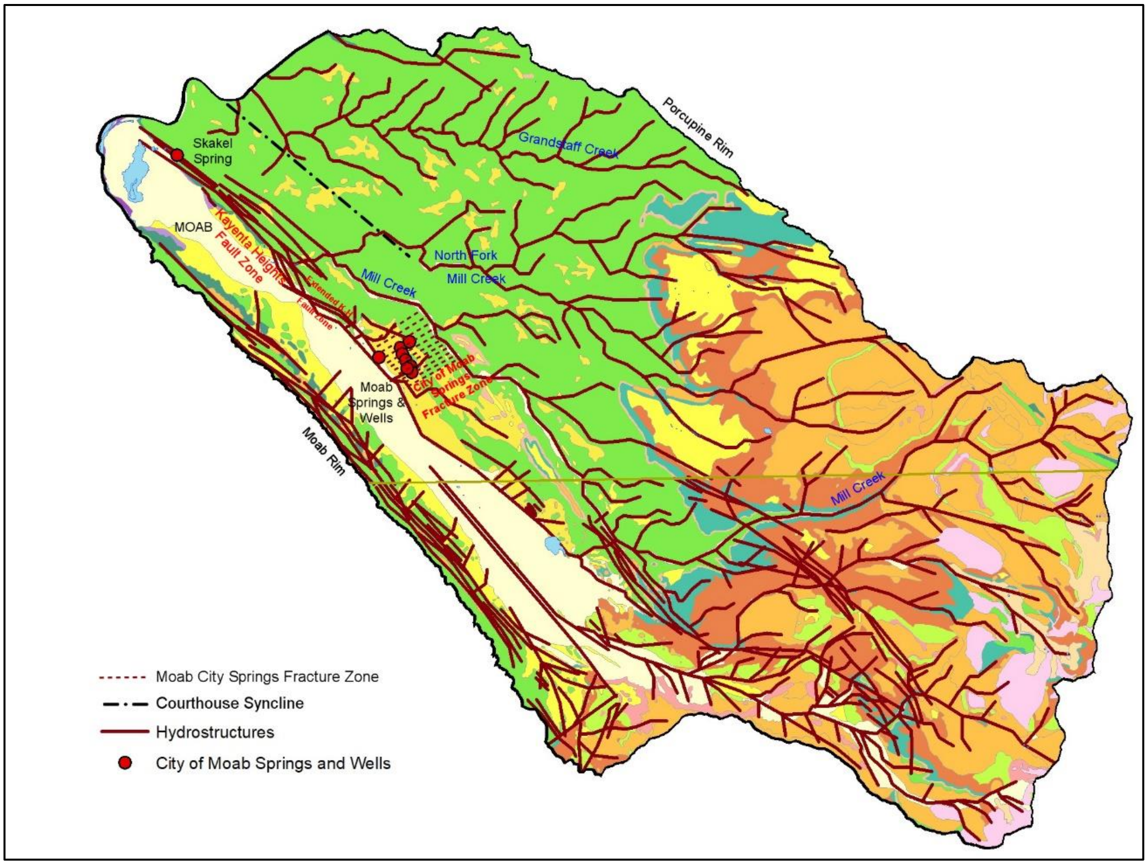

Figure 5. Plan view of the hydrostructures on top of the hydrogeologic units of the MCSW study area. Modified from Figure 18 in Kolm and van der Heijde (2018).

As stated in Section 2.5.2 in Kolm and van der Heijde (2018), there are two significant hydrogeologic groups in the GCMC Subsystem, which includes Mill Creek and its tributaries: 1) Quaternary unconsolidated clastic materials (Figure 15; Table 2a in Kolm and van der Heijde, 2018), which are predominantly Stream Alluvium (Qal) and Eolian Sand (Qes); partially overlying 2) Mesozoic bedrock units (Figure 16; Table 2b in Kolm and van der Heijde, 2018), 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 in the GCMC Subsystem of significance to the hydrogeology in general and to groundwater flow directions in particular (Figure 5): 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 and east-west trending fracture zones are observed in most of the Mill Creek tributaries such as Rill Creek, the lower part of North Fork Mill Creek, and the "Spring 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. In addition, the main fracture zone from the "Middle Fork" of Mill Creek to the City of Moab springs and wells at the golf course has this same trend. 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 5 and 6). In the case of the fracture zone at the junction of the "Spring 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 5and 6) and is quite important to the springs and wells protection.

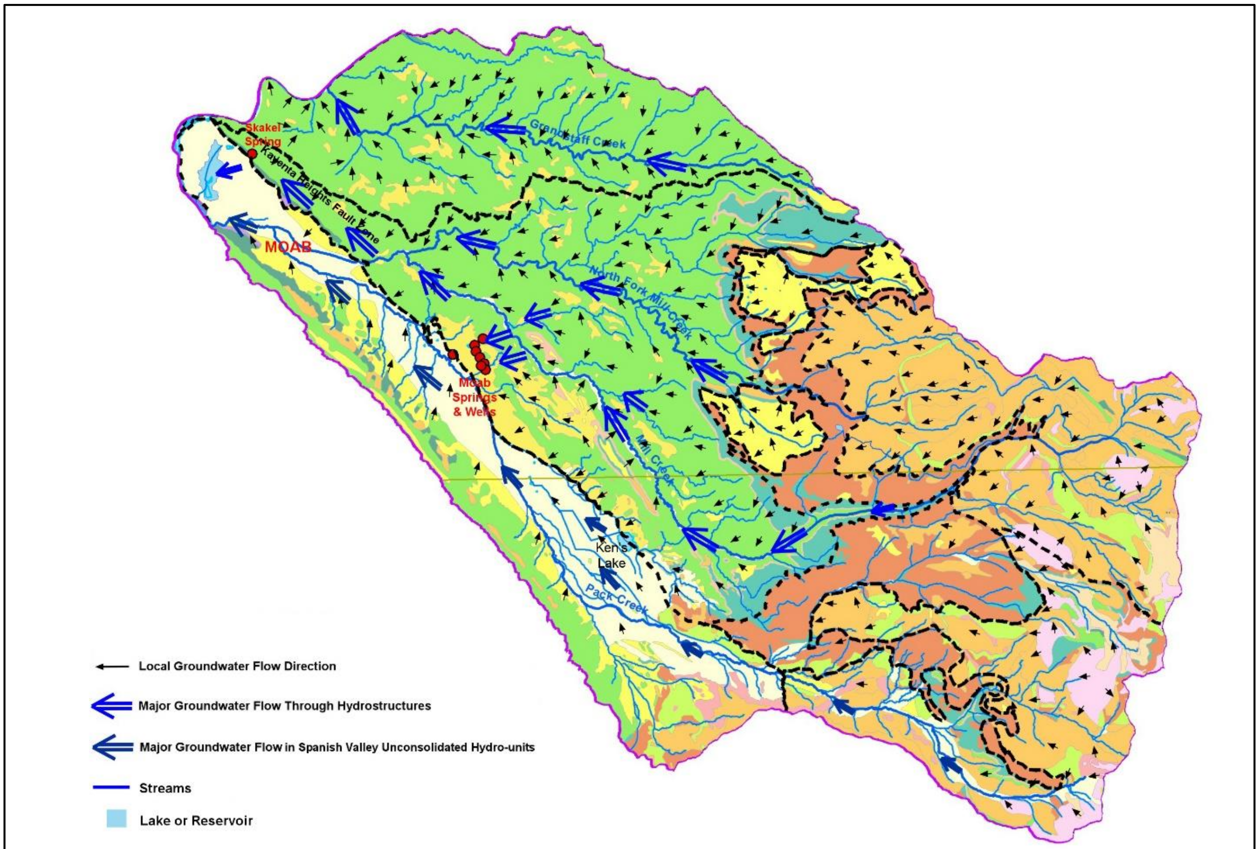

Figure 6. Plan view of the flow directions in the groundwater system on top of the hydrogeologic units of the MCSW study area. The small arrows are local groundwater flow directions. The larger blue arrows show groundwater flow direction along major hydrostructures and the major groundwater flow direction in the Spanish Valley area. Modified from Figure 22 in Kolm and van der Heijde (2018).

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 (Figures 5 and 6). These zones 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 the name Kayenta Heights Fault Zone along the City of Moab and Extended Kayenta Heights Fault Zone between Mill Creek and the City of Moab Springs Fracture Zone (Figures 5 and 6). 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 this fault zone may serve as a conduit, but also 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.

The shallow Quaternary unconsolidated materials in this subsystem are located in two strategic locations: 1) directly along the main channels of the stream (Qal); and 2) scattered on the mesa tops (Qes) (Figure 15 and Table 2a in Kolm and van der Heijde, 2018). 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 0.3 – 1.0 ft/day (Jobin, 1962; Blanchard, 1990; Lowe and others, 2007); and the fracture flow can be as high as 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 of Kolm and van der Heijde (2018). 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 (Figure 6). 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 4). 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 and the amounts that may be entering the system by this mechanism are at this stage of preliminary water budget analysis considered negligible.

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 (Figure 6). 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 (Figure 6). 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 are discussed and illustrated in detail in Kolm and van der Heijde (2018).

Groundwater discharges out of the GCMC subsystem in two places due to complex hydrostructures: 1) The (Extended) Kayenta Heights (K-H) Fault Zone that delivers groundwater to various springs and seeps along its path including Skakel Spring at the northwest end of Spanish Valley and springs located between the Milk Creek delta and the City of Moab springs; and 2) The City of Moab Springs Fracture Zone that delivers groundwater to the City of Moab springs (Figure 7). 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 6 and 7).

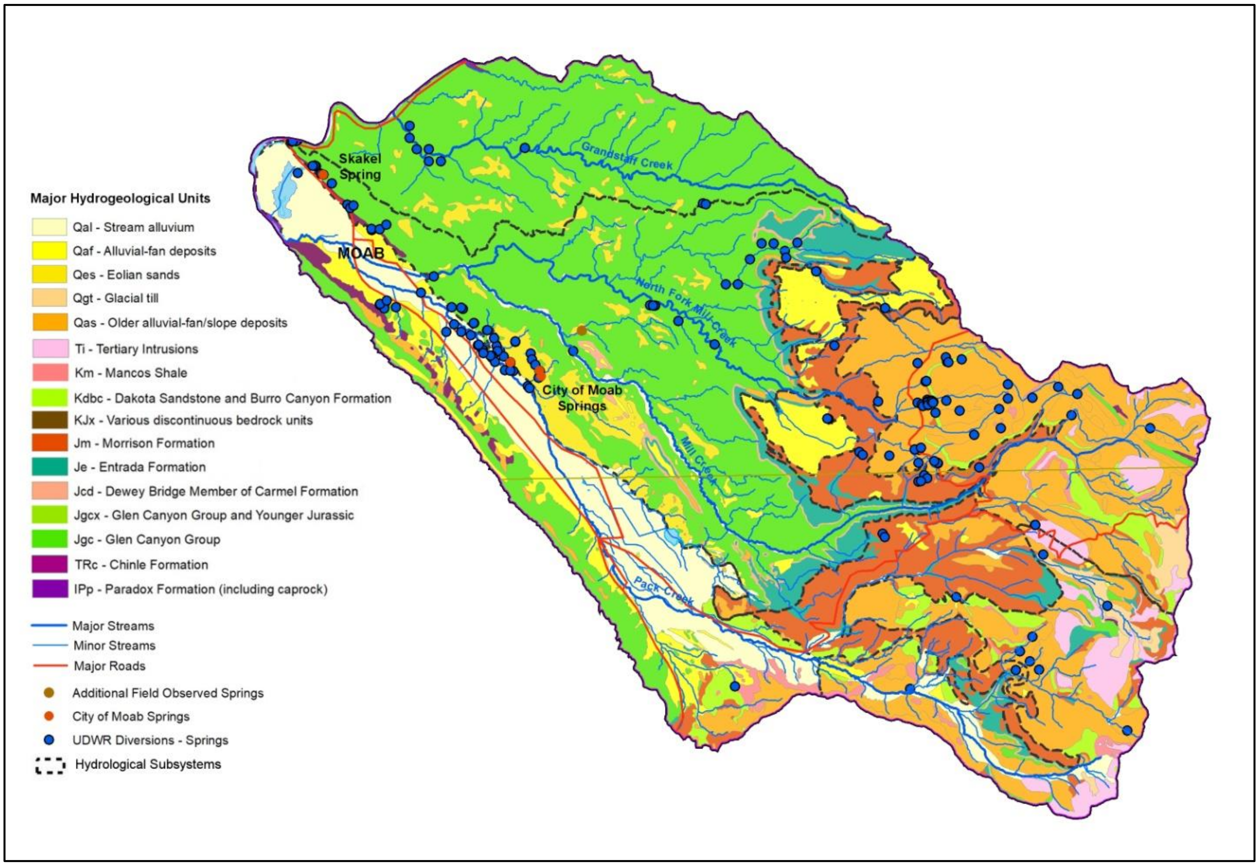

Figure 7. Plan view of the location of spring areas, and the conceptual site model subsystems, hydrogeologic units, and streams of the MCSW Study Area. Modified from Figure 24 in Kolm and van der Heijde (2018).

3 PRELIMINARY WATER BUDGET OF GLEN CANYON GROUP MILL CREEK HYDROLOGIC SUBSYSTEM OF THE MCSW STUDY AREA

In section 2 of this report, the components of the Glen Canyon Group Mill Creek (GCMC) hydrogeologic system and the surface water and groundwater flow systems have been discussed. The GCMC has been analyzed with respect to surface water dynamics (stream input or stream flux in, stream flow through the given area, stream output or stream flux out) and available stream flow data have been collected (for example, Blanchard, 1990; USGS Surface-Water Dailey Statistics, Mill Creek at Sheley Tunnel Sites, 2019). In addition, precipitation data relevant for the watershed have been collected in table and map format (Kolm and van der Heijde, 2018). Likewise, the major elements of the dynamics of the hydrogeologic system -- groundwater input or recharge areas, groundwater output or discharge areas, and the (internal) groundwater flow system -- have been determined (See Section 2.0 and Kolm and van der Heijde, 2018). Well and spring data to quantify groundwater output have been collected from various sources (Lowe and others, 2007; Kolm and van der Heijde, 2018; Utah Water Rights Data Base, 2017, 2018). Published groundwater level data have enabled the determination of groundwater flow direction and amount of water storage and well yield at a given point in the groundwater system (Lowe and others, 2007), which can be used to calculate groundwater flux and storage over time.

In order to further understand how the GCMC hydrologic system works, and to determine quantitatively if the hydrologic system is properly analyzed, a water budget may be developed for the GCMC hydrologic system. The hydrologic system water budget, or water balance, is the quantitative listing of the surface water and groundwater inputs and outputs, and changes in internal storage over a particular period of time. In its most simple form, the period of time is chosen such that the internal storage changes are so small that they do not have to be taken into account. Considering climatic variability, often a multi-year period with averaged inputs and outputs is selected to determine the water budget for a particular hydrologic system. The water budget inputs should be equal to or "balance" the water budget outputs. The selection of the time period for which to calculate the water budget depends, among others, on the nature of the climatic variability, and the availability of climatic and hydrologic records. Frequently this is done for a one- or multi-year period to capture a full cycle of seasons, or multi-year trends. For shorter periods of time, such as the growing season, water budget calculations may involve estimating the release from or addition to internal storage. This may also be the case if there is a systematic dewatering of an aquifer involved for, for example, over-pumping (i.e., “mining” of groundwater).The change in storage could be seasonal changes in measured water tables, long term decline in groundwater levels, or changes in (surface water) reservoir water levels.

The first step in determining a water budget for the GCMC hydrologic system is to determine the correct hydrologic system conceptual model using HESA. With HESA, individual components of the hydrologic system are analyzed, followed by evaluating the aggregate of components and their interactions, to locate and quantify relevant hydrologic subsystems. The results of the HESA for the GCMC analysis area are given in Section 2 of this report. Step 2 in determining the water budget is setting up a logic diagram based on the conceptual models to show all the significant hydrologic components and processes, including the external hydrologic system inputs, outputs, and internal components or storage areas, and exchanges between internal components. Step 3 is to subset the overall conceptual model area to a manageable area where quantification of the hydrologic system will be most practical and accurate given the available data and the landscape terrain measurability (i.e., estimates of inputs and outputs where engineering data is not available or not practical/cost-effective at this time).

3.1 Water Budget Logic Diagram

The diagram shown in Figure 8 shows the relevant generalized hydrologic system components and processes identified during the HESA of the MCSW study of Phase 1. In this diagram, hydrologic and hydrogeologic units or storage components are represented by boxes and the hydrologic exchange processes or fluxes by arrows. Note that the processes internal to the hydrologic units, such as atmospheric flow, stream flow, and groundwater flow, are not included. The main hydrologic units are: 1) atmosphere; 2) surface water system (streams); 3) unsaturated zone (between ground surface and water table); 4) shallow groundwater zone (saturated valley-fill unconsolidated sediments); and 5) deep groundwater zone (bedrock hydrogeologic units and hydrostructures). Figure 8 also shows the process-type interactions between these hydrologic units. These processes can be quantified as fluxes or flow rates such as precipitation rates (L/T), groundwater recharge (L/T), spring discharge (L^3/T), groundwater discharge to/recharge from streams (L^3/T/L'), and well discharge (L^3/T). It should be noted that many of the processes are difficult to measure or estimate and introduce significant uncertainty in water budget calculations when used.

Often, to get a better understanding of the water budget components and reduce uncertainty, the complex set of hydrologic units and processes shown in Figure 8 is simplified by reducing the number of units and processes based on HESA evaluated significance of and data availability for each of these components. For example, a water budget may focus on surface water and its interaction with the atmosphere. In that case, the subsurface units and processes, depicted in Figure 8 as the unsaturated zone, the shallow groundwater (saturated zone), and deep groundwater zone (bedrock) and related processes, would be represented by a single gain or loss flux. In the same fashion, a focus on the groundwater system may replace the atmosphere, streams, and unsaturated zone by inputs and outputs only, and any change in storage would be limited the shallow and deep aquifers.

The Conceptual Site Model resulting from the HESA of the GCMC hydrologic system, together with the location of the Mill Creek stream flow gages and other available stream flow measurements, provided guidance on how to delineate the water budget area and how to simplify the complex hydrologic system components and process illustrated in Figure 8 in preparation of a preliminary water budget for GCMC hydrologic system.

3.2 Preliminary Water Budget for the GCMC Hydrologic System

A preliminary water budget (PWB) for the GCMC hydrologic system is calculated based upon the information previously collected and analyzed by Kolm and van der Heijde (2018), and the HESA-based conceptual model of the GCMC hydrologic system determined in Phase 1 of this project. The area in GCMC for which the water budget is determined is based, in part, on 1) the locations of various stream gages on Mill Creek and North Fork of Mill Creek (Blanchard, 1990); 2) the location of most anthropogenic activities (diversions, domestic and agricultural water use); 3) the natural boundaries of the GCMC hydrologic system including Mill Creek and tributaries; and 4) the hydrogeologic and hydrostructural boundaries of the Glen Canyon Aquifer as determined by HESA (Figures 9 and 10). The water budget area is outlined in both Figures 9 and 10 and is bounded by the Glen Canyon Group Grandstaff Creek Subsystem (GCGC) to the north; the Morrison Formation to the east and southeast; and the Pack Creek Lower Alluvium Subsystem (PCLA) to the west and southwest (Figures 4, 9 and 10). The PWB area used in this report covers almost all of the GCMC hydrologic system, except for a small area upstream of the Sheley diversion near stream measurement site MC-03 (Blanchard, 1990).

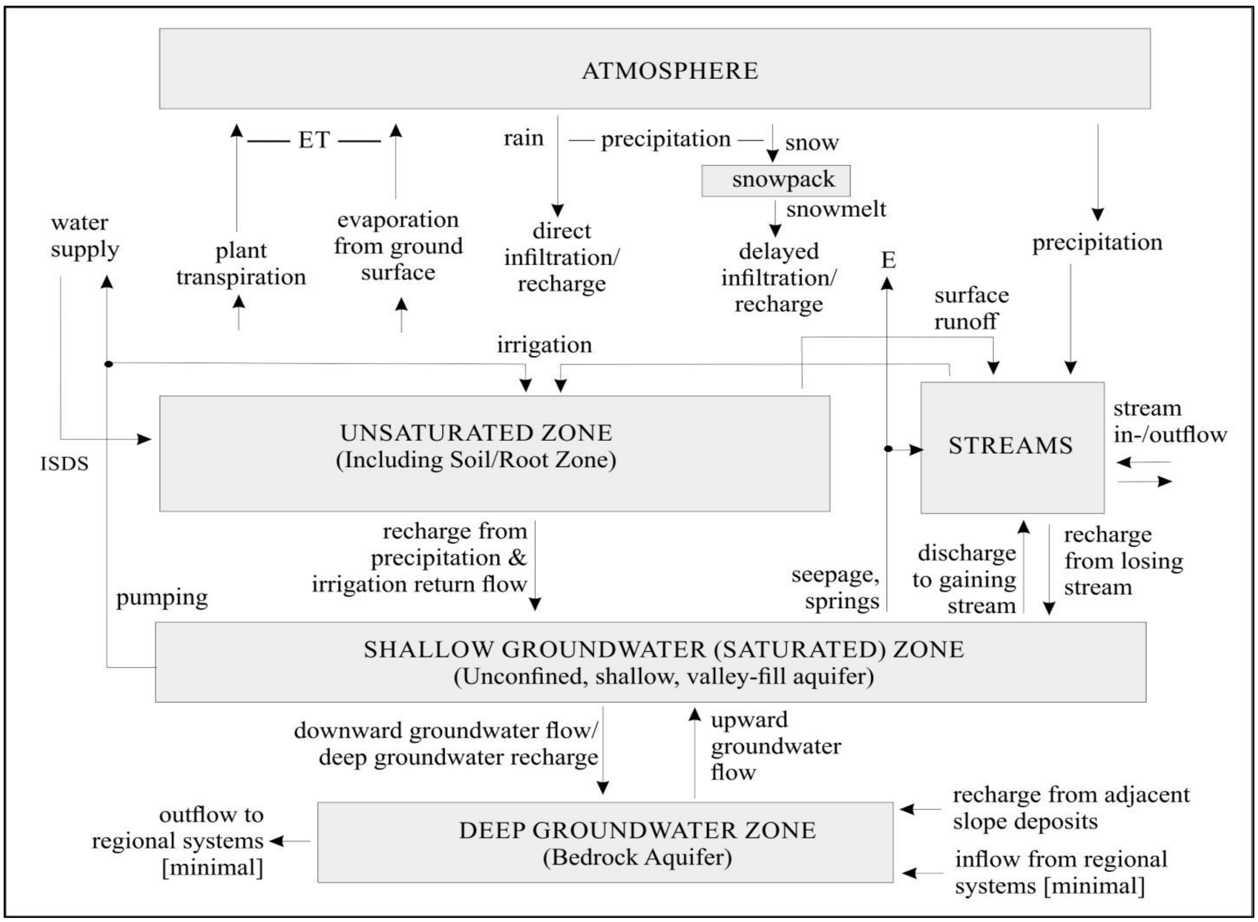

Figure 8. Generalized hydrologic system components and processes.

The surface and subsurface hydrologic systems or storage components and the hydrologic exchange processes or fluxes considered relevant for the PWB of the GCMC hydrologic system were derived from the conceptual models developed in the Phase 1 HESA as illustrated in Figure 9 (hydrogeological units) and Figure 10 (boundary conditions) and are shown in the diagram in Figure 11. The significant inputs of the PWB are: 1) Mill Creek surface water at the SE corner of the water balance area; 2) Mill Creek groundwater flux, called groundwater underflow, in the fractured Glen Canyon hydrogeologic units (Jgc) at the SE corner of the water budget area; 3) recharge by infiltration of precipitation (rain and snow) across the entire PWB area using the concept of *hydro zones* explained later in this report; and 4) direct runoff of precipitation to streams. Note that precipitation itself and evapotranspiration (ET) for the area not covered by riparian vegetation is not included in the PWB, but is discussed in following sections.

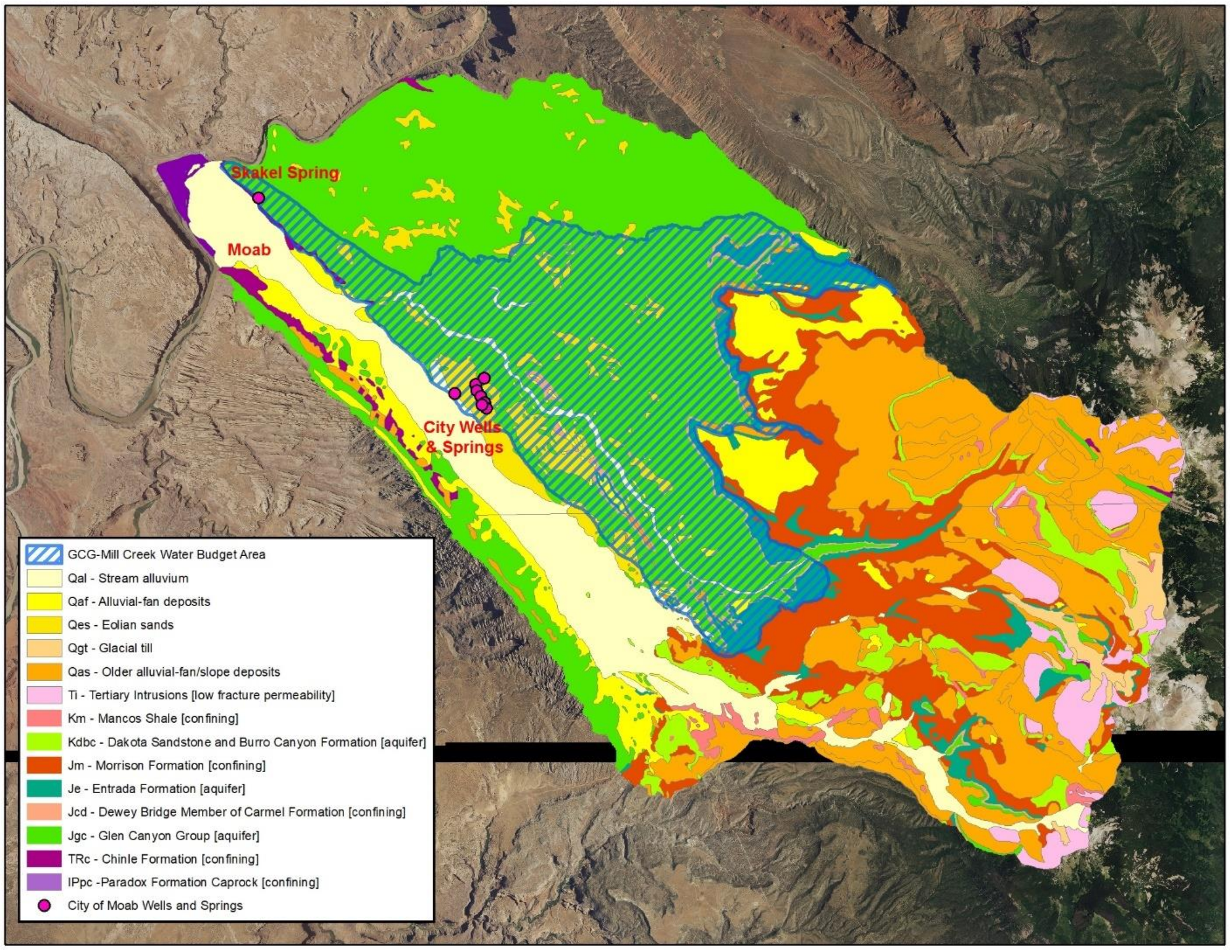

Figure 9. Map showing the location of the Preliminary Water Budget (PWB) area of the GCMC hydrologic system on top of the hydrogeologic units of the MCSW study area prepared by Kolm and van der Heijde (2018).

The outputs of the PWB are: 1) Mill Creek surface water outflow at the northern end of Spanish Valley along the Mill Creek Delta just downstream from the Powerhouse; 2) evapotranspiration or consumptive use by native phreatophytes (cottonwoods, willows, tamarisk, and other riparian species); 3) groundwater discharge from the fractured GCMC hydrogeologic units along the northwestern and southwestern edges of the PWB area, 4) City of Moab wells and springs; and 5) domestic consumptive use by private wells (Figures 10a and 10b). Figure 11 shows a diagrammatic representation of these water budget components. It should be noted that the groundwater inflow components "irrigation return flow" and "septic tank leach field infiltration" shown in Figure 11 are considered small enough not to be taken into consideration for the PWB.

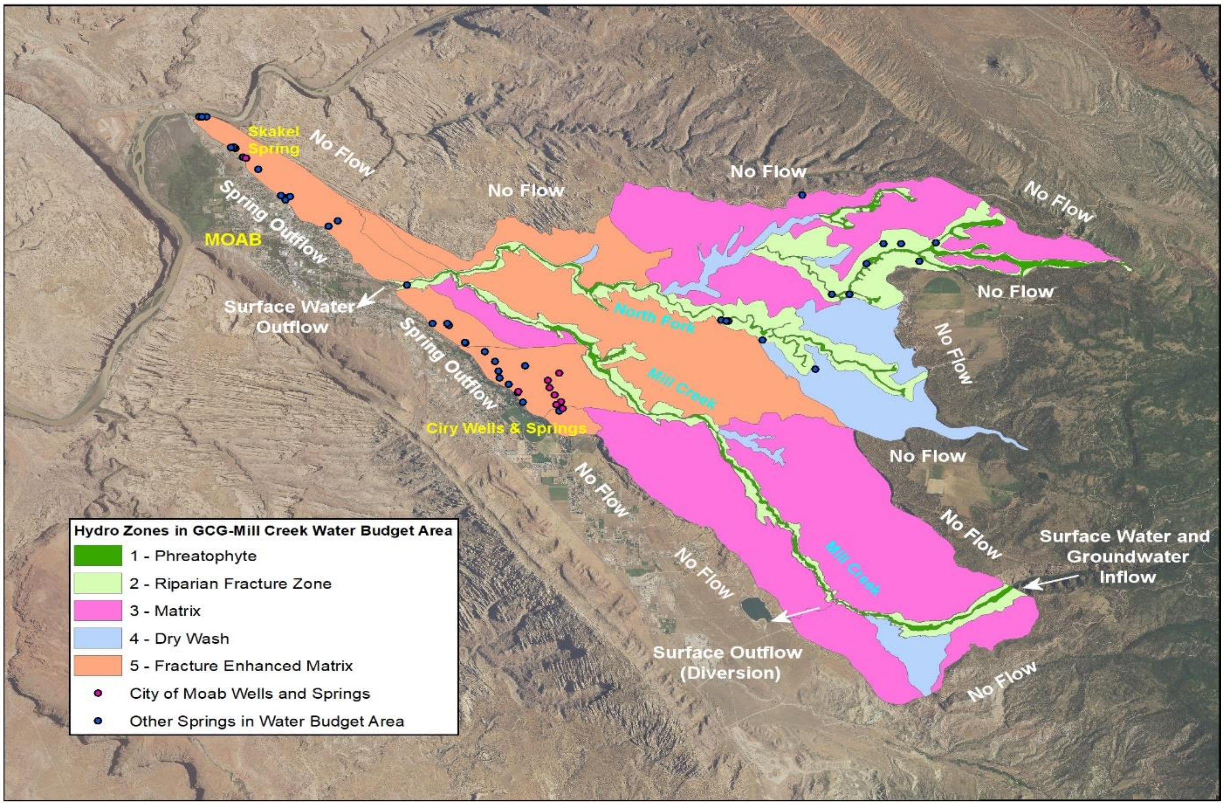

Figure 10a. Map showing the location of the Preliminary Water Budget (PWB) area and Hydro Zones of the GCMC hydrologic system with boundary conditions and spring locations.

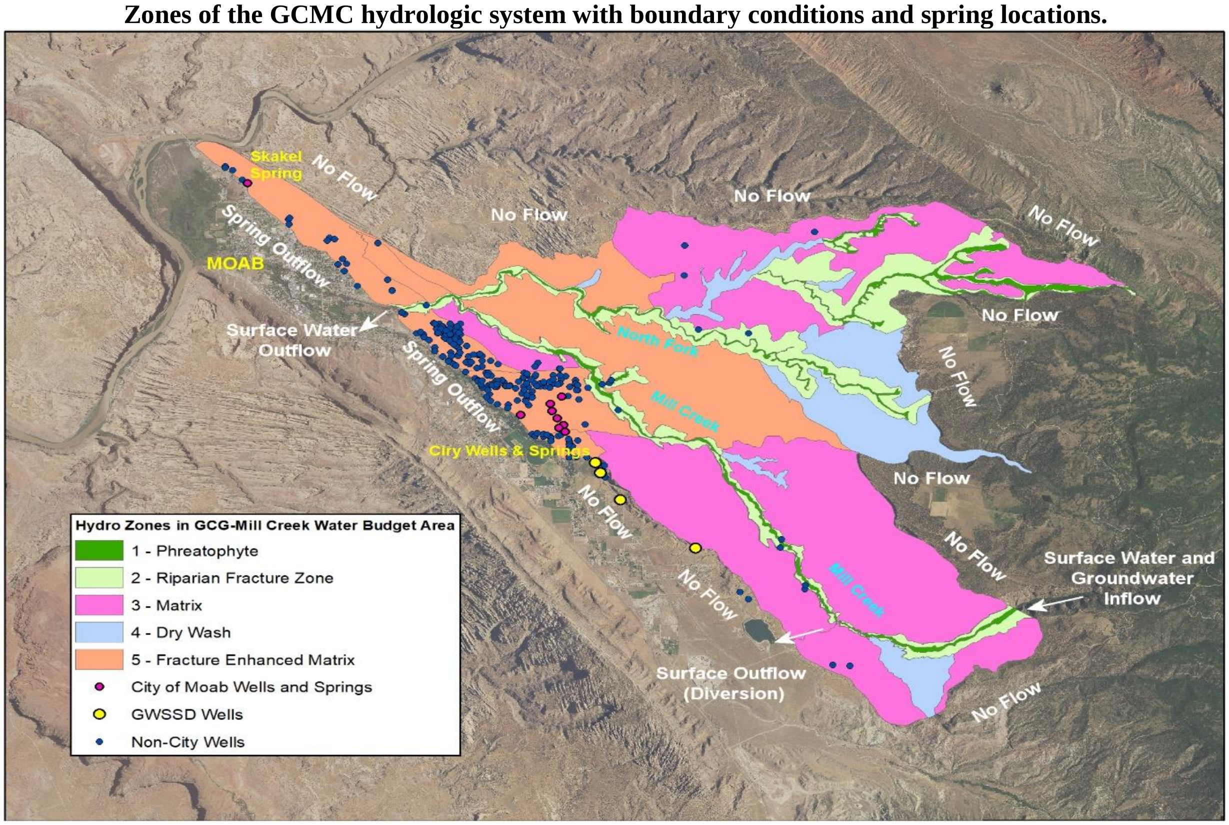

Figure 10b. Map showing the location of the Preliminary Water Budget (PWB) area and Hydro Zones of the GCMC hydrologic system with boundary conditions and well locations.

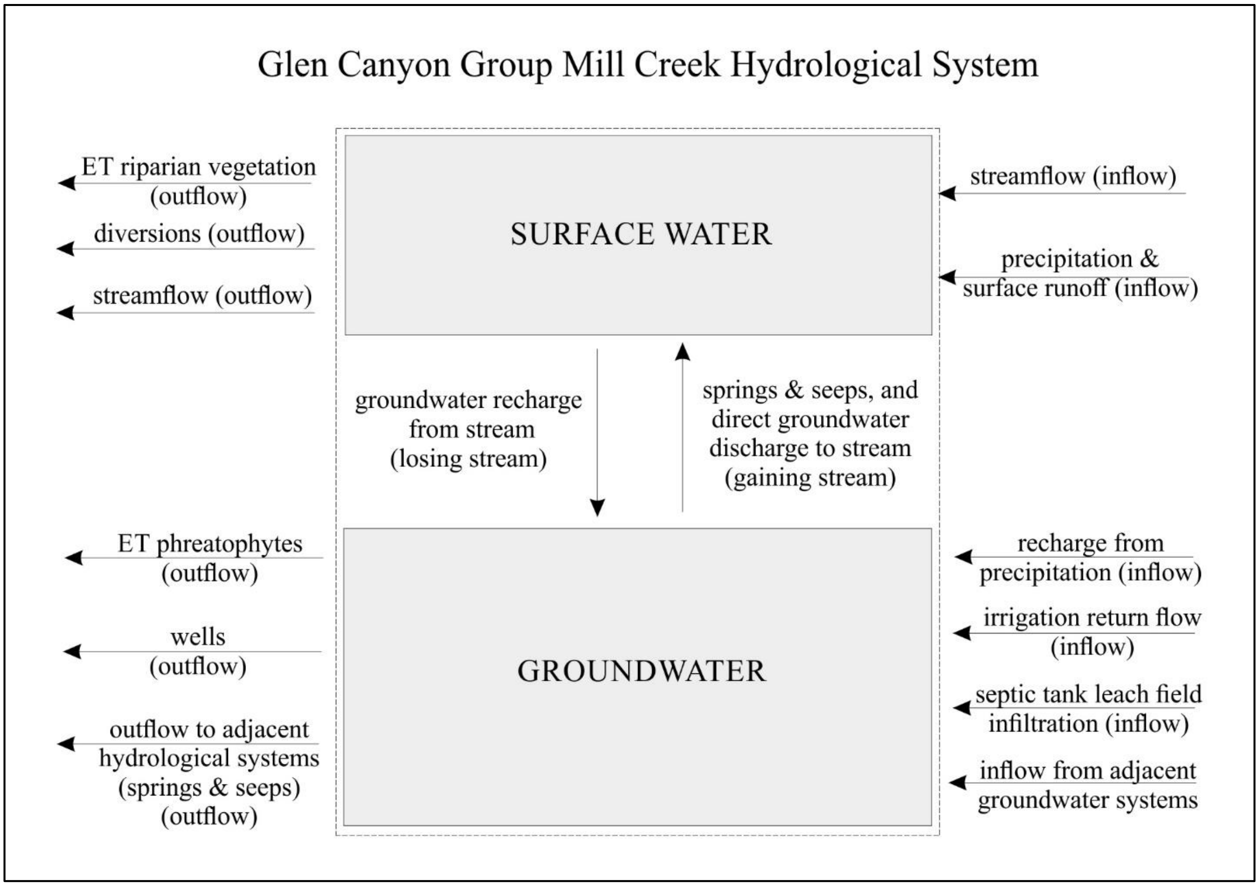

Fig 11. Simplified diagram of inflows and outflows for the GCMC hydrologic system.

A starting point for determining the PWB is the climate data collected for the weather station 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 (see Figure 3 and Tables 1a, 1b and 1c in Kolm and van der Heijde; 2018). 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, and the Moab station has a continuous record from 1971 to the present for analysis regarding predevelopment and current water budgets. The climate data for the Moab and La Sal Mountain stations, together with other neighboring stations, have been used to develop maps showing the spatial distribution of average annual precipitation for the period 1971-2000 and 1981-2010 (available from the Natural Resources Conservation Service; see Figure 4 in Kolm and van der Heijde; 2018). 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 GCMC study area to greater than 20 inches near the eastern edges of the GCMC hydrologic system. The availability of the spatial data sets for these two periods form the base for selecting these periods in determining precipitation related PWB terms.

In addition, several other sources of published data provided input into the PWB: 1) Mill Creek and North Fork Mill Creek discharge measurements on October 21, 1985 and October 14, 1986 as published in Blanchard (1990) provided both surface water and groundwater inputs and outputs to the GCMC hydrologic system along these streams (see Figure 8a-c in Kolm and van der Heijde; 2018); 2) USGS stream gage data collected above and below the Sheley diversion provided a long-term data set regarding stream flows in the upper reach of Mill Creek and the effects of the Sheley diversion (Appendix 3); 3) Adjudicated maximum spring and well use information culled from the State of Utah Division of Water Rights data base, together with spring and well data from the City of Moab, provided a first approximation of groundwater discharge (outputs) in the GCMC hydrologic system; and 4) Phreatophyte consumptive use measurements published by Muckel and Blaney (1945) provided data regarding outputs due to natural vegetation effects in the GCMC hydrologic system.

3.3 Approach to Preliminary GCMC Water Budget Calculations

The identified data sets mostly provide a "snap shot" of a particular variable in time and were gathered at various, non-compatible moments in time. The challenge in this project is to extrapolate from measured values where necessary. The starting point is the determination of the pre-development (pre-1980s) annual averaged water budget components. This period is chosen, because of availability of distributed precipitation data, the coming on-line of the Sheley diversion in the early 1980s, and the increased municipal and domestic water use in the later period. The estimated pre-development direct runoff to streams, together with adjustments to some of the other water budget components, is then used for the post-development (1980s- and later) water budget.

In order to quantify some of the components of the preliminary GCMC water budget given the sparseness of published data, the GCMC hydrologic system was spatially categorized into 5 types of hydro zones based upon the hydrogeology and geomorphology, groundwater and surface water hydrology, and distribution of phreatophytes (Figures 10a, 10b and 12; Appendix A). Hydro Zone 1 is the phreatophyte zone with gaining stream reaches and phreatic consumptive use. Hydro Zone 2 is the riparian high-K fracture zone (French Drain) and is characterized by fractured canyon type recharge and storage; note that this zone overlaps the phreatophyte discharge zone, but extends between opposite canyon walls beyond the riparian vegetation. Hydro Zone 3 is the matrix (non-fractured) zone and represents very slow recharge and small storage. Hydro Zone 4 is the dry wash high-K fracture zone (French Drain) having the same hydro functions as zone 2, but having insignificant phreatophyte discharge occurring in the same area. Hydro Zone 5 is the fracture enhanced high-K matrix zone. To correctly attribute the parameters for these zones, each hydro zone has been divided in hydro sub-zones indicated by the numbers in Figure 12, which correspond with the OBJECTID numbers in Appendix A. The City of Moab provided assistance in digitizing the hydro zones and sub-zones.

The preliminary pre-development GCMC water budget (pre-1980s) has as inputs: 1) groundwater recharge from precipitation using the averaged climate data for the period 1971-2000; 2) direct runoff of precipitation to streams; 3) groundwater underflow along the Mill Creek fracture zone; and 4) Mill Creek inflow at the point of entry to the GCMC hydrologic system above the Sheley diversion (Figures 10a, 10b and 12). Preliminary pre-development GCMC water budget (pre-1980s) has as outputs: 1) consumptive use riparian vegetation; 2) springs on the Kayenta Fault Zone and its southern extension (including Skakel Spring overflow); 3) municipal water use (City of Moab Springs and Wells); 4) domestic consumptive use, irrigation and stock water; and 5) Mill Creek outflow at its delta near the Powerhouse (Figures 10a, 10b and 12; Table 1a). Each of these terms are discussed in detail in following sections.

Preliminary post-development GCMC water budget calculations (from the early 1980s to present) are completed with the recharge, direct runoff and consumptive use inputs determined in the pre-development water budgets, adjusted with the climate data for the period 1980-2010, to evaluate the average annual change in water storage due to changes in climate and anthropogenic activities (Table 1b). Specifically, the effects of the Sheley diversion, the changes in municipal use, and domestic consumptive use on input and output are evaluated, and the change of storage is calculated. Storage calculations are also evaluated separately for individual hydro zones of the GCMC hydrologic system based on hydrogeology and hydro-fractures, and the percentage of storage change is evaluated in the context of the overall storage capacity in Section 4.

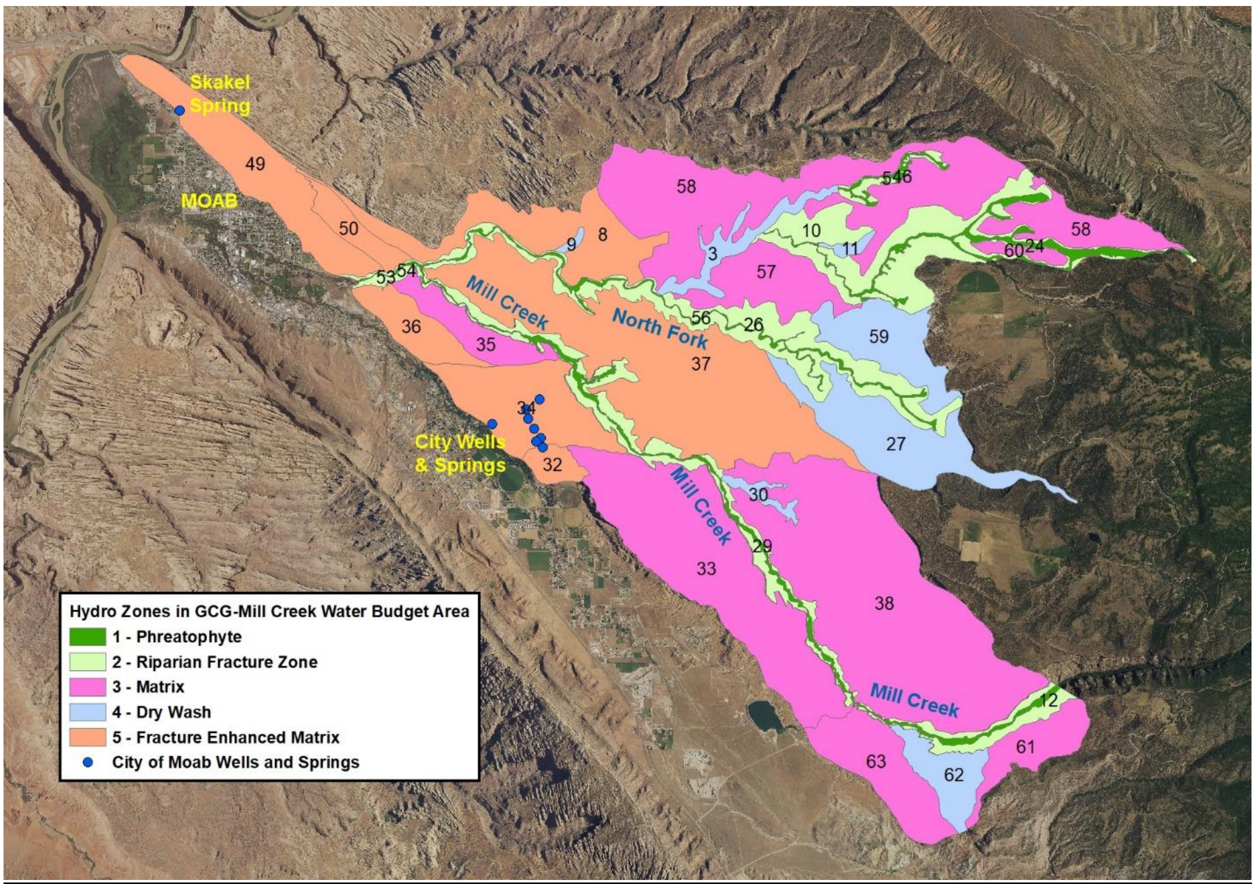

Figure 12. Map showing the location of the Preliminary Water Budget (PWB) Area and the hydro zones of the GCMC hydrologic system. The numbers in the figure refer to the hydro sub-zones specifically defined and digitized for the development of the PWB.

3.4 Calculation of Groundwater Recharge and Direct Runoff to Streams

Average annual precipitation ranges from about 9 inches in Moab in the far northwestern corner of the GCMC hydrologic system to greater than 20 inches near the eastern edges of the GCMC hydrologic system. To evaluate recharge, three recharge scenarios have been evaluated as a function of the spatial distribution and amount of precipitation in each hydro zone: 1) low estimate using 10% of precipitation for all hydro zones; 2) a high estimate using 10% of precipitation for unfractured matrix hydro zones combined with 20% to 30% of precipitation for the fracture-enhanced matrix and fractured canyons/ dry wash hydro zones; and 3) a "best" estimate using 10% of precipitation for unfractured matrix hydro zones combined with 20% of precipitation for the fracture-enhanced matrix and fractured canyons/ dry wash hydro zones. The average annual precipitation was calculated for each hydro sub-zone in both inches and acre-ft for both the periods 1971-2000 and 1981-2010 by overlaying the sub-zone GIS layer with the two precipitation GIS layers. The calculations are listed in Appendix A and can be summarized as follows: 1) for the period 1971-2000 the low estimate is 3050 ac-ft/yr, the high estimate is 7168 ac-ft/yr; and the "best" estimate is 5509 ac-ft/yr; 2) for the period 1981-2010 the low estimate is 2921 ac-ft/yr, the high estimate is 6875 ac-ft/yr, and the "best" estimate is 5284 ac-ft/yr (Tables 1a and 1b). Note that the "best" estimate for recharge in both periods amounts to about 18 % of overall precipitation in the PWB area. Note also that groundwater recharge of 1-3 inches per year are common estimates in groundwater modeling and water budget studies for these types of environments.

The Preliminary Water Budget closing term (i.e., balancing term) for the pre-development scenario (Table 1a) consists of direct runoff of precipitation to streams and amounts to 4842 ac-ft/yr. This term, corrected for the decline in precipitation between the two climate periods for a total of 4648 ac-ft/yr, is used in the post-development scenario (Table 1b) where the closing term is release from groundwater storage (see also Section 3.11). Note that this also includes surface runoff from Wilson Mesa and South Mesa. Note also that direct evapotranspiration (ET) in the PWB area (excluding riparian vegetation), calculated as precipitation minus groundwater recharge and direct runoff to streams, amounts to 20,143 ac-ft/yr for the pre-development period and to 19,270 ac-ft/yr for the post-development period, or about 65%. All these numbers are based on 30-year averages for the two climate periods.

3.5 Calculation of Groundwater Underflow

The basis for the calculation of groundwater underflow of the Mill Creek fracture zones in the southeastern boundary of the PWB area (Figures 10a and 10b; at about the location of MC-03 in Figure 13) is Darcy's Law:

$$Q = KIA;$$

where Q is discharge per unit time; K is hydraulic conductivity of the fractured Hydrogeologic Unit; I is dH/dL or hydraulic gradient (change in head H over a distance L); and A is cross-sectional area. Q will be the groundwater input/inflow into the water budget that is derived from the upper La Sal Mountain subsystems. K is determined by aquifer tests, which reveal a range of values that average approximately 50 ft/day for shallow fractured bedrock in the PWB area (Sunrise Engineering, 2002*)*. Hydraulic gradient is determined using the topographic gradient between MC01 and MC04 in Figure 13 (Blanchard 1990) of 0.086. The cross-sectional area to calculate groundwater underflow flux is estimated as the geometry of the fractured Glen Canyon aquifer French drain: 500 ft depth (from well measurements) and 100 ft width (from topographic data). As the value of K decrease with depth to a very low value at 500 ft, an average K value for the underflow component of the PWB of 25 ft/day is used This results in a groundwater underflow flux (inflow) of 901 ac-ft/yr (Tables 1a and 1b).

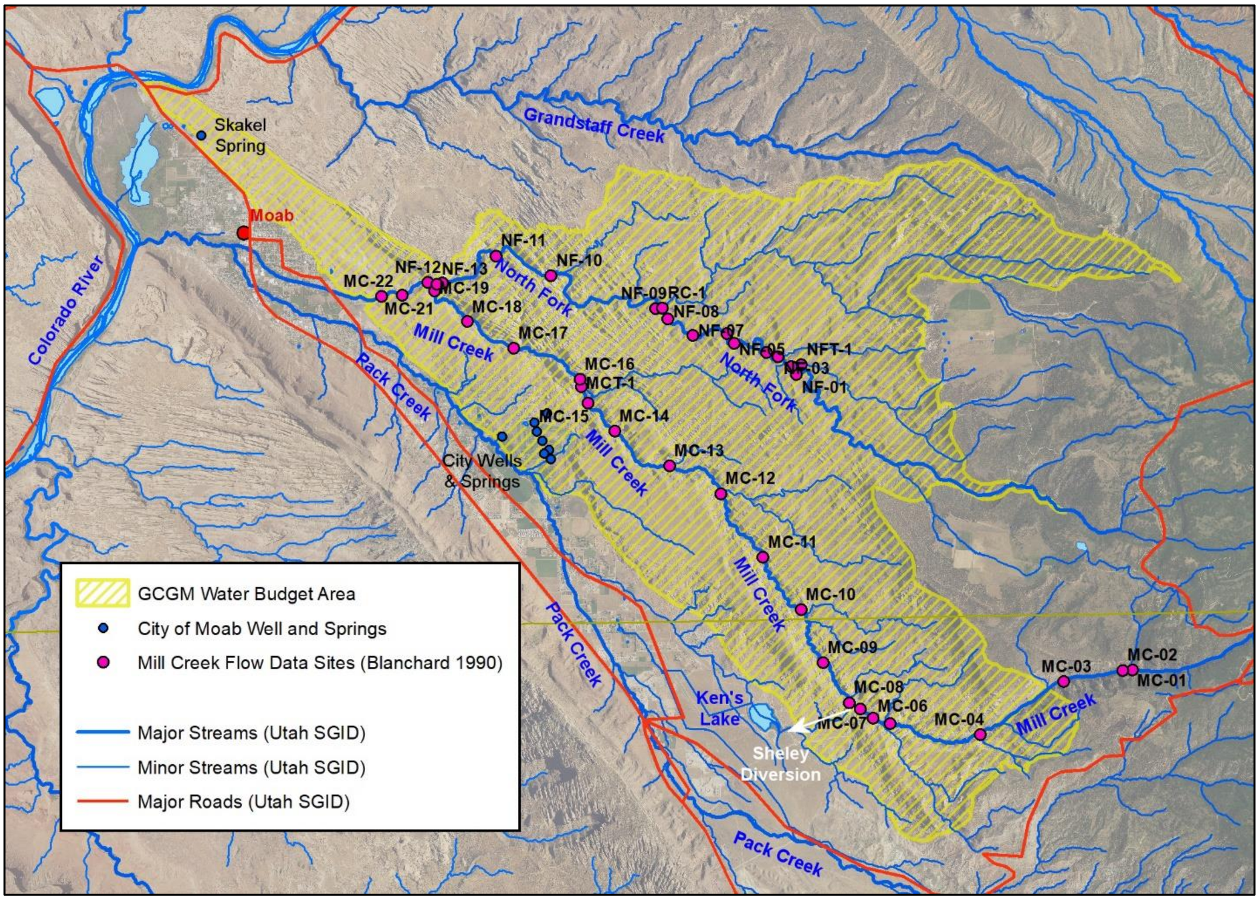

Figure 13. Map showing the location of Preliminary Water Budget (PWB) area and the location of the discharge stations as published by Blanchard (1990).

3.6 Calculation of Mill Creek Surface Water Inflow and Outflow

There are three datasets available for the calculation of the Mill Creek inflow and outflow components: 1) a dataset published by Blanchard (1990) concerning flow rates measured at various locations along Mill Creek and North Fork on October 21, 1985 and October 14, 1986; 2) daily gage readings by the USGS at USGS 09183500 just above the current Sheley diversion (1954-present with a gap from 1958 through 1987) (located at MC07 in Figure 13) and at USGS

09183600 below the Sheley diversion (2003-present) (MC08 in Figure 13); and 3) daily gage readings by the USGS at USGS 09184000 in the vicinity of MC21 in Figure 13 (period 1949-1993). The average annual flow at gage 09183500 for the period of record is 7546 ac-ft/yr; in the absence of data for the period 1958-1987, this long-term average is used in the pre-development PWB as a first approximation (Table 1a). The average annual flow at gage 09183600 for the period of record is 3084 ac-ft/yr. The average annual flow at gage 09184000 for the period o1949-1980 is 9928 ac-ft/yr, and for the period 1981-1993 9020 ac-ft/yr (Tables 1a and 1b)

The effect of the Sheley diversion on flows in Mill Creek is analyzed for the period 2004-2017 using the 2 USGS gages. The average annual discharge at gage 09183500 for this period is 6814 ac-ft/yr, while the average annual discharge at gage 09183600 for the same period is 3149 ac-ft/yr, a difference of 3665 ac-ft/yr or 54% of the discharge at gage 09183500. This is the average annual amount of water taken out of the GCMC hydrologic system at the Sheley diversion. The latter two terms have been used in the post-development PWB (Table 1b). Note that the average annual flow at gage 09183500 for the period 2004-2017 is 732 ac-ft/yr less than for the entire period of record 1954-2017 (minus data gap), a decline of about 10%.

The stream flow data given by Blanchard (1990) are used to obtain insight in the relative flows along Mill Creek between the Sheley diversion and the outflow into Spanish Valley at the Mill Creek delta during low flow or base flow conditions. The Blanchard (1990) data reflect the post-development conditions. According to Blanchard (1990), the discharge at measuring site MC 08 below the Sheley Diversion on October 21, 1985 was 3.99 cfs, while at the same date the flow at MC19 (above the confluence with North Fork, Figure 13) was 3.21 cfs, a loss of about 20%. According to the October 14, 1986 data, North Fork contributed 3.73 cfs and Mill Creek MC19 at 3.09cfs to downstream flows, a 55% and 45% share respectively. Applying the 20% flow reduction along Mill Creek above the confluence with North Fork on the average annual pre-development discharge at MC07 of 7546 ac-ft/yr gives a flow of 6037 ac-ft/yr just above the confluence with North Fork. This, together with the contribution from North Fork of about 2890 ac-ft/yr, results in a pre-development average annual outflow at Mill Creek delta near the Powerhouse of about 8927 ac-ft/yr. In a similar approach, post-development outflow at Mill Creek delta/Powerhouse is calculated as 0.8 * 3084 (flow at MC08) + 2850 (North Fork contribution reduced by climate change between pre- and post-development) = 5317 ac-ft/yr. Comparing these calculations with the measured values at USGS gage 09184000 show that under base flow conditions significant less water exits the GCMC hydrologic system at the Mill Creek delta than under spring flow and intense storm runoff conditions.

3.7 Calculation of Consumptive Use by Riparian Vegetation

Muckel and Blaney (1945), Mayboom (1964), and Gatewood and others (1950) determined that riparian vegetation (notably Cottonwoods, Willows, and Tamarisk) had consumptive use ranging from 40 – 93 in/year depending upon percentages of each species present, the healthiness or stress level of the vegetation, and the location in the ecosystem (seeps, springs, stream bottoms and floodplains). A recent study by Crowley (2004) on the Matheson Wetland Preserve located by the City of Moab inventoried the published data regarding consumptive use of riparian vegetation in the Moab, Utah area, and calculated consumptive use of vegetation at that location. For the purposes of calculating the preliminary water budget of the GCMC hydrologic system, Muckel and Blaney's (1945) mixed riparian category of 60 – 92.7 in/year was used to calculate the Phreatic Consumptive Use Low estimates (60 in/yr) and the Phreatic Consumptive Use High estimates (92.7 in/yr) for the Hydro Zone Type 1 Phreatophyte areas as digitized from recent aerial photography. This resulted in a range of 4009-6193 ac-ft/yr. Taking the increased stresses on water availability for the riparian vegetation into consideration, the average value of 5101 ac-ft/yr is used in the PWB (Tables 1a and 1b, Appendix A).

3.8 Calculation of Spring Discharge

The values for GCMC hydrologic springs were collected from the Utah State Division of Water Rights database as being the maximum sustained amounts produced by each spring (Utah State Water Rights Data Base, 2017, 2018; Appendix B). The pre-development runoff from these springs was GCMC groundwater output that flowed directly into the Pack Creek hydrologic system (PCLA) as input to the PCLA water budget. There may be springs and seeps that are not accounted for as they are not registered in the water rights data base. For the PWB, the City's springs at the golf course were excluded; for the Skakel Spring only the overflow was taken into account. It should be noted that post-development spring discharge has likely declined due to the Sheley diversion in Mill Creek, but less than the decline in Mill Creek flows as there is a significant local contribution to spring flow from infiltrated precipitation. As a first approximation, it is assumed that the post-development springs and seeps discharge was reduced by 20%.

3.9 Calculation of City of Moab Municipal Use (City Springs and Wells)

The values for City of Moab Municipal Use, including the Moab City Springs and Wells and Skakel Spring for the period 1978-2013 were obtained from the City of Moab Engineering Department. These data indicate an average pre-development municipal use of about 1364 ac-ft/yr and an average post-development municipal use of 1875 ac-ft/yr (Tables 1a and 1b). During pre-development time, excess runoff from the City springs was GCMC groundwater output that flowed directly into the Pack Creek hydrologic system (PCLA). Note that the City of Moab's municipal use has been increasing gradually and has been in recent years on average over 2200 ac-ft/yr. The PWB uses a lower number as it is averaged over a longer period; the recent increase in municipal use may have resulted in further lowering the terms for the springs outflow, Mill Creek outflow, and consumptive use by riparian vegetation from what is listed in Table 1b.

3.10 Calculation of Domestic Consumptive Use

Domestic consumptive use in the GCMC hydrologic system has three factors: 1) household wells; 2) domestic/irrigation/stock water wells; and 3) large irrigation wells. These wells are listed in the Utah State Water Rights Division database (Appendix B). Each consumptive use is estimated separately and combined as one consumptive use amount.

The Ford (2006) report, referring to the data collected in the mid-1990s by Ford and Grandy in the Castle Valley area, determined a domestic use of 0.42 ac-ft/yr per household and the presence of 150 full-time households resulting in 63 ac-ft/yr (1996). In the GCMC hydrologic system, there are about 100 household wells resulting in approximately 40 ac-ft/yr post development. It was estimated that 2/3 of these wells were in production pre-development.

From the UDWR database, there are 20 domestic use/irrigation/stock water wells post-development for up to 50 ac-ft/yr post-development consumptive use (2/3 pre-development). There are also 10 larger irrigation wells post-development for 30 ac-ft/yr (2/3 pre-development). In total, the domestic consumptive use based on the UDWR data is 80 ac-ft/yr pre-development, and 120 ac-ft/yr post-development (Tables 1a and 1b). Note that these consumptive use numbers are a first estimate of actual consumptive use.

3.11 Preliminary Pre-Development and Post Development Water Budgets for the GCMC Hydrologic System

The report presents a preliminary pre-development water budget and a preliminary post-development water budget as discussed in section 3.3. In each PWB, the difference between the calculated and estimated inputs and the calculated and estimated outputs is the PWB closing or balancing term. In the pre-development scenarios, this closing term represents the term for direct runoff to streams and amounts to 4842 ac-ft/yr (Table 1a). The post-development scenario presented in Table 1b incorporates the Sheley Diversion outtake of 3665 ac-ft/yr, which is approximately 20% of the total yearly budget. This leaves a remainder or deficit (closing term) of 3994 ac-ft/yr that is removed from groundwater storage on an average year. This release from storage may be compensated over time by increased recharge in above average precipitation years, or as increased flow to Mill Creek into the GCMC hydrologic systems due to increased groundwater release in upgradient groundwater systems, or increased runoff from higher than average snowpack. This depletion of storage or mining of groundwater is also a concern for the sustainability of the City's water supply.

3.12 PWB and the GCMC Hydrologic System: Discussion of Uncertainty

There are many uncertainties in these preliminary calculations, so further analysis is needed and should be planned. The primary significance of the PWB is that there is a significant amount of surface water and groundwater contributed to the Mill Creek groundwater and surface water from the La Sal Mountain hydrological systems, or in percentages of pre-development input into the GCMC hydrologic system: surface water (Mill Creek) counts for approximately 42%; local recharge from precipitation and direct runoff from precipitation to streams counts for 53%; and groundwater inflow from the La Sal Mountains hydrological subsystems counts for 5%. This means that the La Sal Mountains subsystems contribute more than 45% of the total inflow in the PWB area. By comparison, in the post development time period, the contribution of groundwater storage to the overall input becomes more of a factor, or in percentages of post development input into the GCMC hydrologic system: surface water (Mill Creek) counts for approximately 31%; local recharge from precipitation and direct runoff to streams for 46%; groundwater inflow from the La Sal Mountains hydrological subsystems counts for 4%; and groundwater released from storage accounts for approximately 19%. Note that the Sheley diversion takes out 20% of the total outflow to the GCMC hydrologic system and has resulted in a 40% reduction of Mill Creek outflows towards Spanish Valley under base flow conditions and 20% reduction of springs and seeps discharge in the most likely scenario.

The reduction of water contributions originating from the La Sal Mountain subsystem in amounts and timing of precipitation (rain and snowfall) and snowmelt resulting from climate change may have a significant impact on stream flows, groundwater recharge and subsurface inflow into the valley. In addition, water diversion projects to other watersheds, especially up-valley, will result in decreased surface water flows and groundwater recharge from losing streams. Impacts on the GCMC water budget may also result from deforestation due to lumbering or fire (increased surface runoff and stream flows); increased forestation (increased ET; decrease of runoff and stream flows); and mining (increased or decreased stream flows and groundwater fluxes). Land use conversions/changes resulting in more or less consumptive uses need to be evaluated regarding the surface water output to Mill Creek at the southeast end of the GCMC hydrologic system. Increased consumptive use would result from increased urbanization (more wells, non-native vegetation) or increased irrigation.

Many of the components of the PWB calculations include large uncertainties. The most reliable data are the USGS stream flow data in Mill Creek at and below the Sheley diversion, the springs and wells production data from the City of Moab, and the precipitation data from NOAA used to develop various recharge scenarios. However, these data sets are not all complete or cover comparable time periods. All other data sets provide a "snap shot" of a particular variable in time as they were gathered at various, non-comparable moments in time and, thus, should be considered a first estimate, subject to refining by further field studies.

Consumptive use by phreatophytes (riparian vegetation) is variable seasonally and annually by changes in species composition, species health, spatial distribution of vegetation, and length of growing season among other factors. An estimate of annual evapotranspiration for a water budget misses the seasonal effects of water usage and water availability, as well as multi-year natural or anthropogenic variations in water availability. However, for the cost and effort, it is difficult to improve on the studies that have been published. A possible follow-up study may focus on the changes over time in riparian vegetation coverage using historical aerial photography between the pre-1980s and later.

Spring discharge measurements are based on State of Utah Water Rights data which allude to the available groundwater that is measured at the source when the water right was secured, often without consideration of seasonal and multi-year variability. The actual daily and seasonal flow of the springs is for the most part unmeasured and may fluctuate significantly. Improvements of the springs related PWB terms may be obtained by more regular measuring of the discharge of some of the larger springs.

Non-City of Moab well discharge data are taken from the State of Utah Water Rights data base and considered maximum allowed discharge. Well water usage depends on the type of usage (residence, secondary home, garden watering, irrigation, livestock water) and may fluctuate on a daily, seasonal, and annual basis. The domestic consumptive use is highly variable, and the data are not available to improve upon this is great detail. It is assumed that post-development domestic use is somewhat higher than pre-development use following the establishment of new housing developments in the PWB area, some of which are drawing entirely on groundwater. However, the domestic consumptive use is small by comparison to other PWB terms.

The City of Moab Springs and Wells data base is extensive, and the patterns of daily and seasonally municipal use are well documented.

The Mill Creek gage data at the Sheley diversion, below the Sheley diversion, and at the Powerhouse near the outflow into Spanish Valley are some of the best and most accurate data available to this study, although the data gap in the pre-1988 record limits the accuracy of comparative evaluations. These hydrologic data sets offer insight in annual, seasonal, and daily variability of stream flows and were used to interpret and modify other useful data, for example Blanchard (1990). It should be noted that for optimal management of the City's water resources resuming of monitoring Mill Creek flows at the abandoned USGS gage site USGS 09184000 near the Powerhouse is crucial.

Concurrently, the climate data used to estimate groundwater recharge as infiltration for precipitation (rain and snow, matrix and fracture zone) is some of the best and most accurate data available to this study, although somewhat limited by the overlapping of the 30-year climate periods available in spatially distributed format.

3.13 PWB and the GCMC Hydrologic System: Concerns Regarding Sustainability

There are a number of potential threats to the sustainability of the GCMC hydrologic system and thus to the water supply of the City of Moab, both natural and man-made. Climate change may reduce water contributions originating from the La Sal Mountain subsystem, both in amounts and timing. In addition, water diversion projects to other watersheds, especially up-stream of the GCMC hydrologic system, will result in decreased surface water flows and groundwater recharge from losing streams. Impacts on the GCMC hydrologic system may also result from deforestation due to lumbering or fire (increased unchanneled surface runoff and stream flow peaks, and decreased stream base flow); increased forestation (increased ET; decrease of runoff and stream flows); and mining (increased or decreased stream flows and groundwater fluxes). Land use conversions/changes resulting in more or less consumptive uses need to be evaluated regarding the surface water output to Mill Creek at the southeast end of the GCMC hydrologic system. Increased consumptive use would result from increased urbanization (more wells, non-native vegetation), or increased irrigation. Any long term decline in inflows to the GCMC hydrologic system will result in further decline of outflows such as at Mill Creek near the Powerhouse and various springs, and will likely lead to decline in storage and subsequent lowering of groundwater levels and groundwater availability for phreatic consumption.

3.14 PWB and the GCMC Hydrologic System: Recommendations for Monitoring and Modelling

Based upon associated uncertainties with estimates, the greatest cost-effective improvements to the PWB, primarily post-development, is better monitoring of the Mill Creek surface water system. Gaging stations at Blanchard's stations MC03, MC07 (USGS 09183500 just above the current Sheley diversion), MC08 (USGS 09183600 below the Sheley diversion), MC 14 (above City Wells and Springs), MC15 (below City Wells and Springs), MC 21 (above Skakel protection zone), and MC22 (below Skakel protection zone) that recorded daily, seasonal, and annual information would improve the measurements of the City of Moab protected areas. Water quality measurements would be recommended at these sites as well. In addition, continued monitoring of City Springs and Wells, including Skakel Spring, for daily, seasonal, and annual information regarding flow and water usage is recommended. An analysis of this and the data currently available, in addition to continued analysis of the climate data compared to the City Springs and Wells, and Skakel Spring, is recommended as a future part of this study.

Mathematical groundwater modelling using the USGS Finite Difference MODFLOW Model or other integrated finite difference or finite element groundwater or groundwater/surface water models has been proposed in the past to quantify the GCMC hydrologic system. This study estimates both pre-development (steady state) and post-development (transient) water budgets that would be useful for the calibration of these types of models. Phase 1 of the current study, HESA of the GCMC hydrologic system, provides a surface water and groundwater conceptual model that would be useful for the design, implementation, and calibration for these types of models. However, the HESA revealed that the GCMC groundwater system was complex being both matrix and fracture-type flow, and that the design, implementation, and calibration of this type of model is neither practical nor cost-effective at this time. Given the uncertainties with the data available, the results would tend to be questionable and non-defendable. A more practical and defendable mathematical groundwater model would focus on the Spanish Valley aquifer system. The PWB of the GCMC groundwater system would provide inputs into that model, and the HESA of the GCMC groundwater system would provide boundary conditions for that model.

WATER BUDGET COMPONENT	IN (ac-ft/yr)	OUT (ac-ft/yr)
Direct runoff to streams Closing term (sections 3.4)	4842	-
Recharge Calculated (section 3.4, appendix A)	5509	-
Groundwater underflow at upper Mill Creek boundary (inflow through Mill Creek fracture zone) Calculated (section 3.5)	901	0
Mill Creek inflow above later location of Sheley diversion Using USGS gage USGS 09183500 data (section 3.6)	7546	-
Irrigation return flow + septic tank infiltration	0	-
Consumptive use crops	-	0
Consumptive use riparian vegetation Calculated (section 3.7, appendix A)	-	5101
Springs at PWB boundaries (excluding City Springs, including Skakel overflow) Estimated (section 3.8)	-	2325
Municipal use City Springs & Wells data from Moab City (section 3.9)	-	1364
Domestic consumptive use Estimated (section 3.10)	-	80
Sheley diversion	-	0
Mill Creek outflow at delta Using gage USGS 09184000 for period 1949 -1980 (section 3.6)	-	9928
Subtotals	18798	18798
Change of storage (Release from groundwater reservoir storage) Naturally balanced system	0	-
TOTALS	18798	18798

Table 1a. Preliminary pre-development water budget estimates for PWB area.

WATER BUDGET COMPONENT	IN (ac-ft/yr)	OUT (ac-ft/yr)
Direct runoff to streams From Table 1a corrected for lower precipitation (0.96 x pre-development) (section 3.4)	4648	-
Recharge Calculated (section 3.4, appendix A)	5284	
Groundwater underflow at upper Mill Creek boundary (inflow through Mill Creek fracture zone) Calculated (section 3.5)	901	-
Mill Creek inflow above Sheley diversion Using USGS gage 09183500 data (section 3.6)	6814	-
Irrigation return flow + septic tank infiltration	0	-
Consumptive use crops	-	0
Consumptive use riparian vegetation Calculated (section 3.7, Appendix A)	-	5101
Springs at PWB boundaries (excluding City Springs, including Skakel overflow) Estimated (section 3.8)	-	1860
Municipal use City Springs & Wells data from Moab City (section 3.9)	-	1875
Domestic consumptive use Estimated (section 3.10)	-	120
Sheley diversion Using USGS gage 09183600 data (section 3.6)	-	3665
Mill Creek outflow at delta Using gage USGS 09184000 for period 1981-1993 (section 3.6)	-	9020
Subtotals (deficit)	17647	21641
Change of storage (Release from groundwater reservoir storage) Updated; closing term (section 3.11)	3994	-
TOTALS	21641	21641

Table 1b. Preliminary post-development water budget estimates for PWB area.

4 PRELIMINARY GROUNDWATER STORAGE CALCULATIONS FOR THE GCMC HYDROLOGIC SYSTEM

4.1Groundwater Storage Quantification

Groundwater is potentially stored, either as part of the saturated zone of the aquifer or the unsaturated zone above the aquifer in the pore spaces between the sand grains of unconsolidated eolian, pedogenic, colluvial, or alluvial materials (Qes, Qls, or Qal), in the pore spaces of the sedimentary bedrock, or in the multiple-scale hydrofractures including fractures, fracture zones, bedding planes, faults, or fault zones. Groundwater that is stored in the pore spaces is considered matrix water and may be in considerable amounts in unconsolidated materials (such as the Mill Creek alluvium) or may be in very small amounts in well consolidated bedrock (such as the non-fractured Glen Canyon Group aquifer). Groundwater that is stored in the hydrostructures may be in very small amounts in microfractures or may be in considerable amounts in large scale fracture and faults zones (for example, the Kayenta Fault Zone and the Mill Creek Fracture Zone). Most of the unconsolidated materials that form the Eolian deposits and soils of the Sand Flats area, for example, are unsaturated and the amount of groundwater storage is small. By comparison, the unconsolidated materials in the Mill Creek gorge are saturated, and their storage is significant as indicated by the extensive phreatophyte vegetation that is observed.

There are multiple descriptors of storage in aquifers. Storativity or the storage coefficient is the volume of water released from storage per unit decline in hydraulic head in the aquifer, per unit area of the aquifer. Storativity is a dimensionless quantity, and ranges between 0 and the effective porosity of the aquifer, or the percentage of open space in a unit of rock from which water can be drained under gravity. For a confined aquifer or aquitard, storage is described by specific storage, i.e., the volume of water released from one unit volume of the aquifer under one unit decline in head. Specific storage is related to both the compressibility of the aquifer and the compressibility of the water itself. Volumetric specific storage (or volume specific storage) is the volume of water that an aquifer releases from storage, per volume of aquifer, per unit decline in hydraulic head (Freeze and Cherry, 1979).

In hydrogeology, volumetric specific storage is much more commonly encountered than mass specific storage. Consequently, the term specific storage generally refers to volumetric specific storage. The compressibility terms relate a given change in stress to a change in volume. Specific yield, also known as the drainable porosity, is a ratio, less than or equal to the effective porosity, indicating the volumetric fraction of the bulk aquifer volume that a given aquifer will yield when all the water is allowed to drain out of it under the forces of gravity. Specific yield is primarily used for unconfined aquifers since the elastic storage component is relatively small and usually has an insignificant contribution. Specific yield can be close to effective porosity, but there are several subtle things which make this value more complicated than it seems. Some water always remains in the formation, even after drainage; it clings to the grains of sand and clay in the formation. Also, the value of specific yield may not be fully realized for a very long time, due to complications caused by unsaturated flow.

4.2 Approach and Calculation of Groundwater Storage for the Glen Canyon Group Aquifer

The Glen Canyon Group Aquifer is a complex mix of nonfractured, fractured and faulted Entrada Sandstone (Je) and Glen Canyon Group Formations (Navajo, Kayenta, Wingate; Jgc), Eolian Sand (Qes), and hydrostructures (fault and fracture zones) which form the robust groundwater system supporting the GCMC hydrologic system. The Glen Canyon Group bedrock has both matrix flow and fracture flow. The matrix flow has ranges estimated from 0.3 – 1.0 ft/day (Jobin, 1962; Blanchard, 1990; Lowe and others, 2007); and the fracture flow can be as high as 88 ft/day (Freethey and Cordy, 1991). Therefore, fracture flow will dominate travel times and will also be most important for estimating groundwater storage.

The Glen Canyon Group groundwater system is mostly unconfined or water table conditions and is characterized with specific yield estimates. The Glen Canyon Group bedrock has both matrix specific yield (small) estimates and fracture specific yield (large) estimates. The matrix specific yield estimates range from 1.0 – 10%; the fracture flow specific yield estimates range from 10 – 40% (Appendix A). Therefore, fracture flow areas will be most important for estimating groundwater storage and will be the areas that need the most protection for water quality and water quantity.

The GCMC groundwater system is classified as four different hydro zone types of storage based on the hydrogeology and hydrostructures identified (see Figures 10a, 10b and 12 for hydro zone location): 1) Zone 2: Riparian Fracture Zone (High-K zone), fractured canyon storage, area variable, depth 500 feet (well log based), specific yield (Sy) range 20% – 40%; 2) Zone 3: Matrix, matrix storage, area variable, depth less than 100 feet except two areas 300 feet, specific yield (Sy) range variable with area 1% - 10%, 10%-20%, 20%-40%; 3) Zone 4: (Riparian) Dry Wash, fractured canyon dry wash storage, area variable, depth ranges from 300 feet – 500 feet, specific yield (Sy) range 20% - 40%; and 4) Zone 5: Fracture Enhanced Matrix, fracture enhanced matrix storage, area variable, depth ranges from 300 feet – 500 feet, specific yield (Sy) range 20% -40% (Appendix A). Low variable storage was estimated using low Sy percentages as a minimum, and high variable storage was estimated using the high Sy percentages as a maximum. Each hydro zone had an estimated volume (GIS area multiplied by depth), and the hydro zone volume was multiplied by the hydro zone Sy to yield a hydro zone storage value (Appendix A).

The calculations show that the GCMC groundwater system has a variable storage low of 153,144 ac-ft, and a variable storage high of 306,288 ac-ft (Appendix A). Hydro zones 2 and 5 (Figures 10a, 10b and 12) had the largest amount of storage with 38,835/77,670 ac-ft and 60,759/121,518 ac-ft respectively. These hydro zones are located along the critical groundwater flow paths that directly affect the yields and water quality of Skakel Spring, and the City of Moab Springs and Wells (Figures 10a and 10b). The earlier City of Moab Springs and Well Protection Plans previously identified these hydro zones as critical (Figure 1), and an update to these plans will be completed in Phase 3 of this project.

In Section 3.11, the post-development water budget scenarios presented in Tables 1b and 2b incorporate the Sheley Diversion outtake of 3665 ac-ft/yr, and shows a deficit of 1249 ac-ft/yr that is removed from groundwater storage on an average year. This amounts to about a 0.8% reduction of variable storage low, and 0.4% reduction of variable storage high per year at the current water use. Given the margin of error, this suggests that under the current water usage, the City of Moab is not significantly impacting the storage of the GCMC hydrologic system.

It should be cautioned that the storage or underground reservoir is primarily a measure of how robust and sustainable the GCMC hydrologic system is under the current climatic and human use conditions. If the reservoir is significantly reduced by aquifer development, the hydraulics of the system will be affected initially by stream flows (riparian habitat both aquatic and vegetation), and by a rapid reduction of spring flows and well yields. In addition, the effects of reduced stream flows in Mill Creek through diversion or climate change will rapidly affect the recharge and storage functions of hydro zones 2 and 5, which are critical to Skakel Spring, and the City of Moab Springs and Wells.

4.3 Storage and the GCMC Hydrologic System: Discussion of Uncertainty

There are many uncertainties in these preliminary calculations, so further analysis is needed, benefitting from more rigorous and continuous data collection. The primary significance of the storage calculations is that there is a significant amount of groundwater stored in the GCMC hydrologic system, particularly in hydro zones 2 and 5, that is directly connected to the City of Moab Wells and Springs, and the Skakel Spring. This storage is accumulated by groundwater recharge from infiltration of precipitation, and by losing reaches of Mill Creek, particularly in hydro zones 2 and 5.

The largest uncertainties in the storage calculations is the correct delineation of each hydro zone area (volume), and the correct attribution of specific yield to each hydro zone. In order to reduce uncertainty, Specific yield ranges were assigned to each hydro zone based on published results of other studies, and hydrogeologic judgement by the investigators.

Basically, the pre-development PWB represents a stable system that is equilibrated between inputs and outputs, and may have short-term deficits alleviated by decline in storage which in turn is replenished in wet years. The post-development PWB shows a long-term deficit which is compensated by a continuous release from storage, which may eventually, or may not at all, be compensated by extra recharge in wet years. It should be noted that the decline in storage is not equally distributed across the PWB area and may focus on the area of pronounced withdrawals.

5. CONCLUSIONS

This report presents the findings of Phase 2 of a 3-phase project focused on improving the understanding of the hydrogeological setting of the water supply sources for the City of Moab, the quantification of the water resources available to the City, and updating the City springs and wells protection against contamination. In Phase 1, a Hydrologic and Environmental System Analysis (HESA) of the Mill Creek and Pack Creek watersheds was performed to identify the hydrological systems of specific importance to the sustainability of the Moab City springs and wells as water supply for the City. It was concluded that the City's water supply was mainly dependent on the hydrologic system formed by the Mill Creek Watershed and the Glen Canyon aquifer underlying the Sand Flats region, including Johnson-on-the-Top. This hydrologic system, referred to as the Glen Canyon Group - Mill Creek (GCMC) hydrologic system, was chosen in Phase 2 of the project as the setting for the quantification of the water resources available to the City, resulting in a preliminary global water budget of the entire GCMC hydrologic system. It is a preliminary water budget as there are many uncertainties with respect to the determination of the individual components given the sparseness of relevant published data.

In order to estimate the upper bounds of the water resources present in the GCMC hydrologic system, a preliminary (global) water budget (PWB) has been developed for the entire GCMC hydrologic system, focused on the external inputs (inflows) and outputs (outflows). In addition, an analysis was made of the storage capacity of the Glen Canyon aquifer in the PWB area. The delineation of the PWB area is based, among others, on the location of City of Moab springs and wells, the location of stream gages in Mill Creek, the location of the Sheley diversion, and the natural boundaries of the GCMC hydrologic system, and covers almost the entire GCMC hydrologic system as determined in the HESA of Phase 1. It is bounded by the Glen Canyon Group - Grandstaff Creek (GCGC) hydrologic system to the north; the low permeability Morrison Formation to the east and southeast; and the Pack Creek - Lower Alluvium (PCLA) hydrologic system to the west and southwest.

There are two distinct periods of anthropogenic stresses in the GCMC hydrologic system: 1) pre-1980s; and 2) from early 1980s until present. During the pre-1980s, limited municipal, domestic and irrigation demand kept most of the hydrologic system of the Sand Flats region in its natural state, a period that in this report is referred to as the pre-development phase. In the early 1980s, the opening of the Sheley diversion, together with the initiation of a rather steady increase in municipal and domestic water use, represented a significant increase in the anthropogenic withdrawals from the GCMC hydrologic system, which continues to the present day. This latter period is referred to as the post-development phase. A preliminary water budget has been developed for each of these two stress periods.

The pre-development GCMC water budget has as inputs: 1) Groundwater recharge by infiltration of precipitation (rain and snowmelt) across the entire GCMC area; 2) Direct runoff of precipitation across the rock surface to streams within the PWB area; 3) Groundwater underflow along the Mill Creek fracture zone at the USGS streamflow gage in Mill Creek; and 4) Mill Creek inflow at the point of entry to the GCMC hydrologic system at the USGS streamflow gage. GCMC water budget outputs are: 1) Consumptive use by riparian vegetation (cottonwoods, willows, tamarisk, and other riparian species) along Mill Creek and tributaries; 2) Springs on the Kayenta Fault Zone (including Skakel); 3) Municipal water use (City of Moab springs and wells at the golf course); 4) Domestic consumptive use (private wells); and 5) Mill Creek outflow into the northern end of Spanish Valley downstream from the Powerhouse. The post-development GCMC water budget has the same type of inputs as the pre-development water budget, but has an additional outflow term, the Sheley diversion, resulting in significant decreases in PWB outflow components, such as spring flow and Mill Creek outflow to Spanish Valley near the Powerhouse.

Using the precipitation data sets for the 1971-2000 and 1981-2010 for the GCMC area a series of potential recharge scenarios have been evaluated based on detailed knowledge of the hydrogeology. In addition, consumptive use by riparian vegetation was varied within the range provided by earlier studies. The presented pre- and post-development PWBs are based on the most likely recharge and consumptive use by vegetation scenarios. According to the post-development scenario, the Sheley diversion represents approximately 20% of the yearly water budget. As a result of the diversion to Ken's Lake, the preliminary post-development water budget calculations show a deficit of 3994 ac-ft/yr or about 19% of the total PWB, representing the amount of water removed from groundwater storage in an average year. This release from storage may be compensated over time by increased recharge during above average precipitation years, or by recharge from Mill Creek (losing stretches) into the GCMC aquifer due to increased runoff in upgradient stretches of Mill Creek from larger than normal snowpack, but is a concern for the sustainability of the City's water supply.

The PWB shows that there is a significant amount of water contributed to the GCMC hydrologic system from the La Sal Mountain hydrological systems as surface water through the upper reaches of Mill Creek, or in percentages of pre-development input into the PWB area: surface water (inflow into Mill Creek from La Sal Mountain system) counts for approximately 42%; local recharge from precipitation and direct runoff to streams within the PWB area counts for 53%; and groundwater underflow counts for about 5%. The PWBs also show a total multi-year, annually averaged inflow into the GCMC hydrologic system of about 17647 ac-ft.

Any decline in upstream total average flows in Mill Creek from natural or man-made causes will have an immediate and significant impact on the various outflows of the GCMC hydrologic system and poses a potential threat to the sustainability of the City of Moab's water supply.

Many of the components of the PWB calculations include large uncertainties. The most reliable data are the USGS stream flow data in Mill Creek at and below the Sheley diversion, the springs and wells production data from the City of Moab, and the precipitation data from NOAA used to develop various recharge scenarios. All other data sets provide a "snap shot" of a particular variable in time as they were gathered at various, non-comparable moments in time and should be considered a first estimate, subject to refining by further field studies. Climate data can be refined by limiting the pre-development climate data set from the period 1971-2000 to the period 1971-1980. This also provides more insight in the effects of climate change on the GCMC water budget. Another area where significant cost-effective improvements to the PWB can be made, is more detailed and frequent monitoring of the Mill Creek surface water system, specifically in the vicinity of the Moab City wells and springs and above and below the area where the Skakel source protection zone intercedes Mill Creek. Finally, more detailed monitoring of selected, "representative" springs, both to the north and south of the Mill Creek delta, should be initiated to obtain an indication of the relationships over time between spring discharge, climate variations, and Mill Creek runoff, as well as an insight in the resilience of the GCMC hydrologic system to external stresses.

The Glen Canyon Group groundwater system is mostly unconfined, i.e., having a readily fluctuating water table, and the aquifer storativity is characterized by so-called specific yield. The Glen Canyon Group bedrock has both matrix specific yield (small) and fracture specific yield (large). The matrix specific yield estimates range from 1.0 – 10.0%; the fracture specific yield estimates range from 10.0 – 40.0%. As there is a significant presence of fracture zones in the GCMC system, fractures are the dominant feature in determining available groundwater storage. The results of GIS-based calculations show that the GCMC groundwater system has a storage minimum of about 153,000 ac-ft, and a storage maximum of about 306,000 ac-ft, indicating significant uncertainty in the actual storage available in the GCMC groundwater system. Areas along the groundwater flow paths that directly affect the yields and water quality of Skakel Spring, and the City of Moab springs and wells at the golf course, have the largest amount of storage. The current City of Moab source protection plans identify these hydro zones as critical.

It should be noted that only a part of this global water budget is available to the City's springs and wells based on hydrologic, hydraulic and technical considerations, and it may be further restricted by water rights considerations, such as those pertaining to the Sheley diversion to Ken's lake. For example, a significant part of the groundwater recharge and direct runoff in the North Fork Mill Creek area only benefits Skakel Spring and adjacent springs and is not available to the current set of City's wells and springs at the golf course. This may involve up to 30% of the recharge and direct runoff term for the entire PWB area. Therefore, a preliminary estimate of the amount of water in the GCMC hydrologic system accessible to the City of Moab is about 6,000 to 7,000 ac.ft/yr.

There is little control on consumptive use by riparian vegetation apart from removing it. Spring flows are dependent primarily on groundwater flow gradients, which in turn are determined primarily by recharge from precipitation and losing stream reaches. As there is no control on the amount of precipitation, ensuring sufficient year round stream flows is crucial (esp. in Mill Creek). Production increase at the City wells is limited by permeability and drawdown constraints; additional water resources may be accessed by new wells in GCMC system or diversions from streams.

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APPENDIX A. RECHARGE, CONSUMPTIVE USE BY RIPARIAN VEGETATION, AND STORAGE CALCULATIONS FOR HYDRO ZONES IN THE PWB AREA OF THE GCMC HYDROLOGIC SYSTEM

OBJECTID (from GIS)	Name	Hydro Type	Area (GIS) Acres	Hydro Function	Sub-Category	Average Annual Precipitation (GIS) 1971-2000 Inches	Average Annual Precipitation (GIS) 1971-2000 Acre-ft	Average Annual Precipitation (GIS) 1981-2010 Inches	Average Annual Precipitation (GIS) 1981-2010 Acre-ft	Phreatic Consumptive Use in/yr	Depth ft	K ft/day	Sy %	Recharge % of Precip	Recharge 1971-2000 Low Acre-ft/yr	Recharge 1971-2000 Best Estimate Acre-ft/yr	Recharge 1971-2000 High Acre-ft/yr	Recharge 1981-2010 Low Acre-ft/yr	Recharge 1981-2010 Best Estimate Acre-ft/yr	Recharge 1981-2010 High Acre-ft/yr	Phreatic Consumptive Use Low Acre-ft/yr	Phreatic Consumptive Use Average Acre-ft/yr	Phreatic Consumptive Use High Acre-ft/yr	Total Water Content Low Acre-ft	Total Water Content High Acre-ft	Variable Storage Low Acre-ft	Variable Storage High Acre-ft
24	Buck Holder Draw	1	278	Discharge	Phreatophytes, Gaining Stream Reaches	15 - 19	372	16	370	60 - 92.7	25 - 30										1389	1767	2146			0	0
29	Mill Creek Middle	1	286	Discharge	Phreatophytes, Gaining Stream Reaches	9 - 27	641	9 - 26	620	60 - 92.7	25 - 30										1429	1818	2207			0	0
46	Rill Creek	1	56	Discharge	Phreatophytes, Gaining Stream Reaches	15 - 17	71	14 -16	69	60 - 92.7	25 - 30										281	357	434			0	0
54	Mill Creek Lower	1	12	Discharge	Phreatophytes, Gaining Stream Reaches	9	9	9	9	60 - 92.7	25 - 30										61	78	94			0	0
56	North Fork - Mill Creek	1	170	Discharge	Phreatophytes, Gaining Stream Reaches	9 - 15	175	9 - 15	165	60 - 92.7	25 - 30										850	1081	1313			0	0
5	Rill Creek	2	152	Recharge, Storage	Fractured Canyon Recharge and Storage, Phreatophyte Discharge	15 - 17	193	14 - 16	186		300	10 to 50	20 - 40	10 to 30	19	39	58	19	37	56				9110	18220	911	1822
10	Buck Holder Draw	2	1616	Recharge, Storage	Fractured Canyon Recharge and Storage, Phreatophyte Discharge	13 - 19	2091	12 - 20	2056		300	10 to 50	20 - 40	10 to 30	209	418	627	206	411	617				96984	193968	9698	19397
12	Mill Creek Middle	2	1354	Recharge, Storage	Fractured Canyon Recharge and Storage, Phreatophyte Discharge	9 - 27	2259	9 - 26	2179		500	50	20 - 40	10 to 30	226	452	678	218	436	654				135430	270860	13543	27086
26	North Fork - Mill Creek	2	1387	Recharge, Storage	Fractured Canyon Recharge and Storage, Phreatophyte Discharge	9 - 17	1470	9 - 16	1408		500	50	20 - 40	10 to 30	147	294	441	141	282	422				138717	277434	13872	27743
53	Mill Creek Lower	2	81	Recharge, Storage	Fractured Canyon Recharge and Storage, Phreatophyte Discharge	9	61	9	61		500	50	20 - 40	10 to 30	6	12	18	6	12	18				8108	16216	811	1622
33	JUOT South	3	2517	Recharge, Storage	Matrix Recharge and Storage	11 - 13	2417	10 - 12	2327		less than 100	1 to 10	10 to 20	10 to 20	242	483	483	233	465	465				25173	50346	2517	5035
35	Kayenta F/F Zone Middle East	3	431	Recharge, Storage	Matrix Recharge and Storage	9 - 11	358	9 - 10	338		less than 100	1 to 10	10 to 20	10 to 20	36	72	72	34	68	68				4309	8617	431	862
38	Matrix	3	4029	Recharge, Storage	Matrix Recharge and Storage	13 - 16	4630	12 - 16	4468		300	10 to 50	20 - 40	10 to 20	463	926	926	447	894	894				241730	483461	24173	48346
57	Matrix	3	711	Recharge, Storage	Matrix Recharge and Storage	11 - 15	763	11 - 14	727		less than 100	0.1 to 1.0	1.0 - 10	10	76	76	76	73	73	73				7111	14221	711	1422
58	Matrix	3	3230	Recharge, Storage	Matrix Recharge and Storage	15 - 16	4106	13 -15	3871		less than 100	0.1 to 1.0	1.0 - 10	10	411	411	411	387	387	387				32300	64600	3230	6460
60	Burk Holder Draw - Mesa	3	100	Recharge, Storage	Matrix Recharge and Storage	17 - 19	150	17 - 18	146		less than 100	0.1 - 1.0	1.0 - 10	10	15	15	15	15	15	15				995	1990	100	199
61	Matrix - Upper system	3	481	Recharge, Storage	Matrix Recharge and Storage	13 -17	601	13 - 16	584		300	10 to 50	20 - 40	10 to 20	60	120	120	58	117	117				28880	57761	2888	5776
63	FEM Southwest	3	822	Recharge, Storage	Matrix Recharge and Storage	11 - 13	890	11 - 13	838		less than 100	0.1 - 1.0	1.0 - 10	10	89	89	89	84	84	84				8216	16432	822	1643
3	Rill Creek	4	315	Recharge, Storage	Fractured Canyon, Dry Wash Recharge and Storage	11 - 15	332	11 - 14	315		500	50	20 - 40	10 to 30	33	66	100	32	63	95				31471	62942	3147	6294
9	North Fork - North	4	27	Recharge, Storage	Fractured Canyon, Dry Wash Recharge and Storage	11	24	10	22		300	10 to 50	20 - 40	10 to 30	2	5	7	2	4	7				1594	3187	159	319
11	Buck Holder Draw	4	54	Recharge, Storage	Fractured Canyon, Dry Wash Recharge and Storage	13 - 15	64	13 - 14	61		300	10 to 50	20 - 40	10 to 30	6	13	19	6	12	18				3234	6468	323	647
27	North Fork - Mill Creek	4	1163	Recharge, Storage	Fractured Canyon, Dry Wash Recharge and Storage	13 - 19	1440	12 -21	1396		300	10 to 50	20 - 40	10 to 30	144	288	432	140	279	419				69781	139562	6978	13956
30	Mill Creek Middle	4	99	Recharge, Storage	Fractured Canyon, Dry Wash Recharge and Storage	13	107	11 - 12	99		500	50	20 - 40	10 to 30	11	21	32	10	20	30				9911	19822	991	1982
59	North Fork - Mill Creek	4	745	Recharge, Storage	Fractured Canyon, Dry Wash Recharge and Storage	15 - 17	936	14	869		300	50	20 - 40	10 to 30	94	187	281	87	174	261				44688	89375	4469	8938
62	Dry Wash - Upper system	4	435	Recharge, Storage	Fractured Canyon, Dry Wash Recharge and Storage	13 - 15	476	12 -14	475		300	10 to 50	20 - 40	10 to 30	48	95	143	48	95	143				26108	52215	2611	5222
8	FEM Northeast	5	1140	Recharge, Storage	Fracture Enhanced Matrix Recharge and Storage	9 - 11	1014	9 - 11	965		300	10 to 50	20 - 40	10 to 30	101	203	304	97	193	290				68390	136781	6839	13678
32	Kayenta F/F Zone South	5	443	Recharge, Storage	Fracture Enhanced Matrix Recharge and Storage	11	406	10 - 11	384		500	50	20 - 40	10 to 30	41	81	122	38	77	115				44341	88682	4434	8868
34	Springs, Moab Wells , Fracture Zone	5	1064	Recharge, Storage	Fracture Enhanced Matrix Recharge and Storage	9 - 11	933	9 - 11	861		500	50	20 - 40	10 to 30	93	187	280	86	172	258				106442	212884	10644	21288
36	Kayenta F/F Zone Middle West	5	448	Recharge, Storage	Fracture Enhanced Matrix Recharge and Storage	9 - 11	336	9	336		500	50	20 - 40	10 to 30	34	67	101	34	67	101				44795	89591	4480	8959
37	FEM Southeast	5	3436	Recharge, Storage	Fracture Enhanced Matrix Recharge and Storage	9 - 15	3329	9 - 14	3146		300	10 to 50	20 - 40	10 to 30	333	666	999	315	629	944				206158	412316	20616	41232
49	Kayenta F/F Zone Northwest	5	1211	Recharge, Storage	Fracture Enhanced Matrix Recharge and Storage	9	908	8 - 9	889		500	50	20 - 40	10 to 30	91	182	272	89	178	267				121109	242218	12111	24222
50	Kayenta F/F Zone Northeast	5	273	Recharge, Storage	Fracture Enhanced Matrix Recharge and Storage	9	204	9	204		300	50	20 - 40	10 to 30	20	41	61	20	41	61				16354	32709	1635	3271
		Total	**28565**				**31769**		**30442**																		
	type 1 is subarea of type 2	Type 1	994				1275		1241																		
		Net Total (No type 1)	**27571**				**30494**		**29202**						**3050**	**5509**	**7168**	**2921**	**5284**	**6875**				**1531439**	**3062879**	**153144**	**306288**
	Hydro Zones (or Types):																										
	1 - Phreatophytes		**802**				**1268**		**1234**						**0**	**0**	**0**	**0**	**0**	**0**	**4009**	**5101**	**6193**	**0**	**0**	**0**	**0**
	2 - Riparian Fracture Zone [High-K Zone]		**4591**				**6074**		**5890**						**607**	**1215**	**1822**	**589**	**1178**	**1767**	**0**		**0**	**388349**	**776698**	**38835**	**77670**
	3 - Matrix		**12320**				**13915**		**13297**						**1392**	**2192**	**2192**	**1330**	**2101**	**2101**	**0**		**0**	**348714**	**697428**	**34871**	**69743**
	4 - (Riparian) Dry Wash		**2837**				**3380**		**3237**						**338**	**676**	**1014**	**324**	**647**	**971**	**0**		**0**	**186786**	**373572**	**18679**	**37357**
	5 - Fracture Enhanced Matrix		**8015**				**7131**		**6784**						**713**	**1426**	**2139**	**678**	**1357**	**2035**	**0**		**0**	**607590**	**1215181**	**60759**	**121518**
		Total	**28565**				**31769**		**30442**						**3050**	**5509**	**7168**	**2921**	**5284**	**6875**	**4009**	**5101**	**6193**	**1531439**	**3062879**	**153144**	**306288**
	type 1 is subarea of type 2	Type 1	994				1275		1241																		
		Net Total (No type 1)	**27571**				**30494**		**29202**																		

APPENDIX B. SPRINGS IN THE GCMC HYDROLOGIC SYSTEM AS REPORTED BY THE UTAH STATE WATER RIGHTS DIVISION

FID	WRNUM	SUMMARY_ST	STATUS	PRIORITY	USES	CFS	ACFT	LOCATION	WIN	OWNER	WRLINK	SOURCE
52	05-581	P	DIL	1896	I	0.009	0	S1245 E665 NW 06 26S 22E SL	0	MARVELEE JOHNSON BREWER	05-581	Bliss Spring
54	05-583	P	DIL	1896	I	0.009	0	S1245 E665 NW 06 26S 22E SL	0	PHILANDER C. MAXWELL	05-583	Bliss Spring
53	05-582	P	DIL	1896	I	0.005	0	S1245 E665 NW 06 26S 22E SL	0	WALTER E. SHUTT	05-582	Bliss Spring
41	05-2893	P	DIL	18880601	DIS	0	12.9	N3263 W858 S4 26 25S 21E SL	0	ELK CREEK CAMPGROUND LLC	05-2893	Goatman Springs and Seeps
47	05-458	P	APPLWUC	19630227	DI	0.007	0	S611 E321 NW 16 26S 22E SL	0	JOE ROMERO	05-458	Joe Romero Spring #2
68	05-9	P	APPLCERT	19100308	S	0.002	0	S820 W1255 N4 06 26S 22E SL	0	THOMAS B. FOY	05-9	Johnson Spring
15	05-1774	P	DIL	1903	S	0.002	0	N765 E777 S4 31 25S 23E SL	0	MOAB DISTRICT USA BUREAU OF LAND MANAGEMENT	05-1774	Little Spring
27	05-2270	P	APPLWUC	19890615	D	0	0.45	S1701 E997 W4 15 26S 22E SL	0	GEORGE S. WEIL	05-2270	Lloyd Somerville Spring
14	05-1706	P	DIL	1896	DIS	0.015	0	S1701 E997 W4 15 26S 22E SL	0	MARY K. WILSON	05-1706	Lloyd Somerville Spring
20	05-2007	P	DILCERT	1903	DIMO	0.21	0	S545 E204 W4 15 26S 22E SL	0	CITY OF MOAB	05-2007	McConkie Spring
64	05-753	P	DIL	1903	DI	0.12	0	N1420 E410 S4 36 25S 21E SL	0	HAROLD C. STEWART	05-753	Perry Foy Spring
42	05-2987	P	SHARCERT	19750127	I	0.112	4.23	S711 E1260 NW 08 26S 22E SL	0	THOMAS A. JOHNSON LIVING TRUST	05-2987	Powerhouse Line Spring
37	05-2762	A	FIXDAPP	19990526	I	1.25	0	S450 W225 NE 35 25S 21E SL	0	THE NATURE CONSERVANCY	05-2762	Skakel Spring
34	05-2740	A	FIXDAPP	19990127	DIMO	1	0	S450 W225 NE 35 25S 21E SL	0	CITY OF MOAB	05-2740	Skakel Spring
72	05-2105	A	APPLAPP	20050218	M	1.252	453.505	N2200 W222 E4 35 25S 21E SL	0	CITY OF MOAB	a29873	Skakel Spring
50	05-578	P	DIL	1896	IS	0.07	0	N1495 W285 S4 36 25S 21E SL	0	CHARLES A. STEEN	05-578	Snyder Spring
56	05-68	P	APPLCERT	19440228	DS	0.006	0	N1227 E695 W4 36 25S 21E SL	0	J. S. WESTWOOD	05-68	Spring Area
11	05-1281	P	APPLWUC	19770315	DI	0.015	0	N1350 E50 S4 36 25S 21E SL	0	CHARLES E EVERY	05-1281	Stewart Spring
21	05-2008	P	DILCERT	18960415	M	0.2	102	N170 W982 S4 15 26S 22E SL	0	CITY OF MOAB	05-2008	Surface Spring
32	05-251	P	APPLCERT	19581020	M	0.207	0	N170 W982 S4 15 26S 22E SL	0	CITY OF MOAB	05-251	Surface Spring
29	05-2414	P	APPLWUC	19921026	O	0.002	1.435	N480 W1380 SE 26 25S 21E SL	0	PALLADIUM FOUNDATION	05-2414	Unnamed Spring
57	05-70	P	APPLCERT	19450313	S	0.001	0	S2706 W353 N4 15 26S 22E SL	0	ALBERT C. TAYLOR	05-70	Unnamed Spring
23	05-2035	P	DIL	1900	DIS	0.033	0	N1185 W820 E4 16 26S 22E SL	0	GERDA STOLTZ	05-2035	Unnamed Spring
43	05-3073	P	APPLCERT	20050824	DIS	0	2.013	S1127 E288 W4 15 26S 22E SL	0	GLEN J LATHROP	05-3073	Unnamed Spring
31	05-247	P	APPLNPR	19581007	DI	0.015	0	S656 E389 NW 16 26S 22E SL	0	JOE D. ROMERO	05-247	Unnamed Spring
45	05-3316	P	APPLCERT	20070425	IO	0	6.13	N1312 E5 S4 36 25S 21E SL	0	LINDY OTTINGER	05-3316	Unnamed Spring
16	05-1924	P	DIL	1903	OS	0.002	0	N1150 E1250 SW 07 26S 23E SL	0	MOAB DISTRICT USA BUREAU OF LAND MANAGEMENT	05-1924	Unnamed Spring
18	05-1939	P	DIL	1903	OS	0.004	0	N1100 E1600 SW 07 26S 23E SL	0	MOAB DISTRICT USA BUREAU OF LAND MANAGEMENT	05-1939	Unnamed Spring
6	05-1921	P	DIL	1903	OS	0.006	0	N660 W660 S4 04 26S 23E SL	0	MOAB DISTRICT USA BUREAU OF LAND MANAGEMENT	05-1921	Unnamed Spring
7	05-1940	P	DIL	1903	OS	0.01	0	S660 W1980 E4 17 26S 23E SL	0	MOAB DISTRICT USA BUREAU OF LAND MANAGEMENT	05-1940	Unnamed Spring
1	05-1893	P	DIL	1903	OS	0.02	0	N660 E660 SW 03 26S 23E SL	0	MOAB DISTRICT USA BUREAU OF LAND MANAGEMENT	05-1893	Unnamed Spring
17	05-1936	P	DIL	1903	OS	0.03	0	N1100 E1800 SW 07 26S 23E SL	0	MOAB DISTRICT USA BUREAU OF LAND MANAGEMENT	05-1936	Unnamed Spring
8	05-1941	P	DIL	1903	OS	0.04	0	S660 W660 NE 18 26S 23E SL	0	MOAB DISTRICT USA BUREAU OF LAND MANAGEMENT	05-1941	Unnamed Spring
48	05-51	P	APPLCERT	19300929	I	0.029	0	N1413 E391 S4 36 25S 21E SL	0	PERRY E. FOY	05-51	Unnamed Spring
30	05-246	P	APPLCERT	19581003	IO	0.017	0	S1998 E1860 NW 26 25S 21E SL	0	MOAB LIONS CLUB	05-246	Unnamed Spring Area
69	05-92	P	APPLCERT	19511024	I	0.022	0	N307 W54 E4 16 26S 22E SL	0	PETE SHUMWAY	05-92	Unnamed Spring Area
10	05-122	P	APPLCERT	19541006	DI	0	42.608	N203 W856 SE 08 26S 22E SL	0	CRYSTAL LEE DAY	05-122	Vicki`s Spring and Well
24	05-2102	P	DIL	1898	IOS	0.075	24.768	S380 W450 NE 35 25S 21E SL	0	CLUB UTAH RESORT GROUP LLC	05-2102	Watercress Spring
36	05-2744	P	DIL	1898	IOS	0.12	38.98	S380 W450 NE 35 25S 21E SL	0	CLUB UTAH RESORT GROUP LLC	05-2744	Watercress Spring
44	05-3113	A	FIXDAPP	20051227	I	0.6	198	S380 W450 NE 35 25S 21E SL	0	THE NATURE CONSERVANCY	05-3113	Watercress Spring
46	05-3456	P	DIL	1898	I	0.246	79.45	S380 W450 NE 35 25S 21E SL	0	THE NATURE CONVSERVANCY	05-3456	Watercress Spring
38	05-2780	P	DIL	1898	I	0.039	12.702	S380 W450 NE 35 25S 21E SL	0	COLIN FRYER	05-2780	Watercress Spring

APPENDIX C-1. STREAM FLOW DATA AT USGS GAGES 09183500 AND 09183600 AT AND BELOW SHELEY TUNNEL: ANNUALLY AVERAGED FLOW IN CUSECS.

USGS 09183500 MILL CREEK AT SHELEY TUNNEL, NEAR MOAB, UT

Available data for this site | Time-series: Annual statistics | GO

San Juan County, Utah
Hydrologic Unit Code 14030005
Latitude 38°28'59", Longitude 109°24'12" NAD27
Drainage area 26.8 square miles
Gage datum 5,500.00 feet above NGVD29

Output formats
HTML table of all data
Tab-separated data
Reselect output format

Water Year	00060, Discharge, cubic feet per second
1955	8.52
1956	6.43
1957	15.8
1958	19.6
1959	6.85
1988	16.3
1989	8.40
1990	6.13
1991	10.1
1992	11.9
1993	20.4
1994	10.9
1995	16.3
1996	9.44
1997	12.5
1998	15.6
1999	10.6
2000	8.92
2001	8.99
2002	4.73
2003	7.05
2004	7.15
2005	17.7
2006	7.23
2007	9.75
2008	8.21
2009	7.54
2010	8.61
2011	13.7
2012	5.46
2013	5.46
2014	7.60
2015	7.96
2016	15.3
2017	10.3

** No Incomplete data have been used for statistical calculation

USGS 09183600 MILL CREEK BELOW SHELEY TUNNEL, NEAR MOAB, UT

Available data for this site | Time-series: Annual statistics | GO

San Juan County, Utah
Hydrologic Unit Code 14030005
Latitude 38°29'08.64", Longitude 109°24'37.56" NAD27
Drainage area 27.6 square miles
Gage datum 5,341 feet above NGVD29

Output formats
HTML table of all data
Tab-separated data
Reselect output format

Water Year	00060, Discharge, cubic feet per second
2004	3.07
2005	8.44
2006	3.71
2007	4.15
2008	3.51
2009	3.28
2010	3.79
2011	5.44
2012	3.61
2013	3.17
2014	3.28
2015	3.53
2016	8.22
2017	3.81

** No Incomplete data have been used for statistical calculation

APPENDIX C-2. STREAM FLOW DATA AT USGS GAGES 09183500 AND 09183600 AT AND BELOW SHELEY TUNNEL: AVERAGED MONTHLY FLOW IN CUSECS.

USGS 09183500 MILL CREEK AT SHELEY TUNNEL, NEAR MOAB, UT

Available data for this site | Time-series: Monthly statistics | GO

San Juan County, Utah
Hydrologic Unit Code 14030005
Latitude 38°28'59", Longitude 109°24'12" NAD27
Drainage area 26.8 square miles
Gage datum 5,500.00 feet above NGVD29

Output formats
HTML table of all data
Tab-separated data
Reselect output format

YEAR	00060, Discharge, cubic feet per second, Monthly mean in ft3/s (Calculation Period: 1954-10-01 -> 2017-10-31)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1954										7.41	4.44	4.30
1955	4.88	4.61	5.07	7.59	21.6	15.9	10.0	9.37	6.60	5.15	4.58	4.79
1956	4.96	4.48	5.02	6.71	11.9	10.9	7.46	5.72	5.40	4.84	3.89	5.01
1957	4.60	4.89	4.88	7.44	23.1	67.9	33.7	16.3	12.7	12.1	9.49	8.79
1958	8.06	7.41	6.87	22.2	70.5	49.0	15.6	12.9	11.6	8.28	6.94	6.97
1959	6.16	5.83	6.17	8.24	10.3	7.08	5.32	5.77				
1987										12.0	15.6	11.0
1988	8.82	8.06	9.43	18.4	42.3	34.0	15.0	10.3	11.1	9.82	7.60	7.63
1989	6.89	6.70	7.88	10.7	10.6	9.13	8.16	8.99	6.56	6.81	5.80	5.55
1990	5.75	5.20	5.37	5.42	8.03	7.34	5.71	4.69	7.87	8.34	7.49	6.77
1991	5.94	6.23	5.22	10.1	22.1	20.9	11.5	9.56	7.02	6.79	7.14	6.61
1992	6.31	5.88	7.65	15.9	33.1	23.4	14.0	8.55	7.10	6.49	5.96	6.13
1993	6.22	5.87	7.13	13.2	68.4	65.4	26.7	18.7	13.5	12.0	9.40	7.91
1994	6.56	5.99	6.55	13.2	27.6	19.7	8.77	6.11	6.08	5.45	5.83	5.66
1995	5.41	5.35	7.45	9.34	28.1	55.2	40.7	16.3	10.3	9.67	9.40	7.49
1996	6.29	5.61	5.62	9.06	21.5	14.6	7.78	5.40	10.8	7.61	5.90	5.14
1997	5.02	4.65	5.95	10.5	35.6	32.5	13.0	11.9	11.2	15.4	10.3	8.77
1998	8.30	7.14	8.34	13.2	37.9	34.5	21.4	12.2	9.22	11.0	9.09	7.86
1999	6.39	6.04	6.33	7.43	13.0	19.5	14.1	15.3	10.6	7.20	6.98	6.70
2000	6.50	5.69	6.13	12.8	22.5	13.2	6.99	6.51	5.79	5.38	5.54	4.93
2001	4.68	4.50	4.81	7.98	26.4	13.5	10.2	12.2	7.36	5.56	5.64	5.21
2002	4.72	4.39	4.30	6.87	6.55	4.40	2.78	2.49	3.92	3.64	3.63	3.72
2003	3.66	3.59	3.84	7.42	20.9	18.0	6.16	5.56	4.36	3.85	4.48	4.48
2004	4.19	4.05	4.80	6.20	18.1	15.5	7.83	5.97	6.36	6.38	5.85	4.73
2005	4.42	4.05	4.75	14.6	56.1	63.4	26.0	12.9	8.97	7.45	7.40	6.33
2006	5.60	4.98	4.87	8.68	14.8	9.86	5.51	6.06	5.11	18.1	7.67	6.46
2007	5.70	5.65	6.97	9.70	21.6	13.6	6.27	6.19	8.67	7.60	5.23	4.32
2008	4.16	4.36	4.77	7.15	17.2	22.9	9.29	6.66	4.89	5.68	5.93	5.44
2009	5.29	5.27	5.46	8.40	19.9	12.0	6.64	5.05	5.28	5.11	5.31	4.93
2010	4.78	4.78	4.89	9.44	14.2	21.1	8.95	13.1	6.70	6.51	5.75	5.42
2011	4.88	4.84	5.73	9.79	22.0	48.2	27.3	12.3	11.3	8.30	7.13	5.82
2012	5.24	5.04	6.42	8.04	6.01	4.42	3.42	2.99	2.61	2.94	4.30	4.04
2013	4.16	3.82	4.08	4.87	9.55	6.45	4.14	5.32	11.8	5.98	6.16	5.66
2014	5.17	5.01	5.43	8.09	14.9	13.8	6.94	6.93	6.99	6.05	6.07	5.40
2015	4.86	4.45	5.20	7.23	11.8	20.6	11.5	6.44	5.84	6.19	7.39	6.14
2016	5.92	6.24	8.10	18.1	40.1	53.3	16.5	9.10	7.01	7.69	8.11	6.77
2017	6.99	6.71	9.29	13.8	18.9	20.3	10.0	7.92	6.59	5.30		
Mean of monthly Discharge	5.6	5.4	6.0	10	24	25	12	8.9	7.9	7.6	6.8	6.1

** No Incomplete data have been used for statistical calculation

USGS 09183600 MILL CREEK BELOW SHELEY TUNNEL, NEAR MOAB, UT

Available data for this site | Time-series: Monthly statistics | GO

San Juan County, Utah
Hydrologic Unit Code 14030005
Latitude 38°29'08.64", Longitude 109°24'37.56" NAD27
Drainage area 27.6 square miles
Gage datum 5,341 feet above NGVD29

Output formats
HTML table of all data
Tab-separated data
Reselect output format

YEAR	00060, Discharge, cubic feet per second, Monthly mean in ft3/s (Calculation Period: 2003-10-01 -> 2018-05-31)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2003										3.41	2.57	2.16
2004	1.23	1.06	2.36	3.28	4.27	3.90	4.20	4.72	3.60	3.64	3.99	3.86
2005	3.55	3.58	2.66	3.18	19.3	39.5	9.18	4.72	4.22	4.65	5.19	4.26
2006	3.43	3.13	3.27	3.71	3.42	3.52	3.25	3.51	3.18	8.85	3.58	3.58
2007	3.01	3.05	3.20	3.60	5.28	3.70	3.24	3.50	5.12	3.49	3.37	2.92
2008	2.79	2.75	2.93	2.28	5.15	4.41	4.35	4.43	3.23	3.27	3.09	2.78
2009	2.64	3.63	2.98	2.73	3.87	3.35	3.56	3.49	3.94	3.29	3.19	2.92
2010	2.71	3.02	2.53	3.51	3.93	4.73	3.92	7.88	3.80	2.87	3.85	2.52
2011	2.18	2.54	3.34	2.89	5.03	18.2	11.8	3.98	6.15	4.37	5.03	4.32
2012	3.11	3.23	3.57	3.83	3.57	3.22	3.29	3.01	2.79	2.89	3.05	3.07
2013	2.72	3.13	3.06	3.07	3.11	3.15	3.20	3.26	4.32	3.29	3.42	3.25
2014	3.31	3.43	2.92	3.15	3.28	2.99	3.24	3.15	3.92	3.41	4.36	3.21
2015	2.88	2.98	2.95	3.05	3.13	3.96	5.63	3.14	3.62	4.13	3.24	3.49
2016	3.43	3.20	3.52	4.01	29.6	30.7	6.67	3.34	3.25	3.10	5.00	3.74
2017	3.08	3.09	3.08	3.21	3.65	6.66	4.35	3.12	3.71	3.23	3.31	3.18
2018	3.31	3.53	3.06	3.16	3.30							
Mean of monthly Discharge	2.9	3.0	3.0	3.2	6.7	9.4	5.0	3.9	3.9	3.9	3.7	3.3

** No Incomplete data have been used for statistical calculation