

**\_HYDROLOGIC AND HYDROGEOLOGIC ASSESSMENT OF THE  
SURFACE WATER AND GROUNDWATER RESOURCES AFFECTING  
THE MOAB CITY SPRINGS AND WELLS, MOAB, UTAH:  
PHASE 4: PRELIMINARY HESA-BASED WATER BUDGET AND  
AQUIFER STORAGE EVALUATION FOR SPANISH VALLEY AND  
COMBINED MILL CREEK / PACK CREEK HYDROLOGIC SYSTEMS**

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**Prepared For:**

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Front Page: View of Moab, Utah in the northern area of the Pack Creek Lower Alluvium (PCLA) Subsystem from the Moab Rim Trail. Mill Creek and Pack Creek are perennial streams that flow in the Quaternary Alluvium Aquifer (Hydrogeologic Unit).

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# **HYDROLOGIC AND HYDROGEOLOGIC ASSESSMENT OF THE SURFACE WATER AND GROUNDWATER RESOURCES AFFECTING THE MOAB CITY SPRINGS AND WELLS, MOAB, UTAH:**

## **PHASE 4: PRELIMINARY HESA-BASED PRELIMINARY WATER BUDGET AND AQUIFER STORAGE EVALUATION FOR THE PACK CREEK LOWER ALLUVIUM (PCLA) AND COMBINED PCLA AND GCMC PRELIMINARY WATER BUDGET**

**Report prepared for City of Moab, Utah, January 2020**

**by**

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### **EXECUTIVE SUMMARY**

This report presents the findings of Phase 4 of a 4-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. In July, 2019, the project was expanded as Phase 4 to include performing a Hydrogeologic and Environmental Systems (HESA) Analysis (including an expanded water budget and storage analysis) of the Spanish Valley, which is the Pack Creek Lower Alluvium (PCLA) hydrologic system as part of protecting the remaining City wells and for water management and water rights purposes. Preliminary water budgets (PWB) for pre-development (natural) and post-development (natural and current) combined GCMC/PCLA hydrologic systems was completed. In summary, the results of the HESA of the MCSW area performed in Phase 1 were documented in Kolm and van der Heijde (2018), the results of the HESA and water budgets for the GCMC area performed in Phase 2 are documented in Kolm and van der Heijde (2019), and the results of the HESA and water budgets for the PCLA area and the combined GCMC/PCLA area performed in Phase 4 are in this document.

The Pack Creek Lower Alluvium (PCLA) hydrologic system is a complex mix of Alluvium and Alluvial Fan sediments overlying or adjacent to fractured and faulted Glen Canyon Group rock, 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 Spanish Valley springs and wells particularly in the

southern two-thirds of the Valley. The HESA completed in phase 4 showed that the PCLA 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 PCLA hydrologic system, a preliminary (global) water budget (PWB) has been developed for the PCLA hydrologic system, focused on the external inputs (inflows) and outputs (outflows). In addition, an analysis was made of the storage capacity of the PCLA aquifer in the PWB area. The area in PCLA for which the water budget is determined is based, in part, on the locations of various stream gages on Pack Creek and Mill Creek (Blanchard, 1990; USGS Surface-Water Dailey Statistics, Mill Creek at Sheley Tunnel Sites, 2019); the location of most anthropogenic activities (diversions, domestic and agricultural water use); the natural boundaries of the PCLA hydrologic system including Pack Creek and tributaries; and the hydrogeologic and hydrostructural boundaries of the Pack Creek Alluvium Aquifer as determined by HESA. The water budget area is bounded by the Glen Canyon Group Mill Creek Subsystem (GCMC) to the northeast and east; the Morrison Formation to the east and southeast; the La Sal Mountain Upper Alluvial Subsystem (LSMA-P) Pack Creek Headwaters to the southeast; the Moab Rim and Kane Creek hydrological divides to the south, southwest, and west; and the Colorado River to the northwest. The PWB area used in this report covers almost all of the PCLA hydrologic system.

There are two distinct time periods of anthropogenic stresses in the PCLA hydrologic system: pre-development or natural conditions; and post-development or current conditions, which includes both natural and anthropogenic conditions. The most significant anthropogenic change in conditions happened in the early 1980s, the start of the Sheley diversion, together with the initiation of a steady increase in municipal and domestic water use that represents a significant increase in the anthropogenic withdrawals from the PCLA 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 (PWB) has been developed for each of these two time periods.

The pre-development PCLA water budget has as inputs: 1) direct runoff of precipitation to streams; 2) recharge by infiltration of precipitation (rain and snow) across the entire PWB area using the concept of *hydro zones* explained later in this report; 3) Pack Creek groundwater flux, called groundwater underflow, in the Quaternary hydrogeologic units (Qal) at the SE corner of the water budget area; 4) Brumley Creek groundwater flux, called groundwater underflow, in the Quaternary hydrogeologic units (Qal) at the SE corner of the water budget area; 5) Mill Creek groundwater flux, called groundwater underflow, in the Quaternary hydrogeologic units (Qal) at the Mill Creek delta (Powerhouse); 6) Pack Creek surface water inflow above the later ditch diversion in the SE corner of the water balance area; 7) Brumley Creek surface water inflow to Pack Creek in the SE corner of the water balance area; 8) Mill Creek surface water inflow at the Mill Creek delta (powerhouse) in the northeast water balance area; 9) Sheley diversion in post-development/current conditions; and 10) springs at eastern PWB boundary from the GCMC system (including City Springs and Skakel spring). The outputs of the PWB are: 1) evapotranspiration or consumptive use by native phreatophytes (cottonwoods, willows, tamarisk, and other riparian species); 2) evaporative loss open water; 3) Mill Creek surface water outflow

at the northern end of Spanish Valley to the Colorado River; and 4) groundwater discharge to the Colorado River. 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.

The post-development PCLA water budget has the same type of inputs as the pre-development water budget, but has an additional inflow term, the Sheley diversion). The post-development PCLA water budget has the same type of outputs as the pre-development water budget, but has additional anthropogenic terms: 1) consumptive use of crops; 2) net municipal use (GWSSA and losses/return flow of City Water); and 3) domestic consumptive use by private wells.

Recharge to groundwater is estimated using 5-25% of precipitation dependent on hydro zone type. The average annual precipitation was calculated for each hydro zone for both the periods 1971-2000 (considered representative for pre-development conditions) and 1981-2010 (representative for “current” conditions) resulting for the period 1971-2000 in 3170 ac-ft/yr or 1.9 inches across the entire PWB area; and for the period 1981-2010 in 2765 ac-ft/yr or 1.6 inches across the entire PWB area. Note that the estimate for recharge in both periods amounts to about 16-17 % of overall precipitation in the PWB area.

Direct runoff of precipitation to streams amounts to 815 ac-ft/yr. This term, corrected for the decline in precipitation between the two climate periods and the increase of direct runoff in buildup/urbanized areas amounting to a total of 1300 ac-ft/yr, is used in the post-development scenario. Direct evapotranspiration (ET) in the PWB area (excluding riparian vegetation), calculated as precipitation minus groundwater recharge and direct runoff to streams, amounts to about 14,525 ac-ft/yr for the pre-development period and to 13,565 ac-ft/yr for the post-development period, or about 75-78% of total precipitation, based on 30-year averages for the two climate periods.

The primary conclusion regarding the PWB is that there is a significant amount of surface water and groundwater contributed to the PCLA hydrological system from the La Sal Mountain and GCMC hydrological systems, or in percentages of pre-development input into the PCLA hydrologic system: surface water and groundwater derived from the GCMC hydrologic system (Mill Creek + groundwater underflow at the Mill Creek delta + springs at eastern PWB boundary from GCMC system) is 13,270 ac-ft/yr and counts for approximately 65%; local recharge from precipitation and direct runoff from precipitation to streams counts for 20%; and directly linked groundwater inflow and surface water inflow (Pack Creek and Brumley Creek) from the La Sal Mountains hydrological subsystems counts for 15%. This means that the La Sal Mountain and GCMC subsystems contribute more than 80% of the total inflow in the PWB area. Note that a combined consumptive use riparian vegetation and evaporative loss open water accounts for 35% of the total water budget out, and remainder is subsurface and surface discharge to the Colorado River. By comparison, in the post development time period, the contribution of the Sheley diversion to the overall input becomes more of a factor, or in percentages of post development input into the PCLA hydrologic system: surface water (Mill Creek + Pack Creek + Brumley Creek) counts for approximately 55%; local recharge from precipitation and direct runoff to streams for 19%; groundwater inflow from the GCMC hydrological subsystems counts for about

9%; and the Sheley diversion provides 17% of the total inflow to the PCLA hydrologic system and has resulted in a 17% reduction of Mill Creek inflows towards Spanish Valley under base flow conditions and 31% reduction of springs and seeps discharge in the most likely scenario. Therefore, any decline in upstream total average flows in Mill Creek, Pack Creek, or Brumley Creek from natural or man-made causes will have an immediate and significant impact on the various outflows of the PCLA hydrologic system and poses a potential threat to the sustainability of the City of Moab's and the County'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 GWSSA, 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. Another area where significant cost-effective improvements to the PWB can be made is more detailed and frequent monitoring of the Pack Creek surface water system. Gaging stations at Mill Creek (Powerhouse, Junction with Pack Creek, Colorado River), Pack Creek (City Springs and Perennial Flow locations, Pack Creek Bridge, Settlement of Pack Creek, and Brumley Creek that record daily, seasonal, and annual information would improve the measurements of the City of Moab and Spanish Valley 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.

The Quaternary alluvium and fan gravels, and the fractured 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 alluvium and alluvial fan gravels has matrix specific yield with estimates of 10 – 30%, and 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 bedrock of the PCLA system, fractures are the dominant feature in determining available groundwater storage at these locations. The results of GIS-based calculations show that the PCLA groundwater system has a variable storage low of 38,375 ac-ft, and a variable storage high of 101,400 ac-ft. The Quaternary alluvial deposits, designated storage zone 1, had the largest amount of variable storage with a range of 24,850-74,550 ac-ft. Areas along the groundwater flow paths that directly affect the yields and water quality of the GWSSA wells have the largest amount of storage. The current City of Moab source protection plans identify some of these hydro zones as critical, and an update to these plans will be completed in Phase 3 of this project.

In order to develop a preliminary water budget of the combined Pack Creek Lower Alluvium (PCLA) and Glen Canyon Group Mill Creek (GCMC) Subsystems of the MCSW study area, it was first necessary to 1) create a true PWB of the Pre-development natural

conditions of the GCMC subsystem and to 2) slightly revise the PWB of the post development (current) conditions based on new information obtained since the original release of Kolm and van der Heijde (2019) report on the GCMC subsystem. The Kolm and van der Heijde (2019) report discusses the HESA-derived conceptual model for the GCMC subsystem in great detail, and provides PWBs for pre-Sheley diversion conditions (not a true predevelopment scenario since the report focused on the effects of the Sheley diversion on the City of Moab water supply), and the current conditions. A PWB for the GCMC Hydrologic System under natural (pre-development) conditions was developed using a modified PWB described in the Phase 2 report (Kolm and van der Heijde, 2019). This GCMC PWB is then combined with the PCLA PWB to provide estimates for water rights and water management purposes. The water balance inflow terms are the same as those in the Kolm and van der Heijde (2019) Phase 2 report, and all terms are rounded off. By comparison, the pre-development outflow terms have been increased by about 8.3% compared with Kolm and van der Heijde (2019) due to absence of municipal and domestic use. A discussion of these two budgets is provided.

A preliminary water budget (PWB) for the combined GCMC/PCLA hydrologic systems is calculated based upon the information previously collected and analyzed by Kolm and van der Heijde (2018), Kolm and van der Heijde (2019), the HESA-based conceptual model of the GCMC hydrologic system determined in Phase 1, and the HESA-based conceptual model of the PCLA hydrologic system determined in Phase I and refined in Task 1 of this Phase (4) project. The combined GCMC and PCLA water budget area is bounded by the Glen Canyon Group Grandstaff Creek Subsystem (GCGC) to the northeast and east; the Morrison Formation to the east and southeast; the La Sal Mountain Upper Alluvial Subsystem (LSMA-P) Pack Creek Headwaters to the southeast; the Moab Rim and Kane Creek hydrological divides to the south, southwest, and west; and the Colorado River to the northwest. The PWB area used in this report covers almost all of the PCLA and GCMC hydrologic systems.

The significant inputs of the PWB for the combined GCMC/PCLA hydrologic systems are: 1) direct runoff of precipitation to streams; 2) recharge by infiltration of precipitation (rain and snow) across the entire PWB; 3) Mill Creek groundwater flux, called groundwater underflow, at the upper Mill Creek boundary (inflow through Mill Creek fracture zone); 4) Pack Creek groundwater flux, called groundwater underflow, in the Quaternary hydrogeologic units (Qal) at the SE corner of the water budget area; 5) Brumley Creek groundwater flux, called groundwater underflow, in the Quaternary hydrogeologic units (Qal) at the SE corner of the water budget area; 6) Mill Creek inflow above later location of Sheley diversion; 7) Upper North Fork Cr. and Burkholder Draw inflow from Mesas; 8) Pack Creek surface water inflow above the later ditch diversion in the SE corner of the water balance area; and 9) Brumley Creek surface water inflow to Pack Creek in the SE corner of the water balance area. The outputs of the combined PWB are: 1) Consumptive use crops; 2) evapotranspiration or consumptive use by phreatophytes (cottonwoods, willows, tamarisk, and other riparian species); 3) Evaporative loss open water; 4) Net Municipal use GWSSA and losses/return flow City of Moab Water; 5) domestic consumptive use by private wells; 6) groundwater discharge to the Colorado River; 7) Mill Creek surface water outflow at the northern end of Spanish Valley to the Colorado River, and 8) Release from groundwater storage in the post-development (current) PWB.

In the combined GCMC/PCLA pre-development scenario, the water budget closing term represents the term for direct runoff to streams and amounts to 5950 ac-ft/yr. The combined

GCMC/PCLA post-development scenario incorporates human activities, such as the Sheley Diversion intake of 3665 ac-ft/yr, but the water budget treats that as an internal process, which doesn't appear in the global PWB for the combined GCMC/PCLA area. However, due to the diversion, and the increase water use by human activity, the closing term is release from groundwater storage in the GCMC part of the combined system of 3995 ac-ft/yr, which is approximately 14% of the total yearly budget. The deficit may be reduced over time by increased recharge in above average precipitation years, or as increased flow to Mill Creek into the GCMC hydrologic systems upgradient due to increased groundwater release in upgradient groundwater systems, or increased runoff from higher than average snowpack. This depletion of upgradient storage or mining of groundwater is also a concern for the sustainability of both the City's and the PCLA water supply.

The primary significance of the combined PWB is that there is a significant amount of surface water and groundwater contributed to the GCMC and PCLA hydrological systems from the La Sal Mountain systems, or in percentages of pre-development input into the GCMC/PCLA hydrologic system: surface water and groundwater derived from the La Sal Mtns is 11,515 ac-ft/yr and counts for approximately 45%, and local recharge from precipitation counts for 33%. This means that the La Sal Mountain climate regimes can affect directly 78% of the water supply. Note that a combined consumptive use riparian vegetation and evaporative loss open water accounts for 49% of the total water budget out (almost one-half!), and the remainder of 51% is subsurface and surface discharge to the Colorado River. By comparison, in the post development time period, the development of the Sheley diversion to the overall redistribution of the water supply plus the increase in municipal use and consumptive use becomes more of a factor, or in percentages of post development change into the GCMC/PCLA hydrologic system: consumptive use crops accounts for 13%, municipal use and domestic consumptive use accounts for 11%, and groundwater released from storage accounts for approximately 14%. The Sheley diversion yearly amounts is almost entirely accounted for in the consumptive use of crops and domestic consumptive use. The most notable decline is the amount of Mill Creek outflow to the Colorado River of 1,620 acre-ft/year or 13%.

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; Pack Creek in the southeastern part of the Spanish Valley; Mill Creek in the GCMC system, 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.

There are a number of potential threats to the sustainability of the GCMC/PCLA hydrologic system and thus to the water supply of the City of Moab and Grand County, 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/PCLA hydrologic system, will result in decreased surface water flows and groundwater recharge from losing streams. Impacts on the GCMC/PCLA 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, Pack Creek and Brumley Creek at the east and southeast end of the GCMC/PCLA 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/PCLA hydrologic system will result in further decline of outflows such as at Mill Creek, Pack Creek and Brumley Creek in the eastern and southern part of the study area and various springs, and will likely lead to decline in storage and subsequent lowering of groundwater levels and groundwater availability for phreatic consumption.

Based upon associated uncertainties with estimates, the greatest cost-effective improvements to the PWB, primarily post-development, is better monitoring of the Mill Creek and Pack Creek surface water system. Gaging stations at Mill Creek (Powerhouse, Junction with Pack Creek, Colorado River), Pack Creek (City Springs and Perennial Flow locations, Pack Creek Bridge, Settlement of Pack Creek, and Brumley Creek that record daily, seasonal, and annual information would improve the measurements of the City of Moab and Spanish Valley 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. This Phase IV HESA revealed that the GCMC/PCLA groundwater system was complex being both matrix and fracture-type flow, and that the design, implementation, and calibration of a mathematical model can be done, and may be cost-effective at this time. Given the uncertainties with the data available, the results would still tend to be questionable. The PWB of the GCMC groundwater system in Phase II would provide inputs into a Spanish Valley model, and the HESA of the PCLA and GCMC groundwater systems would provide boundary conditions for that model.

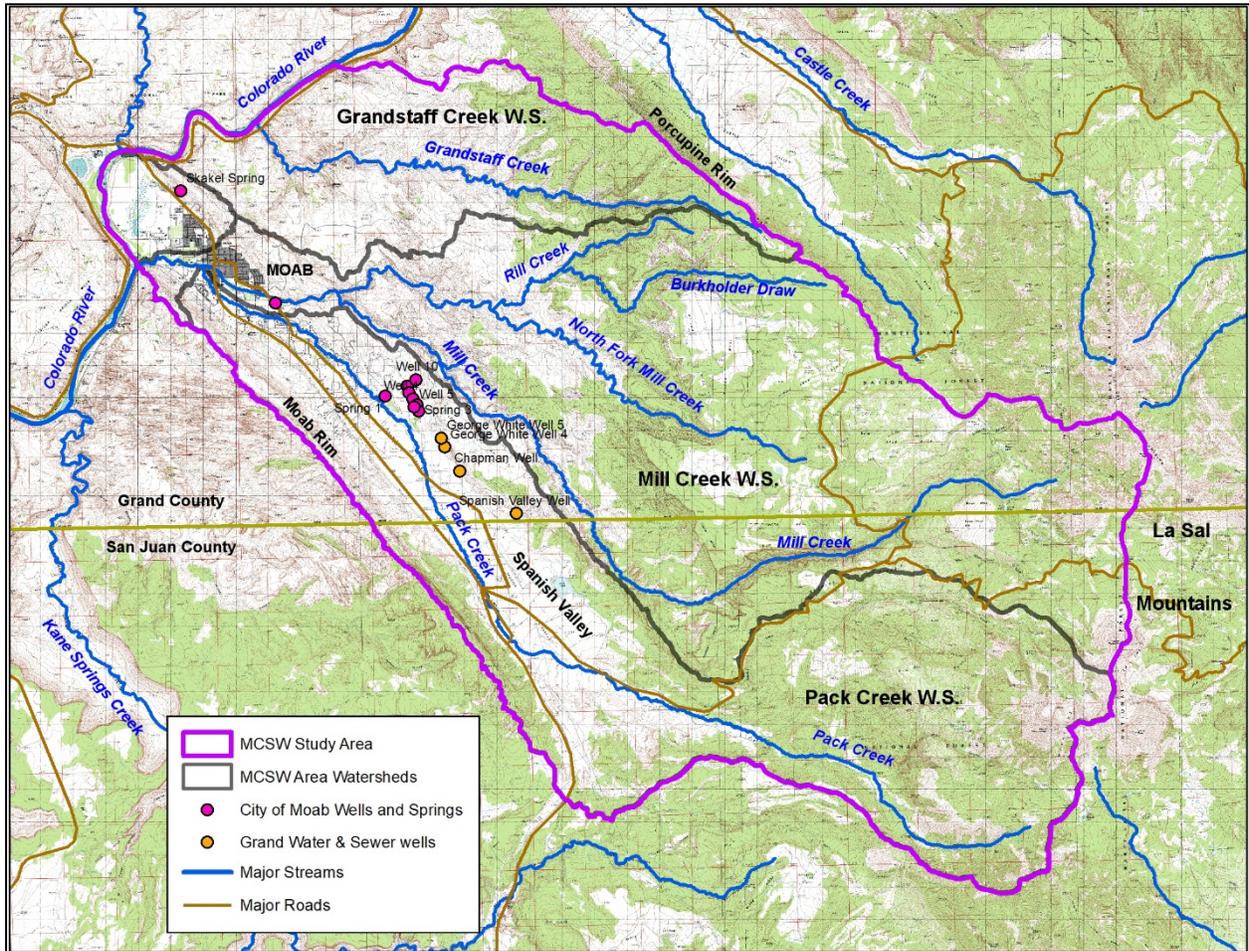
# 1. INTRODUCTION

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). In July, 2019, the agreement was expanded to include Task 4: Perform a Hydrogeologic and Environmental Systems (HESA) Analysis (including an expanded water budget and storage analysis) of the Spanish Valley as part of protecting its remaining wells and for water management and water rights purposes, and a combined water budget analysis for the combined Pack Creek Lower Alluvium (PCLA) and Glen Canyon Mill Creek (GCMC) hydrologic subsystems of the MCSW. Each of these tasks constitutes a phase of the project. This report contains the results of Phase 4: Collect hydrological, hydrogeological and other data, and develop an as-accurate-as-possible water budget for PCLA hydrologic system, covering the Spanish Valley part of the MCSW area, and the water budget for the combined Lower Pack Creek and Mill Creek hydrological subsystems. The results of the HESA of the entire MCSW area performed in Phase 1 are documented in Kolm and van der Heijde (2018), and the results of the study of the GCMC area performed in Phase 2 are documented in Kolm and van der Heijde (2019).

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 Glen Canyon aquifer and Mill Creek Watershed (GCMC) underlying the Sand Flats region was chosen as the setting for the water budget developed in Phase 2 of this project, and the Pack Creek Watershed and the Quaternary unconsolidated alluvium (PCLA) in the Spanish Valley was chosen as the setting for the water budget developed in Phase 4 of this project. The analysis of these areas will be used for updating the Drinking Water Protection Plans for the springs and wells of the City of Moab planned for Phase 3 (Figure 2). The combined GCMC and PCLA water budgets included both of these areas (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 the second,

and now this 4th 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 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 GWSSA wells**

Various information sources have been consulted in preparation of the Phase 2 and Phase 4 analysis of the preliminary water budget (PWB) 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.



**Figure 2. View of the regional setting of the Moab City springs and wells and the approximate Phase 2 Preliminary Water Budget (PWB) area and Phase 4 Preliminary Water Budget area outlined in yellow (Source: Google Earth, Imagery October 2016).**

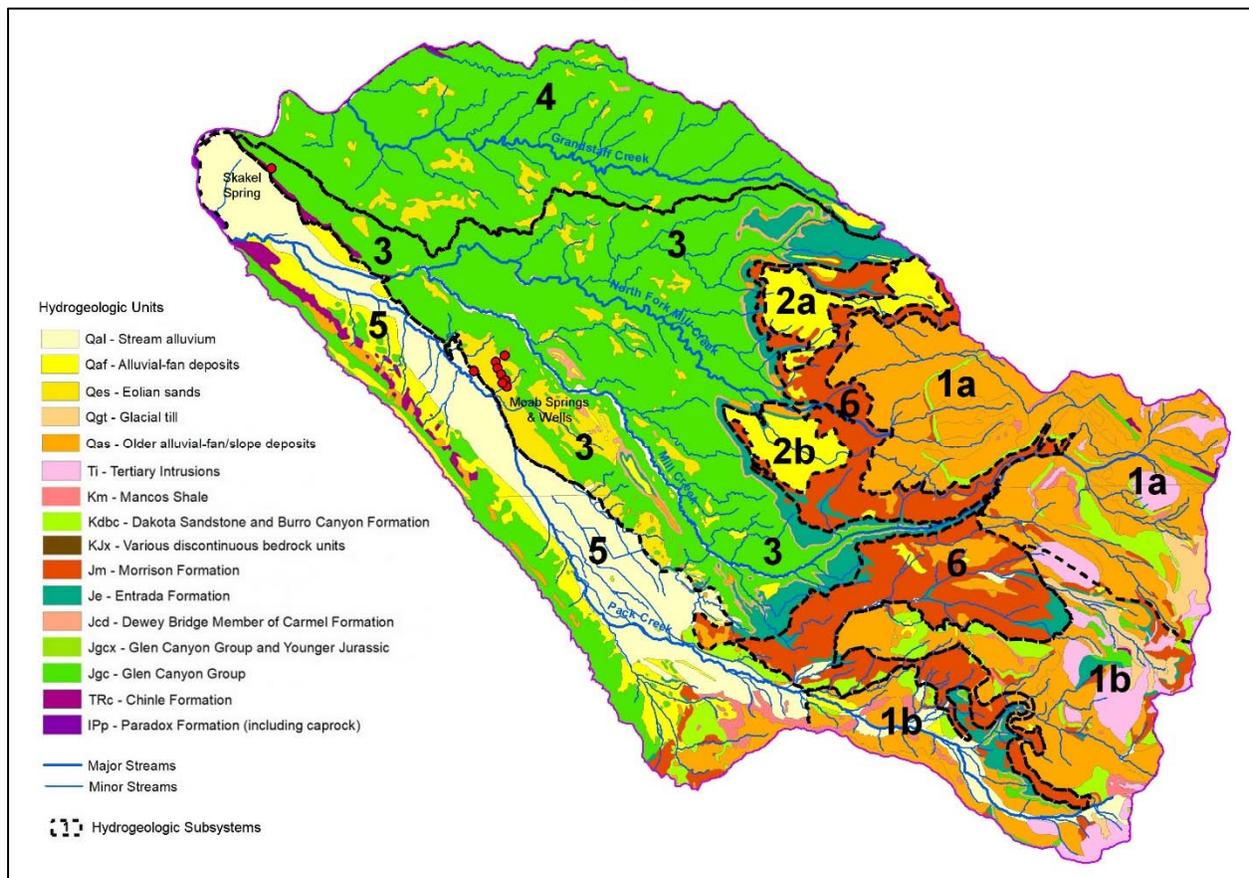
It should be noted that that this report will not obviate the need for additional hydrogeologic analysis on a site-specific/parcel-specific basis by developers and/or the City, or in any water right, geotechnical, or environmental study requiring due diligence. The information in this report is intended 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 PACK CREEK LOWER ALLUVIUM (PCLA) 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 hydrologic subsystems were identified within the MCSW study area in Phase 1 of this project (Kolm and van der Heijde, 2018) (Figure 3). Each of these subsystems is characterized by a unique combination of surface water system, hydrogeologic setting, and groundwater flow system and is described in detail in the Phase 1 report. Section 2 of the Phase 4 report summarizes the HESA-based conceptual model of the Pack Creek Lower Alluvium (PCLA) Hydrologic Subsystem of the MCSW study area presented in the Phase 1 report. This subsystem is the focal point of the preliminary water budget analysis presented in later sections of this report.

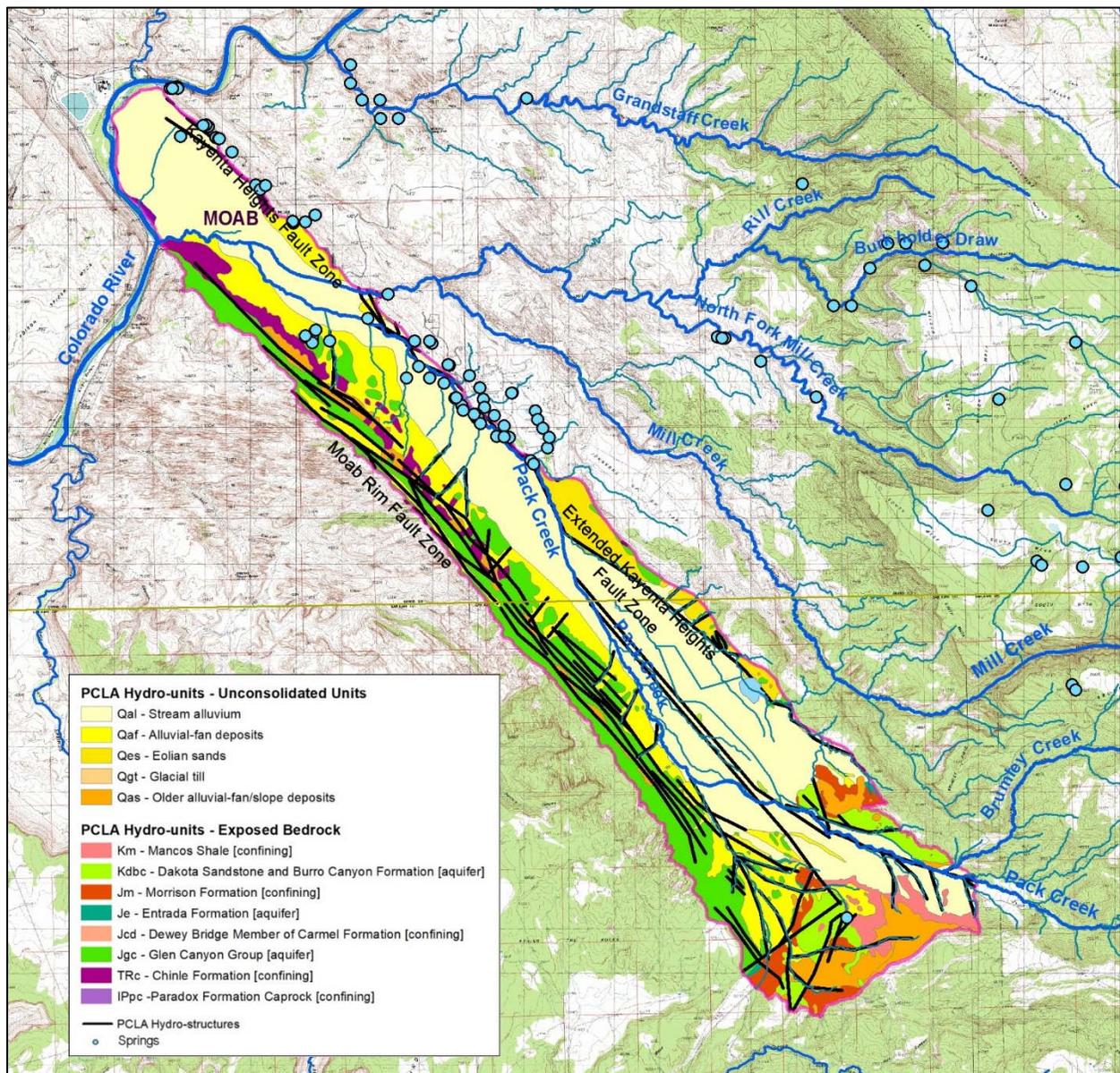
The Pack Creek Lower Alluvium Subsystem (PCLA), located in the southwestern part of the study area (CSM 5 in Figure 3), is a complex mix of fractured and faulted, and unfractured Glen Canyon Group (Jgc), Stream alluvium (Qal), Alluvial fan deposits (Qaf/Qas) and hydrostructures (fault and fracture zones) which form the robust groundwater system and surface water system that is directly connected to the City of Moab and Grand County wells in the central part of the Spanish Valley (Figures 4, 5 and 6). Compared with the other 5 subsystems, PCLA is the second most important subsystem for the City of Moab wells sustainability and protection, and directly affects most of the Valley users for culinary water supply, although knowledge of the GCMC and LSMA-P subsystems is crucial in protecting these assets. This subsystem is hydraulically connected to the Glen Canyon Group Mill Creek (GCMC) and La Sal Mountain Upper Alluvium Subsystem (LSMA-P) upgradient primarily by surface water (Mill Creek and Pack Creek, respectively, by 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 with adjacent hydrologic subsystems.



**Figure 3. 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); 5. Pack Creek Lower Alluvium Subsystem (PCLA); and 6. Morrison Formation and other Confining Formations. Modified from Figure 21 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 PCLA Subsystem, which includes Pack 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 Alluvial Fan deposits (Qaf/Qas); partially overlying 2) Mesozoic bedrock units (Figure 16; Table 2b in Kolm and van der Heijde, 2018), including the following potentially water-bearing units: the Glen Canyon Group (Jgc), including the Navajo Sandstone (Jn), the Kayenta Sandstone when fractured (Jk), and the Wingate Sandstone (Jw).

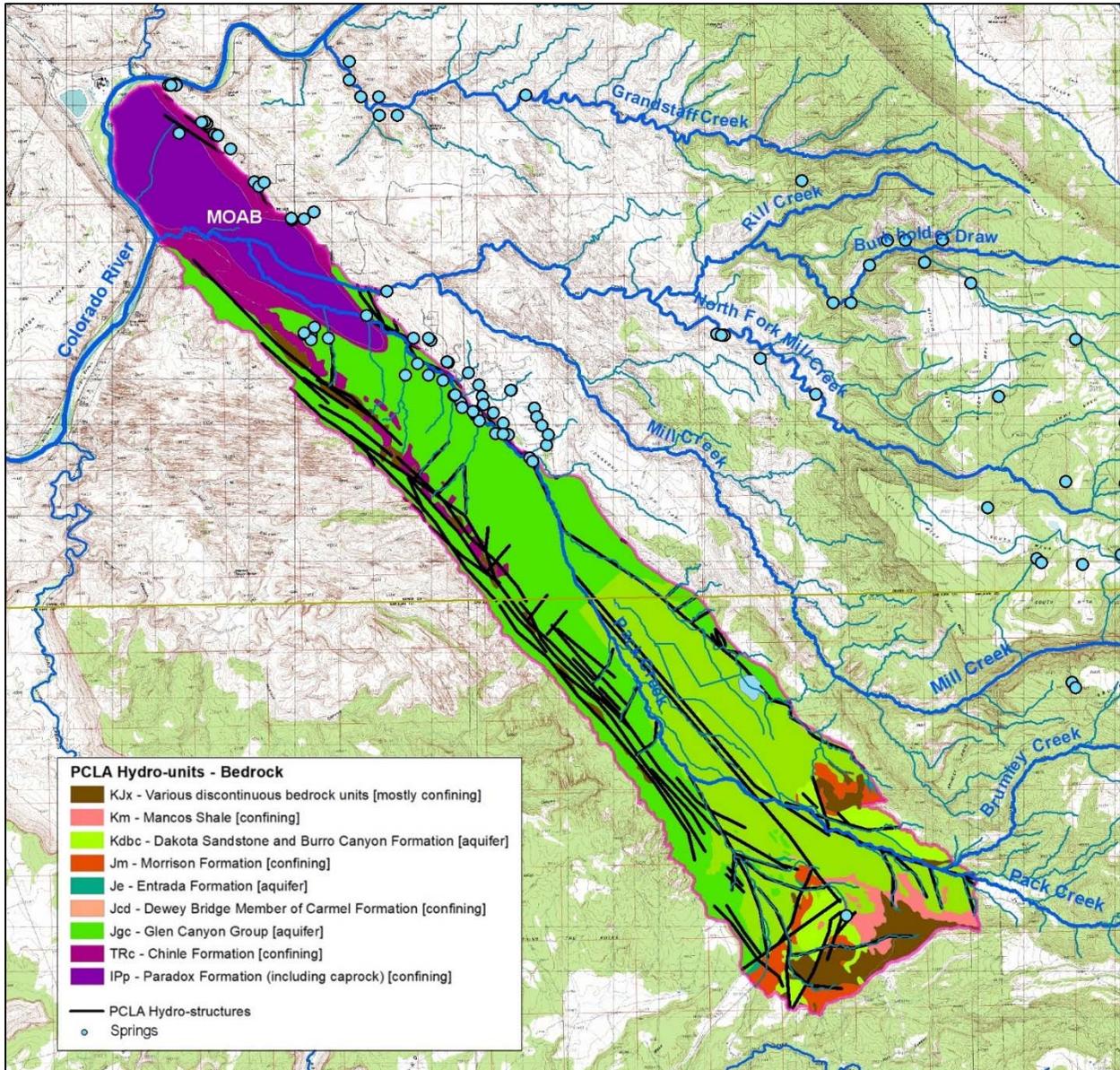
In addition, there are two types of geological structures in the PCLA Subsystem of significance to the hydrogeology in general and to groundwater flow directions in particular (Figures 4 and 5): 1) northeast-southwest and north-south trending fault/fracture zone hydrostructures; and 2) northwest-southeast trending faults, and fault/fracture zones.



**Figure 4. Plan view of the hydrostructures on top of the hydrogeologic units of the PCLA study area.**

The two major northwest-southeast fault zones of importance to the PCLA hydrologic subsystem are located on both sides of the Spanish Valley (Figures 4 and 5). The northeastern fault zone 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. 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 serves as a conduit and connects water leaking from Ken’s Lake with various Grand County wells to the northwest (Figure 6), but can also serve 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

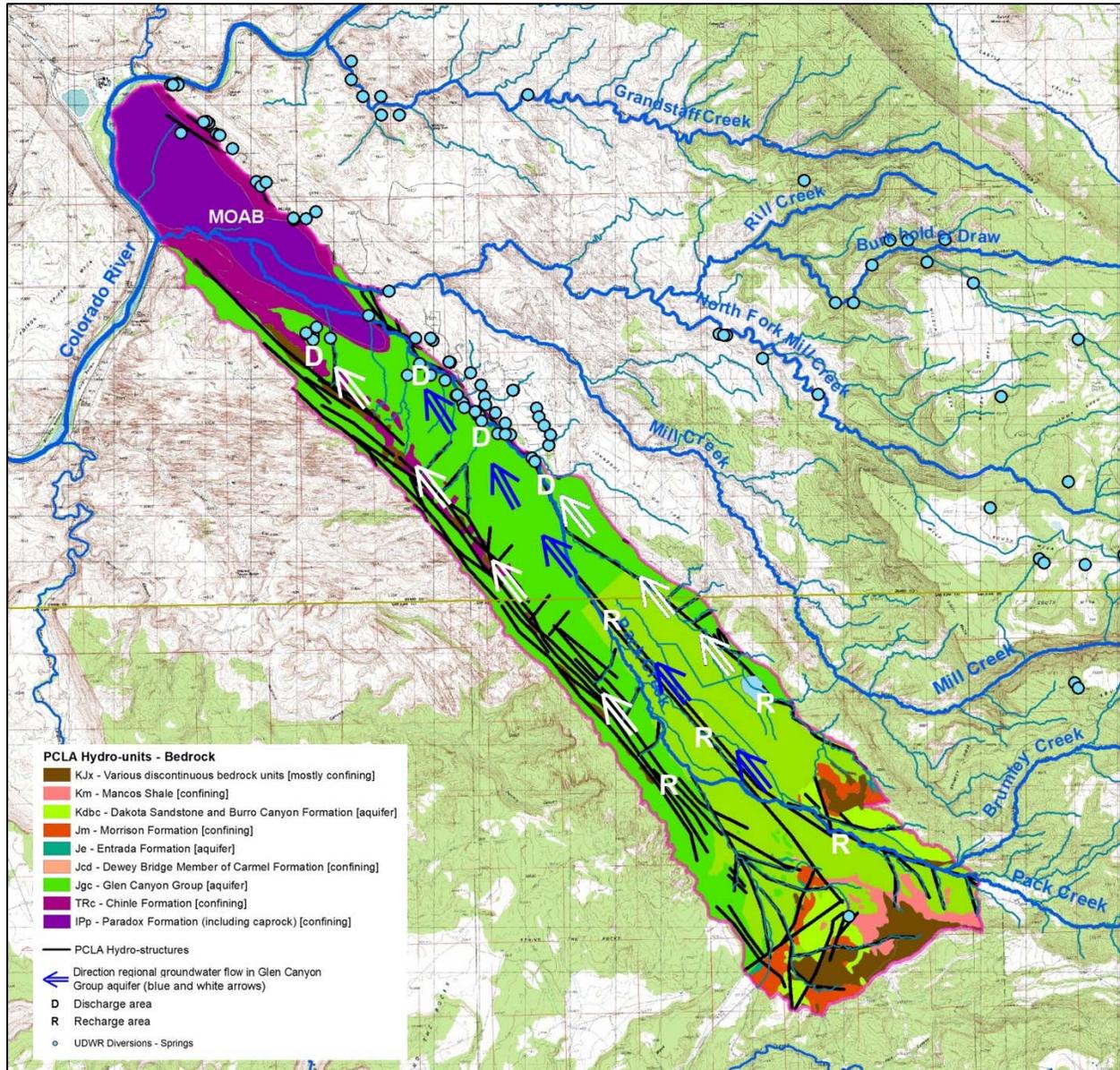
Moab golf course. The southwestern fault zone along the Moab Rim also serves as a groundwater conduit, and allows water to flow from the southwestern part of Spanish Valley northwestward to a set of springs just southwest of the Moab City center (Figure 6).



**Figure 5. Plan view of the hydrostructures on top of the bedrock hydrogeologic units of the PCLA study area.**

The shallow Quaternary unconsolidated materials in this subsystem are located in two strategic locations: 1) directly along the main channels and subsurface paleochannels of the stream (Qal); and 2) aligned along the Moab Rim walls connected to the main channels (Qaf) (Figure 7 and Table 2a in Kolm and van der Heijde, 2018). These alluvial (Qal) highly-permeable deposits are heterogeneous, mostly sand and gravels, and regionally derived from fluvial and glacial activity associated with the La Sal Mountains. The alluvial fan (Qaf) deposits are locally derived from the weathering, mass wasting, and fluvial activity associated with the

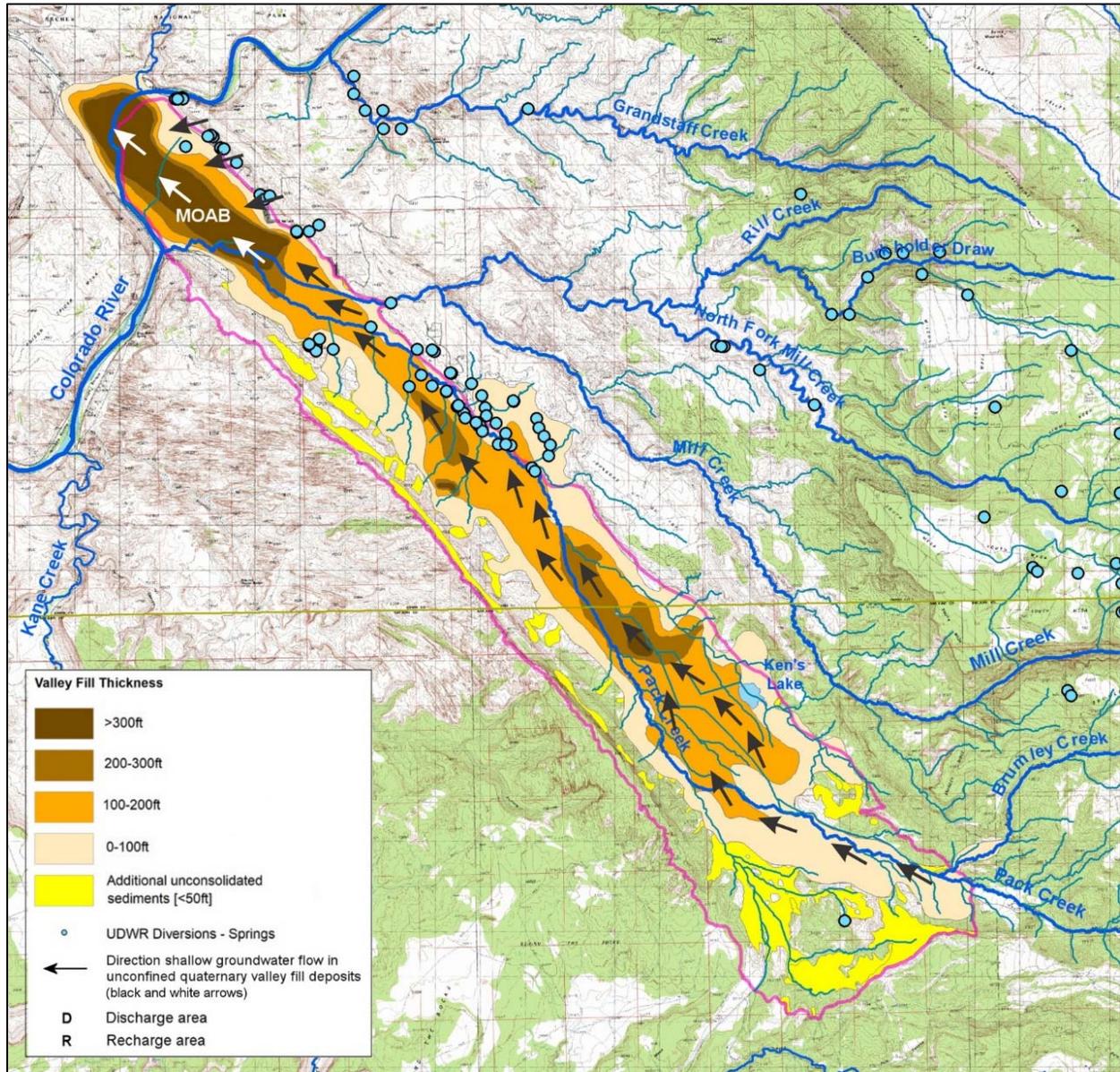
mixed sedimentary rocks of the Moab Rim bedrock. The mixed history of the sedimentary rocks is partially responsible for the high TDS water quality of the shallow aquifer discussed in a later chapter.



**Figure 6. Plan view of the flow directions in the groundwater system on top of the bedrock hydrogeologic units of the PCLA Subsystem area. The blue arrows are groundwater flow directions. The larger white 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 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 matrix flow is mostly located in the center of the central and southern Spanish Valley where the Glen Canyon Group located underneath is present, whereas the fracture flow is mostly associated with the two fault and fracture zones located on either side of the Valley (Figure 6).

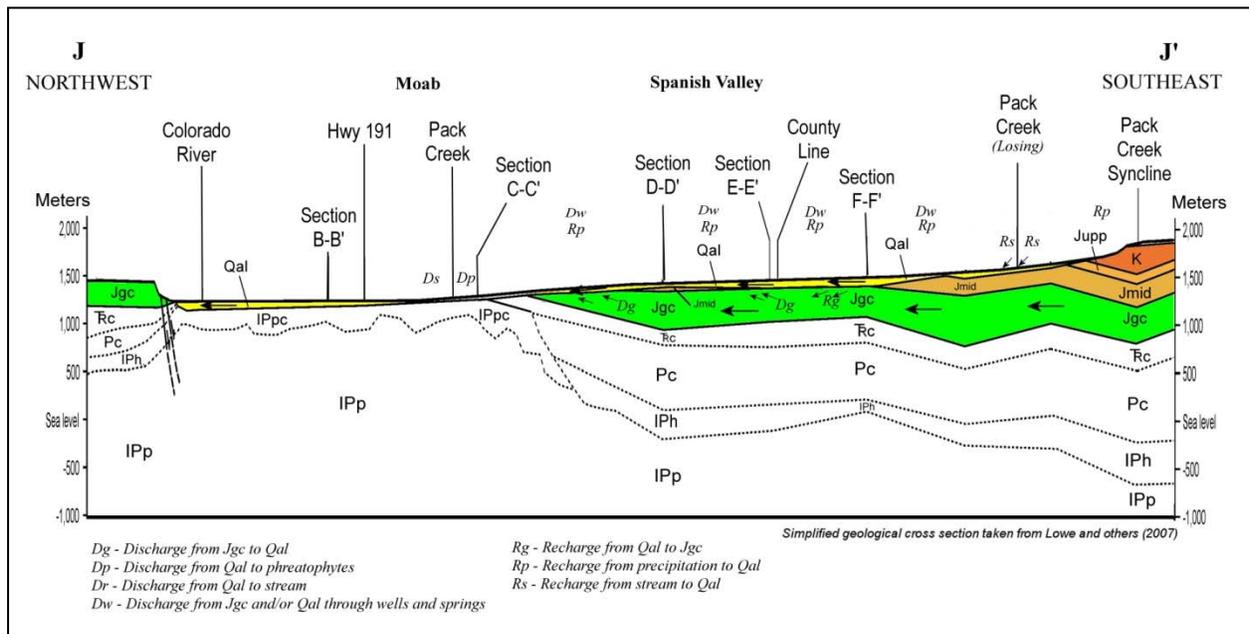


**Figure 7. Plan view of the flow directions in the shallow groundwater system on top of the Unconsolidated Hydrogeologic units of the PCLA Subsystem area. The arrows show groundwater flow direction along major subsurface paleovalleys and the major groundwater flow direction in the Spanish Valley area. Modified from Figure 22 in Kolm and van der Heijde (2018).**

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)(Figure 8). Figure 8 (Figure 31 in Kolm and van der Heijde; 2018) specifically illustrates the groundwater flow paths along the

longitudinal axis of the Spanish Valley. The PCLA shallow groundwater flow systems (Qal and Qaf/Qas) recharge the Glen Canyon Group hydrogeologic units beneath the upper Spanish Valley as is illustrated by the losing reaches of Pack Creek and the Pack Creek diversion ditch. The PCLA subsystem then discharges groundwater as gaining stream reaches and springs in the lower Spanish Valley (Figures 6,7, and 8).

In the lower Spanish Valley from the Moab City limits to the Colorado River, the shallow groundwater in the Pack Creek Lower Alluvial subsystem has little connection to the local bedrock or subregional groundwater systems, given the very low permeability Pennsylvanian Paradox Formation (IPpc) (Figure 8). As the shallow groundwater flows over this bedrock, a tremendous amount of salt is leached greatly reducing the water quality.



**Figure 8. Schematic Northwest-Southeast Cross-sectional View of Part of the Conceptual Site Model of the PCLA Subsystem Along the Axis of the Spanish Valley, Utah (J-J' in Figure 25 of Kolm and van der Heijde, 2019; modified from Figure 31 of Kolm and van der Heijde, 2018).**

Recharge to the PCLA subsystem is by: infiltration of precipitation (snow and rain) directly into the unconsolidated deposits (Qal and Qaf/Qas); losing reaches of ephemeral streams from the Valley sides; losing reaches of Pack Creek, Mill Creek, and the Pack Creek diversion ditch; leakage from Ken’s lake and Faux Falls stream; return flow from irrigation (crops and lawns) and septic tanks; groundwater underflow from the LSMA-P, Brumley Creek, and Mill Creek near the Powerhouse; and springs overflow along the Kayenta Fault and Fracture Zone (Figures 6,7, and 8). Groundwater flow in the PCLA unconsolidated materials is with topography from hilltop and ridgetop down the hillslope to the valley bottom, and then parallel with the valley bottom streams (Figures 7 and 8). Groundwater in the valley bottom stream unit moves in the same direction as the stream with various stream reaches being gaining or losing depending on subsurface topography, saturated thickness of the alluvium, or the seasonal variations caused by snowpack runoff or storm events.

In the lower part of the PCLA subsystem, the alluvial deposits are underlain by a paleo-topographic surface carved out by paleo mass wasting and fluvial systems that eventually deposited the Quaternary unconsolidated materials that are the aquifers being evaluated. It is noted that the paleo-alluvial and modern alluvial systems followed structural fault zone controlled valleys and account for increased aquifer thicknesses in these paleo-valleys (Figure 7). Throughout the subsystem, there is groundwater discharge from the alluvium by phreatophytes, locally by groundwater wells and springs, gaining reaches of streams notably Pack and Mill Creeks from the City Springs area to the Colorado River, and as groundwater underflow to the Colorado River (Figures 7 and 8).

### **3. PRELIMINARY WATER BUDGET OF THE PACK CREEK LOWER ALLUVIUM HYDROLOGIC SUBSYSTEM OF THE MOAB CITY SPRINGS AND WELLS (MCSW) STUDY AREA**

In section 2 of this report, the components of the Pack Creek Lower Alluvium (PCLA) hydrogeologic system and the surface water and groundwater flow systems have been discussed. The PCLA 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, 2019). 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; Masbruch and others, 2019), which can be used to calculate groundwater flux and storage over time.

In order to further understand how the PCLA hydrologic system works, and to determine quantitatively if the hydrologic system is properly analyzed, a water budget may be developed for the PCLA 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 PCLA 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 PCLA 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

Figure 9 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, lakes and reservoirs); 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 9 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.

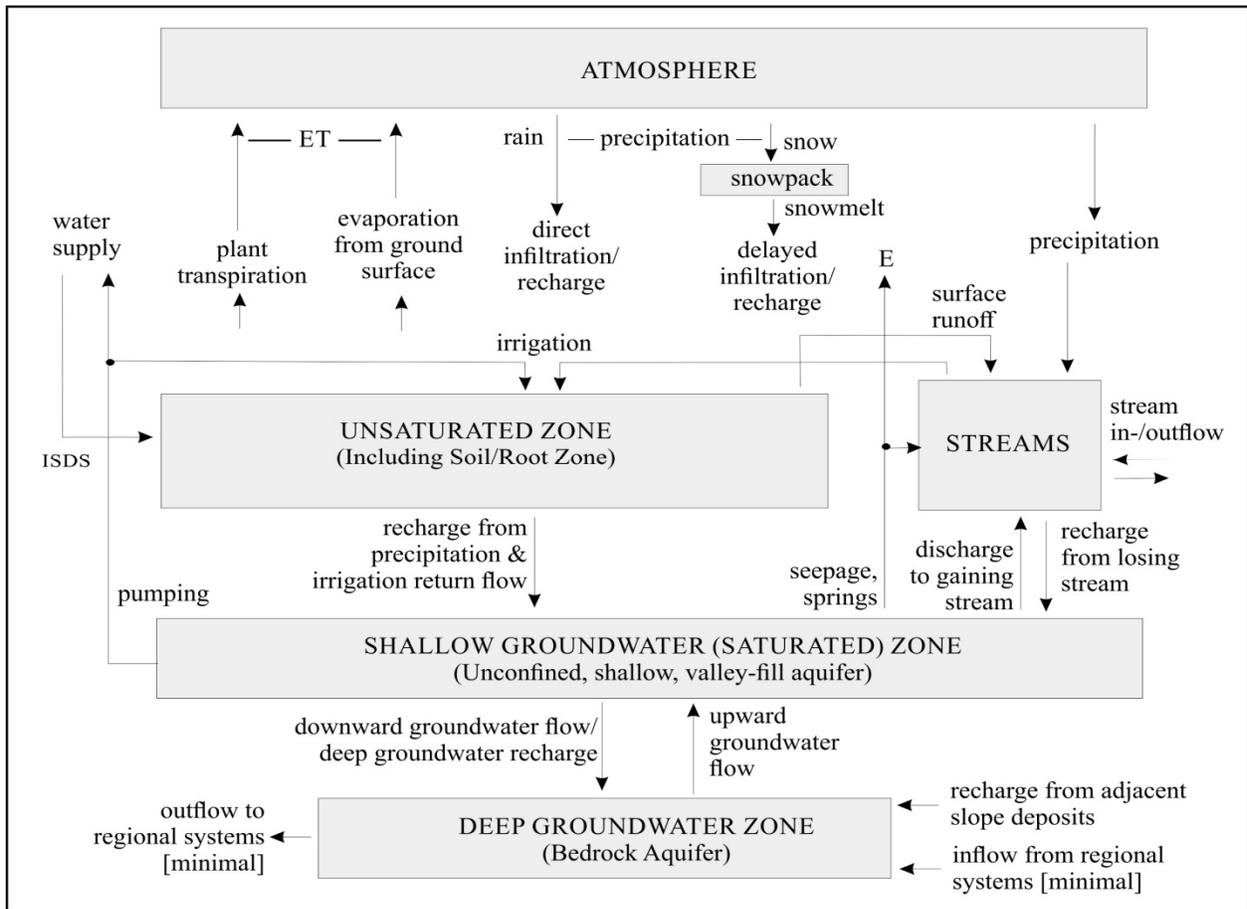
Often, to get a better understanding of the water budget components and reduce uncertainty, the complex set of hydrologic units and processes shown in Figure 9 is simplified by reducing the number of units and processes based on HESA evaluated significance of and data availability for each of these components. 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 9 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 comparison, 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 to the shallow and deep aquifers.

The Conceptual Site Model resulting from the HESA of the PCLA hydrologic system, together with the location of the Pack 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 9 in preparation of a preliminary water budget for PCLA hydrologic system.

### 3.2 Preliminary Water Budget for the PCLA Hydrologic System

A preliminary water budget (PWB) for the PCLA hydrologic system is calculated based upon the information previously collected and analyzed by Kolm and van der Heijde (2018), and

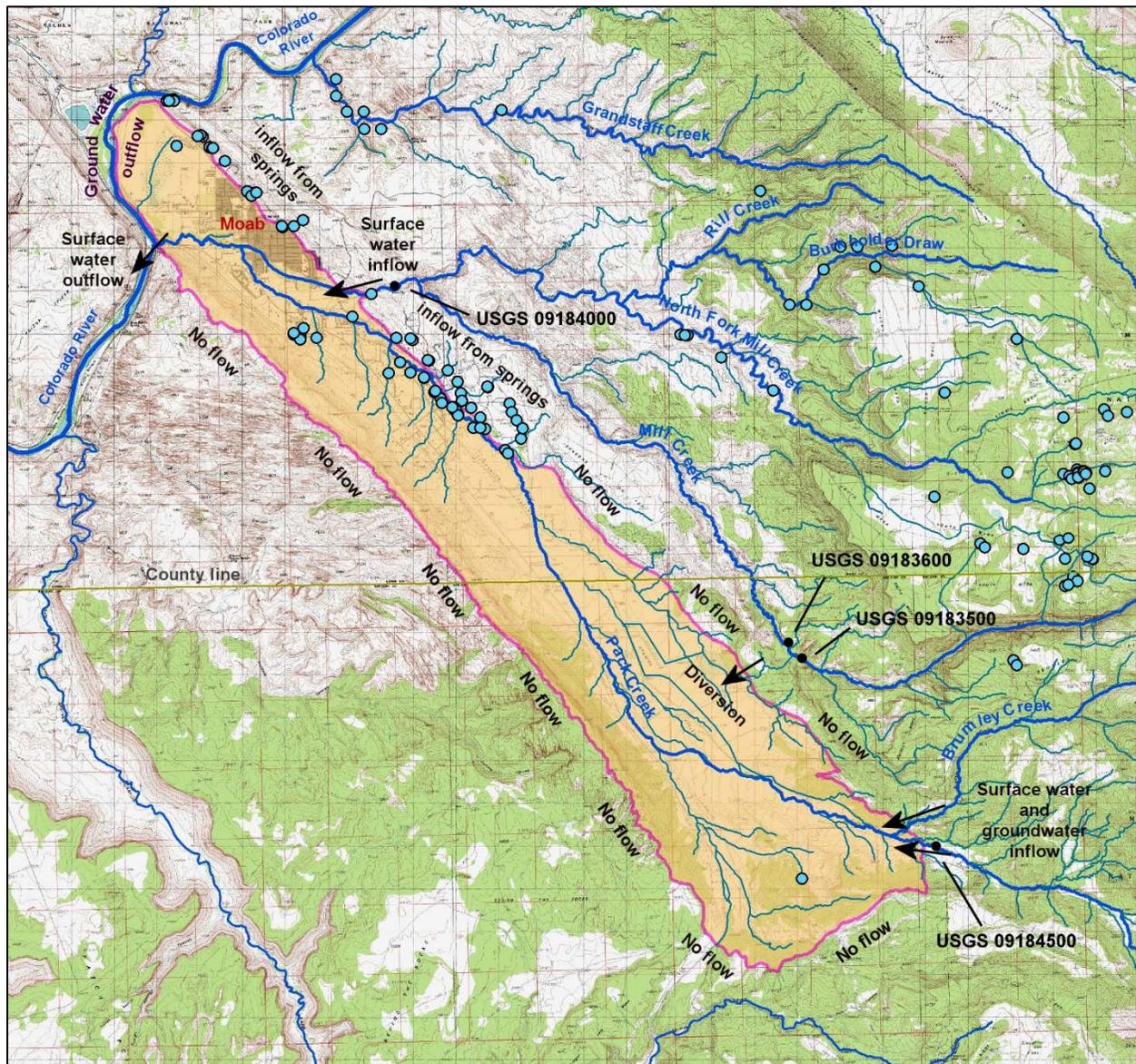
the HESA-based conceptual model of the PCLA hydrologic system determined in Phase I and refined in Task 1 of this Phase (IV) project. The area in PCLA for which the water budget is determined is based, in part, on 1) the locations of various stream gages on Pack Creek and Mill Creek (Blanchard, 1990; USGS Surface-Water Dailey Statistics, Mill Creek at Sheley Tunnel Sites, 2019); 2) the location of most anthropogenic activities (diversions, domestic and agricultural water use); 3) the natural boundaries of the PCLA hydrologic system including Pack Creek and tributaries; and 4) the hydrogeologic and hydrostructural boundaries of the Pack Creek Alluvium Aquifer as determined by HESA (Figure 10). The water budget area is outlined in both Figures 4 and 10 and is bounded by the Glen Canyon Group Mill Creek Subsystem (GCMC) to the northeast and east; the Morrison Formation to the east and southeast; the La Sal Mountain Upper Alluvial Subsystem (LSMA-P) Pack Creek Headwaters to the southeast; the Moab Rim and Kane Creek hydrological divides to the south, southwest, and west; and the Colorado River to the northwest (Figures 4 and 10). The PWB area used in this report covers almost all of the PCLA hydrologic system.



**Figure 9. 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 PCLA hydrologic system were derived from the conceptual models developed in the Phase 1 HESA as illustrated in Figure

10 (boundary conditions), Figures 11 and 12 (hydro zones with springs and wells), and Figure 13 (irrigated areas and riparian vegetation) and are shown in the diagrams in Figures 14a and 14b.



**Figure 10. Map showing the location of the Preliminary Water Budget (PWB) area of the PCLA hydrologic system with boundary conditions, springs and relevant USGS gage locations.**

The significant inputs of the PWB are: 1) direct runoff of precipitation to streams; 2) recharge by infiltration of precipitation (rain and snow) across the entire PWB area using the concept of *hydro zones* explained later in this report; 3) Pack Creek groundwater flux, called groundwater underflow, in the Quaternary hydrogeologic units (Qal) at the SE corner of the water budget area; 4) Brumley Creek groundwater flux, called groundwater underflow, in the Quaternary hydrogeologic units (Qal) at the SE corner of the water budget area; 5) Mill Creek groundwater flux, called groundwater underflow, in the Quaternary hydrogeologic units (Qal) at

the Mill Creek delta (Powerhouse); 6) Pack Creek surface water inflow above the later ditch diversion in the SE corner of the water balance area; 7) Brumley Creek surface water inflow to Pack Creek in the SE corner of the water balance area; 8) Mill Creek surface water inflow at the Mill Creek delta (powerhouse) in the northeast water balance area; 9) Sheley diversion in post-development/current conditions; and 10) springs at eastern PWB boundary from the GCMC system (including City Springs and Skakel spring). 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. The outputs of the PWB are: 1) consumptive use crops; 2) evapotranspiration or consumptive use by phreatophytes (cottonwoods, willows, tamarisk, and other riparian species) (Figure 13); 3) evaporative loss open water; 4) net municipal use (GWSSA and losses/return flow of City Water); 5) domestic consumptive use by private wells (Figure 12b); 6) Mill Creek surface water outflow at the northern end of Spanish Valley to the Colorado River; and 7) groundwater discharge to the Colorado River.

To obtain an understanding on how development in the Spanish Valleys has changed the area's water budget, two PWBs have been developed for: 1) natural conditions as they existed pre-development (no surface water and groundwater diversions, irrigation, etc.); and 2) natural and anthropogenic conditions as they exist today. Figures 14a and 14b show a diagrammatic representation of these water budget components.

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 PCLA study area to greater than 13 inches near the southeastern edges of the PCLA 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.

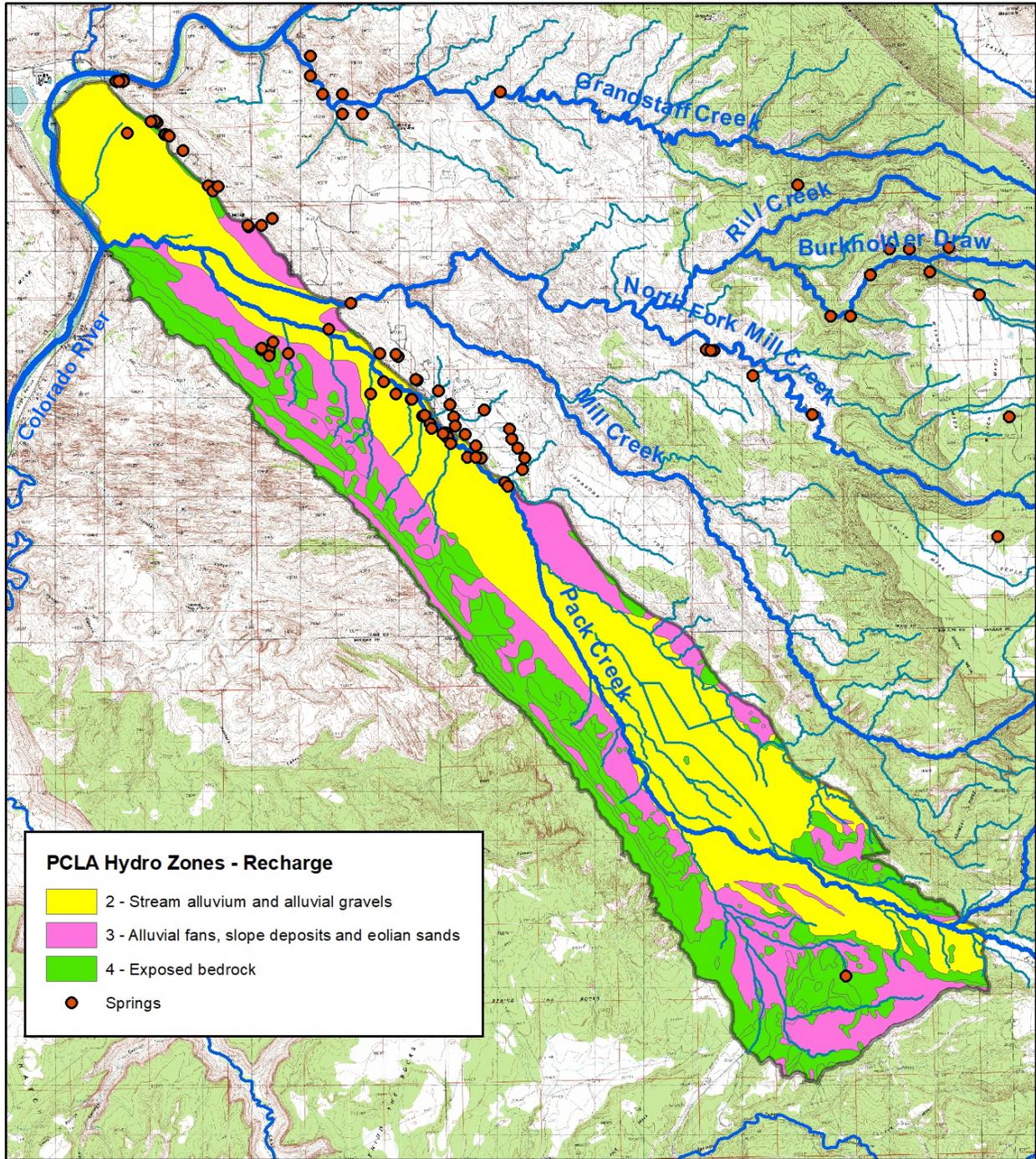
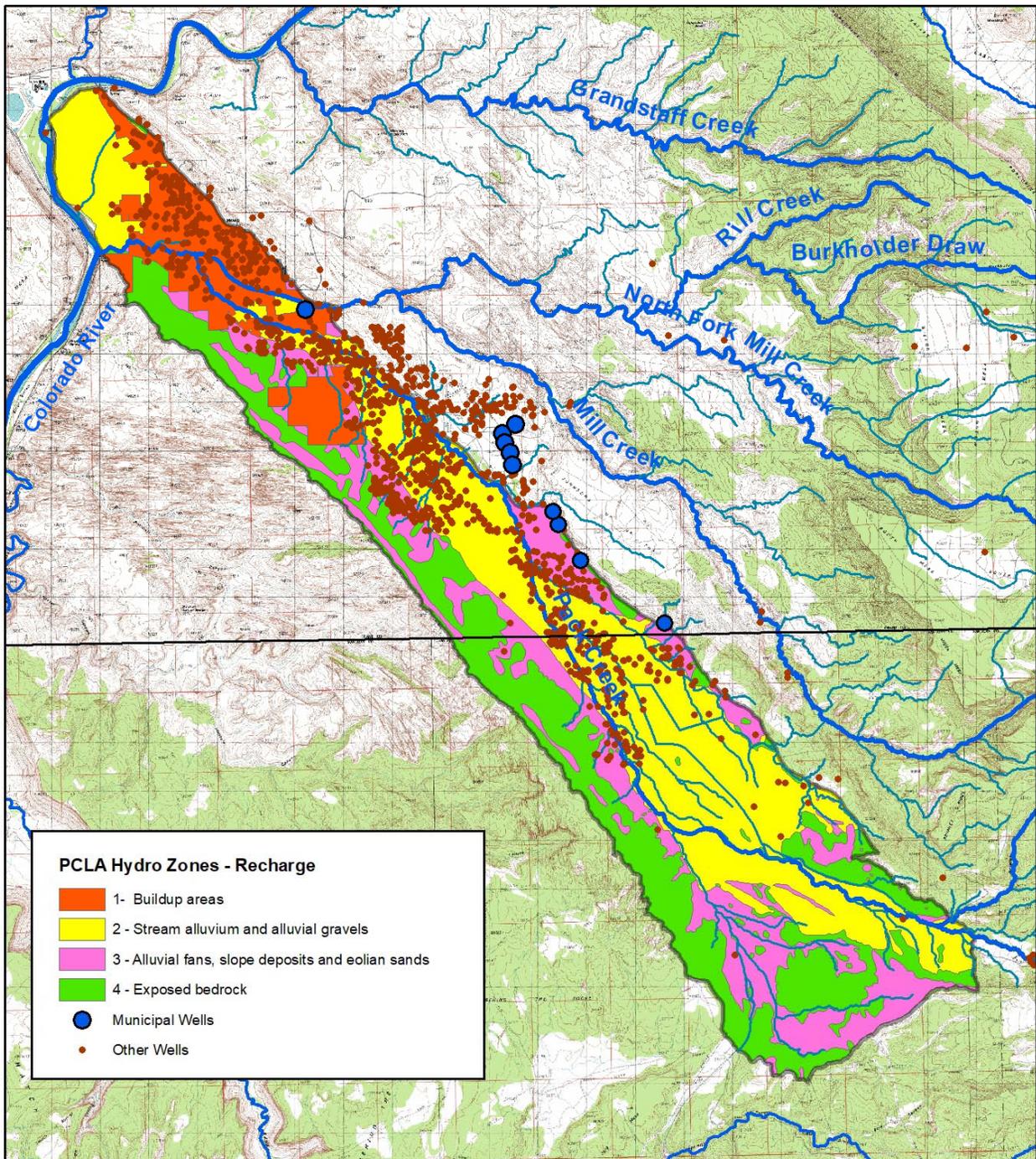
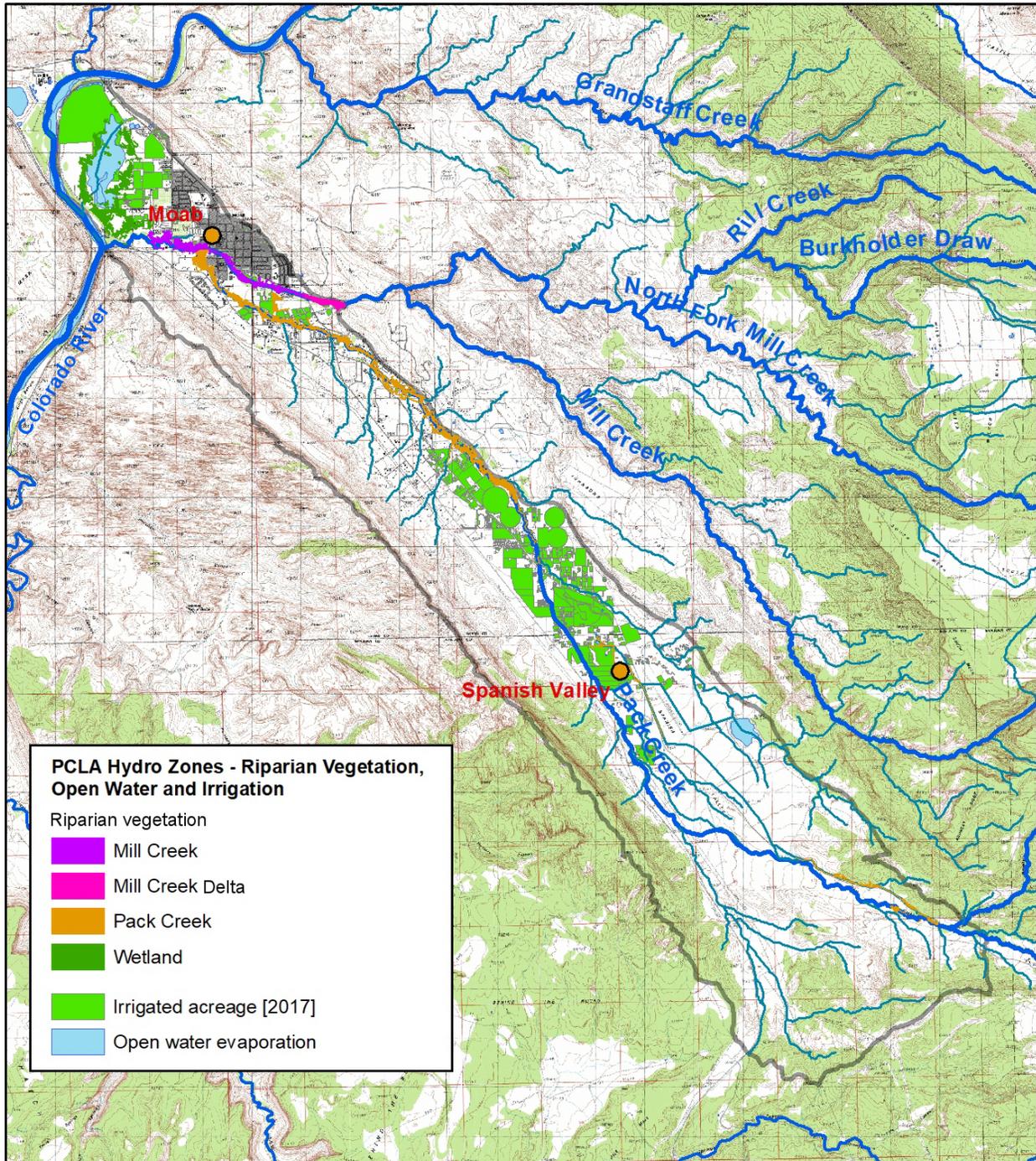


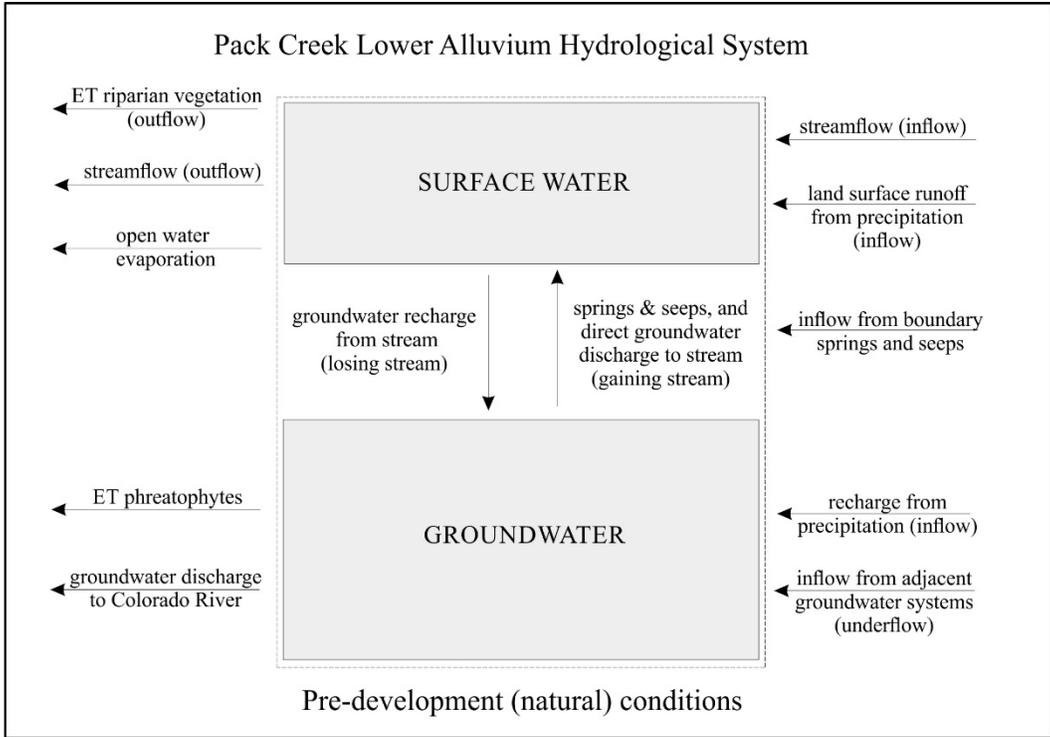
Figure 11. Map showing the location of the Preliminary Water Budget (PWB) area and pre-development recharge Hydro Zones of the PCLA hydrologic system and spring locations.



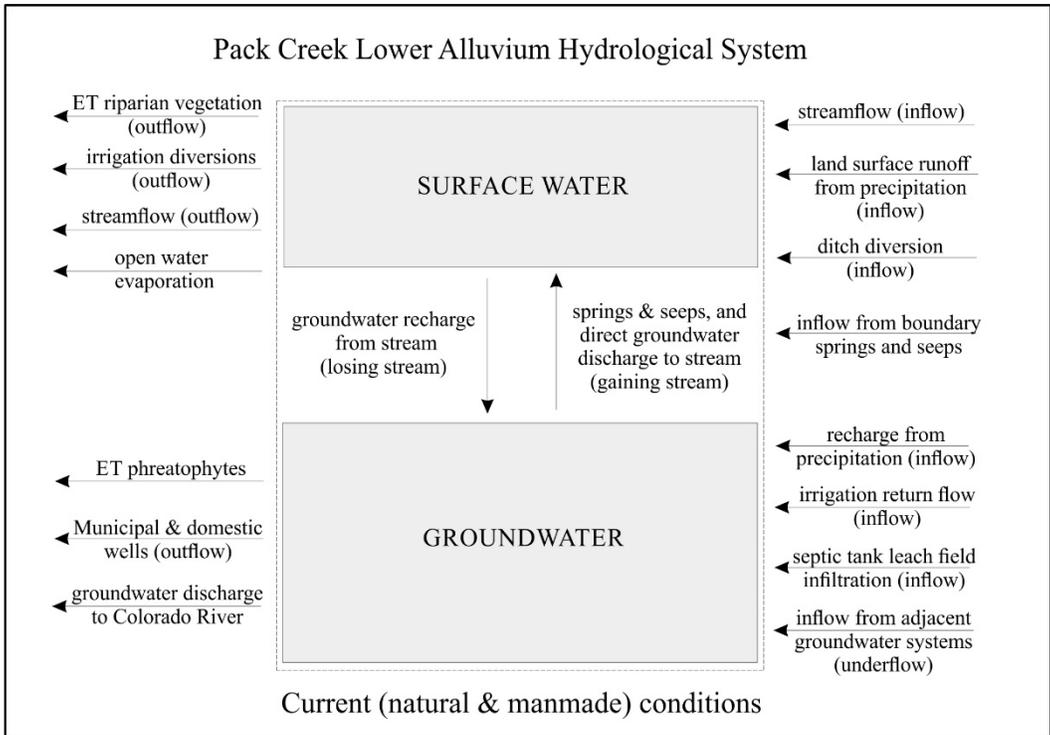
**Figure 12. Map showing the location of the Preliminary Water Budget (PWB) area and post-development recharge Hydro Zones of the PCLA hydrologic system and municipal and private well locations.**



**Figure 13. Map showing the location of riparian vegetation, open water and irrigated land Hydro Zones of the PCLA hydrologic system.**



**Fig 14a. Simplified diagram of inflows and outflows for the pre-development (natural) PCLA hydrologic system.**



**Fig 14b. Simplified diagram of inflows and outflows for the current (natural and anthropogenic) PCLA hydrologic system.**

In addition, several other sources of published data provided input into the PWB: 1) Mill Creek discharge measurements on October 21, 1985 and October 14, 1986 as published in Blanchard (1990) provided surface water inputs to the PCLA hydrologic system at the Mill Creek delta (Powerhouse) (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 Sheley diversion (USGS Surface-Water Dailey Statistics, 2019); 3) historic USGS stream gage data for Mill Creek collected near the Mill Creek delta (Powerhouse) and for Pack Creek in the upper Spanish Valley area of the PWB (USGS Surface-Water Dailey Statistics, 2019); 4) adjudicated maximum sustainable 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 and the Grand Water and Sewer Service Agency (GWSSA), provided a first approximation of related inputs and outputs in the PWB; and 5) phreatophyte consumptive use measurements published by Muckel and Blaney (1945) provided data regarding outputs due to natural vegetation effects in the PCLA hydrologic system.

### 3.3 Approach to Preliminary PCLA Water Budget Calculations

Many of the identified data sets 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 (i.e., pre-human habitation or natural) annual averaged water budget components. 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 (current) water budget.

In order to quantify some of the components of the preliminary PCLA water budget given the sparseness of published data, the PCLA hydrologic system was spatially categorized into 7 types of hydro zones reflecting characteristic hydrologic processes such as recharge, evapotranspiration and evaporation from open water. The delineation of these zones is based upon the hydrogeology and geomorphology, groundwater and surface water hydrology, land use and distribution of phreatophytes (Figures 11 and 12; Figure 13). Hydro Zone 1 is the urban zone and is characterized by relatively impermeable materials (roads, parking lots, houses) with minimal groundwater recharge and storage and maximum surface water runoff (Figures 11 and 12); this hydro zone only features in the post-development PWB calculation.

Hydro Zone 2 is the area covered by stream alluvium and alluvial gravels (Qal) and represents very rapid recharge and large storage. This zone is underlain by matrix (relatively non-fractured) Glen Canyon Group rocks that have minimal groundwater flow and storage compared to the overlying alluvium.

Hydro Zone 3 are the areas covered by alluvial fan and slope deposits (Qaf and Qas) and represents very rapid recharge and potentially large storage when saturated. This zone is primarily underlain by highly-fractured and faulted Glen Canyon Group rocks that may have significant groundwater storage comparable to the overlying alluvium. Hydro Zone 3 on the

northeast and east side of the valley consists of fan deposits on top of a highly transmissive (high-K) fracture zone (French Drain) that moves water from Ken's Lake to Pack Creek at the GWSSA wells and near the outlet of the City Springs (Figure 11). This part of zone 3 has very large recharge and storage functions, but no significant phreatophyte discharge on the surface. Hydro Zone 3, located on the southwest and west side of the valley (along the Moab Rim), is present from near where Pack Creek (usually dry) makes a bend trending from west to northwest to Jackson and Pioneer springs near the southwest part of the City of Moab. The hydrostructure underneath these fan deposits is also a highly transmissive fracture zone (French Drain) that moves water from the usually dry stream of Pack Creek to the Jackson and Pioneer springs near the southwest part of Moab (Figure 11). Again, this part of zone 3 has very large recharge and storage functions, but no significant phreatophyte discharge on the surface until the springs (Figure 13).

Hydro Zone 4 is exposed bedrock mostly characterized by the presence of hydrostructures. On the southwest and west side of the valley (along the Moab Rim) is a fracture-enhanced high-K bedrock zone observed along most of the Spanish Valley. This hydrostructure is also highly transmissive, moving water from the Rim into the Valley where cross fractures are observed to the high K zone in Hydro Zone 3, which discharges to Jackson and Pioneer springs near the southwest part of Moab (Figure 11). This zone has small recharge and storage functions, and no significant phreatophyte discharge on the surface (Figure 13).

Hydro Zone 5 is the phreatophyte zone with consumptive use by riparian vegetation, including wetlands. Hydro zone 6 represents irrigated lands characterized by consumptive use by crops and return flow of excess irrigation water (recharge). Hydro Zone 7 is open water (lakes, ponds, reservoirs) with evaporative losses to the atmosphere. The extent of hydro zones 5, 6 and 7 is depicted in Figure 13. The City of Moab provided assistance in digitizing the hydro zones and sub-zones.

The preliminary pre-development (natural conditions) PCLA water budget has as inputs (Table 1): 1) direct runoff of precipitation to streams; 2) recharge by infiltration of precipitation (rain and snow) across the entire PWB area; 3) Pack Creek groundwater flux, called groundwater underflow, in the Quaternary hydrogeologic units (Qal) at the SE corner of the water budget area; 4) Brumley Creek groundwater flux, called groundwater underflow, in the Quaternary hydrogeologic units (Qal) at the SE corner of the water budget area; 5) Mill Creek groundwater flux, called groundwater underflow, in the Quaternary hydrogeologic units (Qal) at the Mill Creek delta (Powerhouse); 6) Pack Creek surface water inflow above the later ditch diversion in the SE corner of the water balance area; 7) Brumley Creek surface water inflow to Pack Creek in the SE corner of the water balance area; 8) Mill Creek surface water inflow at the Mill Creek delta (powerhouse) in the northeast water budget area; and 9) spring runoff from the GCMC system at eastern PWB boundary, including the current City springs at the golf course and Skakel spring. 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. The predevelopment (natural) outputs of the PWB are: 1) consumptive use by native phreatophytes (cottonwoods, willows, tamarisk, and other riparian species) (Figure 13); 2) evaporative loss open water; 3) groundwater and spring discharge to the Colorado River; and 4) Mill Creek

surface water outflow at the northern end of Spanish Valley to the Colorado River. Each of these terms are discussed in detail in following sections.

Preliminary post-development PCLA 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 for climate change, land use changes, and diversions (Table 2). Specifically, the effects of the Sheley diversion, the development of municipal and domestic water supply, and irrigation on input and output are evaluated. Although some wells in Spanish Valley show a decline in water levels, uncertainties in the PWB do not support including a continuing, multi-year release of water from subsurface storage at this time.

### 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 PCLA hydrologic system to greater than 13 inches near the southeastern edges of the PCLA hydrologic system, most of which is in the form of rain. To evaluate recharge, three recharge scenarios have been evaluated as a function of the spatial distribution and amount of precipitation in each recharge hydro zone (hydro zones 1-4): 1) low estimate using 5-20% of precipitation dependent on hydro zone type; 2) a high estimate using 5-30% of precipitation and 3) a “best” estimate using 5-25% of precipitation (Appendix A and B). The average annual precipitation was calculated for each hydro sub-zone in both inches and acre-ft for both the periods 1971-2000 (considered representative for pre-development conditions) and 1981-2010 representative for “current” conditions) by overlaying the sub-zone GIS layer with the two precipitation GIS layers. The calculations are listed in Appendix A and Appendix B and can be summarized as follows: 1) for the period 1971-2000 the low estimate is 2500 ac-ft/yr, the high estimate is 3865 ac-ft/yr; and the “best” estimate is 3170 ac-ft/yr or 1.9 inches across the entire PWB area; 2) for the period 1981-2010 the low estimate is 2215 ac-ft/yr, the high estimate is 3315 ac-ft/yr, and the “best” estimate is 2765 ac-ft/yr or 1.6 inches across the entire PWB area (Tables 1 and 2). Note that the “best” estimate for recharge in both periods amounts to about 16-17 % 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 1) consists of direct runoff of precipitation to streams and amounts to 815 ac-ft/yr. This term, corrected for the decline in precipitation between the two climate periods and the increase of direct runoff in buildup/urbanized areas amounting to a total of 1300 ac-ft/yr, is used in the post-development scenario (Table 2). 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 about 14,525 ac-ft/yr for the pre-development period and to 13,565 ac-ft/yr for the post-development period, or about 75-78% of total precipitation. All these numbers are based on 30-year averages for the two climate periods.

### 3.5 Calculation of Groundwater Underflow at Upper Pack Creek Boundary

The basis for the calculation of groundwater underflow at the Upper Pack Creek in the southeastern boundary of the PWB area (Figure 10) 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 1-10 ft/day for stream alluvium and alluvial gravels in the PWB area ((Lowe and others, 2007; Masbruch and others, 2019)). Hydraulic gradient calculated based on potentiometric surfaces published in Lowe and others (2007) and Masbruch and others (2019) of 0.025. The cross-sectional area to calculate groundwater underflow flux is estimated as the geometry of the stream alluvium and alluvial gravels: 20-50 ft depth, average 35 ft. (from well measurements) and 2700 ft width (from topographic data). An average K value for the underflow component of the PWB of 5 ft/day is used. This results in a groundwater underflow flux (inflow) of 100 ac-ft/yr (Tables 1 and 2).

### 3.6 Calculation of Groundwater Underflow at Brumley Creek Boundary

The basis for the calculation of groundwater underflow at the Upper Pack Creek in the southeastern boundary of the PWB area (Figure 10) 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 1-10 ft/day for stream alluvium and alluvial gravels in the PWB area ((Lowe and others, 2007; Masbruch and others, 2019)). Hydraulic gradient calculated based on potentiometric surfaces published in Lowe and others (2007) and Masbruch and others (2019) of 0.025. The cross-sectional area to calculate groundwater underflow flux is estimated as the geometry of the stream alluvium and alluvial gravels: 20-50 ft depth, average 35 ft. (from well measurements) and 600-700 ft width, average 650 ft (from topographic data). An average K value for the underflow component of the PWB of 5 ft/day is used. This results in a groundwater underflow flux (inflow) of 25 ac-ft/yr (Tables 1 and 2).

### 3.7 Calculation of Groundwater Underflow at Mill Creek delta (Powerhouse)

The basis for the calculation of groundwater underflow at Mill Creek delta (Powerhouse) in the northeastern boundary of the PWB area (Figure 10) 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 GCMC subsystem described in the project's phase 2 report (Kolm and van der Heijde, 2019). K is determined by aquifer tests, which reveal a range of values that average approximately 1-10 ft/day for stream alluvium and alluvial gravels in the PWB area ((Lowe and others, 2007; Masbruch and others, 2019)). Hydraulic gradient calculated based on potentiometric surfaces published in Lowe and others (2007) and Masbruch and others (2019) of 0.010 – 0.0125, average 0.01125. The cross-sectional area to calculate groundwater underflow flux is estimated as the geometry of the stream alluvium and alluvial gravels: 20-50 ft depth, average 35 ft. (from well measurements) and 500 ft width (from topographic data). An average K value for the underflow component of the PWB of 5 ft/day is used. This results in a groundwater underflow flux (inflow) of 10 ac-ft/yr (Tables 1 and 2).

### 3.8 Calculation of Pack Creek Surface Water Inflow above Ditch Diversion

For a short period in the 1950s (1955-1959) the USGS operated a stream gage on Pack Creek just upstream from the southeast PWB boundary (USGS gage 09184500 Pack Creek at M4 Ranch near Moab Utah, Figure 10). The annual discharge values for this period range from 0.647 to 5.05 cfs with an average of 2.541 cfs or about 1845 ac-ft/yr. As no other published information on Pack Creek flows in this area is available, the above multi-year average has been used for the pre-development PWB. Recognizing significant variability in the above data and the short collection period, this PWB term should be considered a first approximation. For the post-development Pack Creek inflow term, the pre-development term has been adjusted for the 5% decline in 30-year average precipitation between the 1971-2000 and 1981-2010 climate periods, resulting in a post-development term of 1755 ac-ft/yr. This latter term may need to be further adjusted to compensate for diversions in the upper Pack Creek reaches within the La Sal Mountain hydrologic subsystem that were introduced after the period of record at gage 09184500.

### 3.9 Calculation of Brumley Creek Inflow to Pack Creek

There is no formal stream gage on Brumley Creek to date. Field estimates of 1.5 -2.0 cfs or 1085 – 1450 ac-ft/yr were taken November 2019 during baseflow (no phreatophyte activity, no rainfall or snow events for 5 previous weeks) several miles above the confluence of Brumley and Pack Creeks where the stream was flowing. 1100 ac-ft/yr was used in the water budget calculations.

### 3.10 Calculation of Mill Creek Surface Water Inflow at Mill Creek Delta (Powerhouse)

The Mill Creek inflow into the PCLA PWB is based on the daily gage readings by the USGS at USGS 09184000 in the vicinity of the Powerhouse during the period 1949-1993 with a hiatus from 1958 to 1987 (Figure 10). The average annual flow at gage 09184000 for the period of record is 9928 ac-ft/yr. This number is adjusted for pre-development (natural) conditions taking in consideration the absence of municipal and domestic consumptive use in the GCMC area in the pre-development era (pre-1950s) by redistributing the consumptive use number among the other PWB terms and is estimated at 10755 ac-ft/yr. This number minus the water that the stream loses to groundwater between the gage site and the PWB boundary as is accounted for in the underflow term of 10 ac-ft/yr, is used in the pre-development PWB as a first approximation (10745 ac-ft/yr, Table 1). Note that this number differs from the phase 2 reported “pre-development” or pre-1980 number of 9928 ac-ft/yr as the latter number includes pre-Sheley diversion development of the GCMC and PCLA areas. The post-development Mill Creek outflow reported in Phase 2 (9020 ac-ft/yr) has been further reduced to reflect current conditions including increased municipal and domestic consumptive use and is estimated at 8960 ac-ft/yr. Taking into consideration the loss to groundwater between the gage site and the PWB boundary of 10 ac-ft/yr, the post-development PWB term for the inflow from Mill Creek at the eastern PWB boundary is set at 8950 ac-ft/yr. (Table 2).

### 3.11 Calculation of Sheley Diversion

The inflow in the post-development PCLA PWB from the Sheley diversion (post-2003) is based on the difference between daily gage readings by the USGS at USGS 09183500 just above the location of the Sheley diversion and at USGS 09183600 below the Sheley diversion for the period 2004-2017 (Figure 10). 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 (Table 2). This is the average annual amount of water diverted from the GCMC hydrologic system to the PCLA system. 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%.

### 3.12 Calculation of Input from GCMC Springs at eastern PWB boundary

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) and presented in this project’s phase 2 report. 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. Because the phase 2 report excluded the City’s springs at the golf course and the diversion at Skakel spring, as they were included in municipal consumptive use term, the phase 2 “pre-development” term has been adjusted for the new pre-development (natural) conditions taking in

consideration the absence of municipal and domestic consumptive use in the GCMC area in the pre-development era (pre-1950s) by redistributing the consumptive use number among the other PWB terms and is estimated at 2515 ac-ft/yr (Table 1). Additional decline in spring runoff due to the coming on line of the Sheley diversion in Mill Creek and increased municipal and domestic consumptive use has been taken into account in estimating the “current” (post-development spring runoff term set at 1725 ac-ft/yr (Table 2).

### 3.13 Evaporative Loss Open Water

The two main bodies of open water in the PCLA PWB area are Ken’s Lake and the wetlands in the northwest corner of the PWB area for a total of 1950 acres (Utah SGID Lakes in Grand and San Juan Counties GIS layers, 2019). Assuming an effective open water evaporation rate of 90 in/yr, the PWB term for this process in both pre- and post-development PWB is set at 1460 ac-ft/yr.

### 3.14 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 as guidance for the calculation of the consumptive use of riparian vegetation. The mapped area of current riparian vegetation is about 520 acres. Assuming a consumptive use rate of 90 in/yr this post-development PWB term amounts to 3900 ac-ft/yr. In the pre-development PWB it is assumed that significant more water was available for riparian vegetation. For the purpose of calculating the PWB term it is assumed that the pre-development area of riparian vegetation was about 755 acres; using 90 in/yr of consumptive use, the related pre-development PWB term is 5665 ac-ft/yr.

### 3.15 Calculation of Consumptive Use by Crops

The consumptive use of crops term only applies to the post-development PWB. The Utah SGID Irrigated Lands GIS layer (2019) shows an irrigated area within the PCLA of 2030 acres. As there is an overlap with open water area of about 100 acres, the effective irrigated area is set at 1930 acres of which about 70% is estimated to be actually used. Net consumptive use is estimated at 32 in/yr (Castle Valley, Ford, 2006) for a total of 3600 ac-ft/yr.

### 3.16 Calculation of Municipal Use

The municipal consumptive use term consists of water diverted from either surface water or groundwater within the PCLA PWB area minus water returned to the hydrologic system from leaking pipelines in the distribution and collection systems, lawn watering, etc. There are 2 major municipal water systems in the PCLA area: City of Moab and GWSSA. The City of Moab has its water sources outside the PWB area, while the GWSSA has its water sources within the PCLA area (wells). In 2017 the GWSSA had an annual production of about 815 ac-ft/yr (GWSSA, 2017). Assuming the return flow from the distribution and collection systems at about 100 ac-ft/yr, the post-development (current) PWB term for municipal consumptive use is set at 715 ac-ft/yr.

### 3.17 Calculation of Domestic Consumptive Use

There are many domestic wells in the PCLA area of which about 475 are estimated to be household wells (UDWR, 2019). 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, resulting in approximately 200 ac-ft/yr post-development. Note that this consumptive use number is a first estimate of actual consumptive use, taking into consideration the presence of both permanently and occasionally occupied dwellings.

### 3.18 Groundwater and Spring Discharge to Colorado River

The PCLA PWB term for groundwater and spring discharge to the Colorado River is based on the findings published in a recent USGS study (Masbruch and others, 2019). The report provides a range of 300-1000 ac-ft/yr. As a first approximation 750 ac-ft/yr is used in both the pre- and post-development PWBs.

### 3.19 Mill Creek Outflow to Colorado River

The PCLA PWB term for Mill Creek discharge to the Colorado River is based on the findings published in a recent USGS study (Masbruch and others, 2019). The report sets this number at 10830 ac-ft/yr. This number is used in the post-development PWB. For the pre-development this number has been multiplied by 1.15, the ratio between pre- and post-development streamflow in Mill Creek entering the PCLA PWB area, for a total of 12450 ac-ft/yr.

### 3.20 PWB and the PCLA 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 PCLA hydrological system from the La Sal Mountain and GCMC hydrological systems, or in percentages of pre-development input into the PCLA hydrologic system: surface water and groundwater derived from the GCMC hydrologic system (Mill Creek + groundwater underflow at the Mill Creek delta + springs at eastern PWB boundary from GCMC system) is 13,270 ac-ft/yr and counts for approximately 65%; local recharge from precipitation and direct runoff from precipitation to streams counts for 20%; and directly linked groundwater inflow and surface water inflow (Pack Creek and Brumley Creek) from the La Sal Mountains hydrological subsystems counts for 15%. This means that the La Sal Mountain and GCMC subsystems contribute more than 80% of the total inflow in the PWB area. Note that a combined consumptive use riparian vegetation and evaporative loss open water accounts for 35% of the total water budget out, and remainder is subsurface and surface discharge to the Colorado River. By comparison, in the post development time period, the contribution of the Sheley diversion to the overall input becomes more of a factor, or in percentages of post development input into the PCLA hydrologic system: surface water (Mill Creek + Pack Creek + Brumley Creek) counts for approximately 55%; local recharge from precipitation and direct runoff to streams for 19%; groundwater inflow from the GCMC hydrological subsystems counts for about 9%; and the Sheley diversion provides 17% of the total inflow to the PCLA hydrologic system and has resulted in a 17% reduction of Mill Creek inflows towards Spanish Valley under base flow conditions and 31% 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 PCLA 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 Pack Creek and Brumley Creek at the southeast end of the PCLA 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 and in Pack Creek in the southeastern part of the Spanish Valley; the springs and wells production data from the City of Moab and GWSSA, 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-GWSSA 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, and 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 in great detail. However, the domestic consumptive use is small by comparison to other PWB terms.

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.

Although the Pack Creek inflow into the PCLA system is significant smaller than the Mill Creek contribution (17%), Pack Creek still provides a significant contribution to the PCLA system, especially in the upper section of Spanish Valley. As USGS gage 09184500 has only be in operation for a short time in the 1950s, resuming of monitoring Pack Creek at this site should be considered.

Concurrently, the climate data used to estimate groundwater recharge as infiltration from 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.

### 3.21 PWB and the PCLA Hydrologic System: Concerns Regarding Sustainability

There are a number of potential threats to the sustainability of the PCLA hydrologic system and thus to the water supply of the City of Moab and Grand County, 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 PCLA hydrologic system, will result in decreased surface water flows and groundwater recharge from losing streams. Impacts on the PCLA 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 Pack Creek and Brumley Creek at the southeast end of the PCLA 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 PCLA hydrologic system will result in further decline of outflows such as at Pack Creek and Brumley Creek in the southern part of the study area and various springs, and will likely lead to decline in storage and subsequent lowering of groundwater levels and groundwater availability for phreatic consumption.

### 3.22 PWB and the PCLA 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 Pack Creek surface water system. Gaging stations at Mill Creek (Powerhouse, Junction with Pack Creek, Colorado River), Pack Creek (City Springs and Perennial Flow locations, Pack Creek Bridge, Settlement of Pack Creek, and Brumley Creek that record daily, seasonal, and annual information would improve the measurements of the City of Moab and Spanish Valley 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 PCLA 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, and Phase 4, Chapter 2 of the current study, provides a surface water and groundwater conceptual model that would be useful for the design, implementation, and calibration for these types of models. This Phase 4 HESA revealed that the PCLA groundwater system was complex being both matrix and fracture-type flow, and that the design, implementation, and calibration of this type of model can be done, and may be cost-effective at this time. Given the uncertainties with the data available, the results would still tend to be questionable. The PWB of the GCMC groundwater system in Phase 2 would provide inputs into the Spanish Valley model, and the HESA of the PCLA and GCMC groundwater systems would provide boundary conditions for that model.

WATER BUDGET COMPONENT	IN (ac-ft/yr)	OUT (ac-ft/yr)
<i>Direct runoff to streams</i> Estimated (section 3.4)	815	-
<i>Recharge</i> Calculated (section 3.4)	3170	-
<i>Groundwater underflow at upper Pack Creek boundary</i> Calculated (section 3.5)	100	-
<i>Groundwater underflow at Brumley Creek</i> Calculated (section 3.6)	25	-
<i>Groundwater underflow at Mill Creek delta (Powerhouse)</i> Calculated (section 3.7)	10	-
<i>Pack Creek inflow above later ditch diversion</i> Measured (section 3.8)	1845	-
<i>Brumley Creek flow into Pack Creek</i> Estimated (section 3.9)	1100	-
<i>Mill Creek inflow at MC delta (Powerhouse)</i> Measured (section 3.10)	10745	-
<i>Sheley diversion</i> Not present (section 3.11)	0	-
<i>Springs at eastern PWB boundary from GCMC system</i> <i>(including City Springs and Skakel spring)</i> Estimated (section 3.12)	2515	-
<i>Consumptive use crops</i> Not present (section 3.15)	-	0
<i>Consumptive use riparian vegetation</i> Calculated (section 3.14)	-	5665
<i>Evaporative loss open water</i> Calculated (section 3.13)		1460
<i>Net Municipal use GWSSA and losses/return flow City Water</i> Not present (section 3.16)	-	0
<i>Domestic consumptive use</i> Not present (section 3.17)	-	0
<i>Groundwater &amp; spring discharge to Colorado River</i> Estimated (section 3.18)	-	750
<i>Mill Creek outflow to Colorado River</i> Measured (section 3.19)	-	12450
TOTALS	20325	20325

**Table 1. Preliminary pre-development water budget estimates for PCLA hydrologic system under natural conditions.**

WATER BUDGET COMPONENT	IN (ac-ft/yr)	OUT (ac-ft/yr)
<i>Direct runoff to streams</i> Estimated (section 3.4)	1300	-
<i>Recharge</i> Calculated (section 3.4)	2765	-
<i>Groundwater underflow at upper Pack Creek boundary</i> Calculated (section 3.5)	100	-
<i>Groundwater underflow at Brumley Creek</i> Calculated (section 3.6)	25	-
<i>Groundwater underflow at Mill Creek delta (Powerhouse)</i> Calculated (section 3.7)	10	-
<i>Pack Creek inflow above ditch diversion</i> Measured (section 3.8)	1755	-
<i>Brumley Creek flow into Pack Creek</i> Estimate (section 3.9)	1100	-
<i>Mill Creek inflow at MC delta (Powerhouse)</i> Measured (section 3.10)	8950	-
<i>Sheley diversion</i> Measured (section 3.11)	3665	-
<i>Springs at eastern PWB boundary from GCMC system (excluding City Springs, including Skakel overflow)</i> Estimated (section 3.12)	1725	-
<i>Consumptive use crops</i> Estimated (section 3.15)	-	3600
<i>Consumptive use riparian vegetation</i> Calculated (section 3.14)	-	3900
<i>Evaporative loss open water</i> Calculated (section 3.13)		1460
<i>Net Municipal use GWSSA and losses/return flow City Water</i> Measured (section 3.16)	-	655
<i>Net Domestic consumptive use</i> Estimated (section 3.17)	-	200
<i>Groundwater discharge &amp; spring to Colorado River</i> Estimated (section 3.18)	-	750
<i>Mill Creek outflow to Colorado River</i> Measured (section 3.19)	-	10830
TOTALS	21395	21395

**Table 2. Preliminary post-development water budget estimates for PCLA hydrologic system under current (natural and anthropogenic) conditions.**

## 4. PRELIMINARY GROUNDWATER STORAGE CALCULATIONS FOR THE PCLA HYDROLOGIC SYSTEM

### 4.1 Groundwater 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 (Qaf, Qal, Qas and Qes), 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 Pack Creek alluvium and alluvial fans) 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 extending up to Ken's Lake, and the Moab Rim Fracture Zone). Most of the unconsolidated materials that form the colluvium or fan deposits (Qaf, Qas) and soils (mostly Qes) in the Spanish Valley area, for example, are unsaturated and the amount of groundwater storage is small. By comparison, the unconsolidated alluvium (Qal) in the Spanish Valley Pack Creek gorge is partially saturated, and the storage is significant as indicated by the extensive phreatophyte vegetation that is observed in area with shallow groundwater.

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 PCLA System

The Pack Creek Alluvium (Qal) groundwater systems in Storage Zone 1 (Figure 15) is mostly under unconfined or water table conditions and is characterized by specific yield estimates for unconsolidated sand and gravel deposits in the range 10 – 30%. Due to the extent and depth of these unconsolidated sediments, the Pack Creek alluvium will be most important for estimating total groundwater storage in the Spanish Valley and identify the areas that need the most protection for water quality and water quantity in the main Spanish Valley.

The (Older) Alluvial Fans and Slope Deposits (Qaf/Qas) (Storage Zone 2) are for a large part underlain by the hydrostructures in the Glen Canyon Group (Jgc) and are mostly unsaturated or only seasonal filled with water and are not considered a major storage unit. Precipitation rapidly infiltrates and quickly flows either downwards into the Glen Canyon rocks, or down gradient to the stream alluvium (Qal).

The Glen Canyon Group groundwater systems in Storage Zone 3 is mostly unconfined (water table conditions) and its storage capability is characterized by specific yield estimates. While estimates for the matrix specific yield estimates range from 1.0 to 10%; estimates for the specific yield in fractures dominates zones are in the 20 – 40% range. Therefore, fracture dominated areas will be most important for estimating groundwater storage in these zones and will be the bedrock areas that need the most protection for water quality and water quantity.

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), and hydrostructures (fault and fracture zones) outcropping on the sides of and underlying the central and southern Spanish Valley (Figures 4, 5, and 6). The Moab Rim and the Kayenta Heights Fault and Fracture Zones of the Glen Canyon Group located on the southwest and northeast sides of the Spanish Valley, respectively, are the peripheral groundwater systems supporting the PCLA hydrologic system (Figure 6) and are designated Storage Zone 3 (Figure 15 and Appendix C). The Glen Canyon Group bedrock that underlies the rest of the Spanish Valley (Storage Zone 4) predominantly has matrix flow, and has insignificant storage capabilities. 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 (Freethy and Cordy, 1991). Therefore, fracture flow will dominate travel times in the Glen Canyon Group aquifer and the well-connected fractures in these zones will be most important for estimating groundwater storage.

The Kayenta Heights Fault and Fracture Zone Extension and the Moab Rim Fault and Fracture Zone are Glen Canyon Group fracture zones with fracture storage and an effective depth of up to 500 feet (well log based) and, specific yield (Sy) range 20% – 40% at the surface diminishing to close to 0% at 500 ft. The Pack Creek Alluvium has matrix storage and depths up to 300+ feet. The specific yield (Sy) for this unit is in the range of 10%-30%. Low total water content was estimated using low Sy percentages as a minimum, and high total water content was estimated using the high Sy percentages as a maximum. Each hydrogeologic zone had an estimated volume (GIS area multiplied by a representative average depth), and the storage zone volume was multiplied by the storage zone Sy to yield a hydrogeologic zone water content value (Appendix C) Only part of this total water storage is considered variable or recoverable storage;

accessing additional storage is unsustainable and considered groundwater mining. A first approximation for variable storage (used in the phase 2 report) is 10% of total water content (Appendix C).

The calculations show that the PCLA groundwater system has a variable storage low of 38,375 ac-ft, and a variable storage high of 101,400 ac-ft (Appendix C). Storage zone 1 (Figure 15) had the largest amount of variable storage with a range of 24,850-74,550 ac-ft.

It should be cautioned that the storage or underground reservoir is primarily a measure of how robust and sustainable the PCLA 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 Pack Creek, Brumley Creek, and Mill Creek through diversion or climate change will rapidly affect the recharge and storage functions of hydrogeologic zones 1, 2, 3, which are critical to Geysers Springs, and the City of Moab and Grand County Springs and Wells.

#### 4.3 Storage and the PCLA 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 PCLA hydrologic system, particularly in hydro zones 1 and 3, that is directly connected to the City of Moab Well, Grand County Wells, and discharge to the Colorado River. This storage is accumulated by groundwater recharge from infiltration of precipitation, by losing reaches of Pack Creek, Brumley Creek, and Mill Creek, particularly in hydro zones 1 and 3, and by artificial recharge from Ken's Lake, particularly in hydrogeologic zone 3 (Figure 15).

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

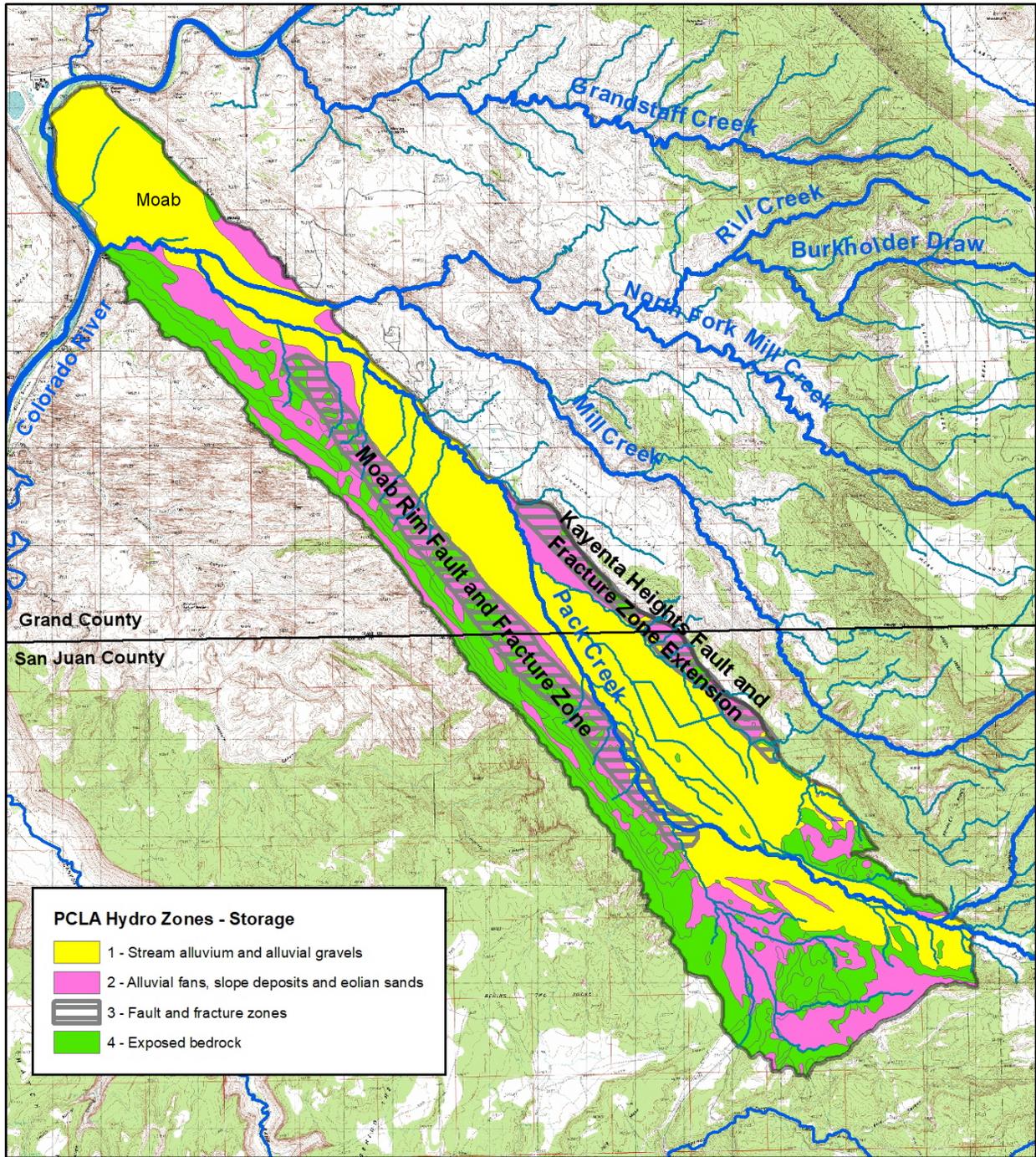


Figure 15. Storage (Hydro) Zones in the PCLA area.

## 5. PRELIMINARY WATER BUDGET OF COMBINED PACK CREEK LOWER ALLUVIUM AND GLEN CANYON GROUP MILL CREEK HYDROLOGIC SUBSYSTEMS OF THE MCSW STUDY AREA

### 5.1 Preliminary Pre-Development and Revised Post Development Water Budgets for the GCMC Hydrologic System

In order to develop a preliminary water budget of the combined Pack Creek Lower Alluvium (PCLA) and Glen Canyon Group Mill Creek ((GCMC) Subsystems of the MCSW study area, it was first necessary to 1) create a true PWB of the pre-development natural conditions of the GCMC subsystem and to 2) slightly revise the PWB of the post-development (current) conditions based on new information obtained since the original release of Kolm and van der Heijde (2019) report on the GCMC subsystem. The Kolm and van der Heijde (2019) report discusses the HESA-derived conceptual model for the GCMC subsystem in great detail, and provides PWBs for pre-Sheley diversion conditions (not a true pre-development scenario since the report focused on the effects of the Sheley diversion on the City of Moab water supply), and the current conditions. Table 3 provides a PWB for the GCMC Hydrologic System under natural (pre-development) conditions modified from the City of Moab Phase 2 report (Kolm and van der Heijde, 2019). This PWB can then be combined with the pre-development PWB for the PCLA hydrologic system to provide estimates for the entire hydrologic system for water rights and water management purposes.

The water balance inflow terms in Table 3 are the same as those in the Kolm and van der Heijde (2019) Phase 2 report, and all terms are rounded off. By comparison, the pre-development outflow terms in Table 3 have been increased by about 8.3% compared with Table 1a in the Kolm and van der Heijde (2019) due to absence of municipal and domestic use. Calculations are derived from the phase 2 report pre-development table minus municipal and domestic use (1364+80=1445) which has been redistributed as follows: 1) Consumptive use riparian vegetation: 5101 (phase 2) + 424 (redistribution) = 5525 ac-ft/yr; and 2) Springs at the PWB boundary: (2325 (phase 2) + 190 (redistribution) = 2515 ac-ft/yr. The Mill Creek outflow at the Powerhouse (some of which will be groundwater underflow out to the PCLA after the location of the old USGS gage): 9928 (phase 2) + 827 (redistribution) = 10755 ac-ft/yr). Note that groundwater inflow into Kayenta Height Fault Zone is considered internal to the GCMC PWB. Note also that the best estimate for Skakel pre-development (including later overflow) is about 350 ac-ft/yr average based on the Utah State Water Rights data base, and the Moab City springs flow rate before the use of City wells is unknown.

Table 4 shows the PWB estimates for the GCMC hydrologic systems under current (natural and anthropogenic) conditions as modified from the Kolm and van der Heijde (2019) report. It should be noted that municipal and domestic use have been increased; whereas consumptive use by vegetation, spring flow and Mill Creek outflow have been reduced by up to 8% in comparison with Table 1b in Kolm and van der Heijde Phase 2 report (2019) due to increased pumping. The spring outflow is impacted the most (Table 4). Note the inflow terms are the same as Table 1b in Kolm and van der Heijde (2019), and that all terms are rounded off.

WATER BUDGET COMPONENT	IN (ac-ft/yr)	OUT (ac-ft/yr)
<i>Direct runoff to streams</i> Estimated	4840	-
<i>Recharge</i> Calculated	5510	-
<i>Groundwater underflow at upper Mill Creek boundary (inflow through Mill Creek fracture zone)</i> Calculated	900	-
<i>Mill Creek inflow above later location of Sheley diversion</i> Measured	7545	-
<i>Upper North Fork Creek and Burkholder Draw inflow from mesa's</i> Estimated	minor	-
<i>Consumptive use crops</i> Not present	-	0
<i>Consumptive use riparian vegetation</i> Calculated	-	5525
<i>Springs at PWB boundaries (including City Springs and Skakel spring)</i> Estimated	-	2515
<i>Municipal use (City of Moab)</i> Not present	-	0
<i>Domestic consumptive use</i> Not present	-	0
<i>Sheley diversion</i> not present	-	0
<i>Mill Creek outflow at delta (including underflow)</i> Measured	-	10755
<i>Release from storage</i> Naturally balanced system	0	-
<b>TOTALS</b>	<b>18795</b>	<b>18795</b>

**Table 3. Preliminary water budget estimates for GCMC hydrologic system under natural (pre-development) conditions (modified from Phase 2 report).**

WATER BUDGET COMPONENT	IN (ac-ft/yr)	OUT (ac-ft/yr)
<i>Direct runoff to streams</i> Estimated	4650	-
<i>Recharge</i> Calculated	5285	-
<i>Groundwater underflow at upper Mill Creek boundary (inflow through Mill Creek fracture zone)</i> Calculated	900	-
<i>Mill Creek inflow above Sheley diversion</i> Measured	6815	-
<i>Upper North Fork Creek and Burkholder Draw inflow from mesa's</i> Estimated	minor	-
<i>Consumptive use crops</i> Estimated	-	minor
<i>Consumptive use riparian vegetation</i> Calculated	-	4945
<i>Springs at PWB boundaries (excluding City Springs, including Skakel overflow)</i> Estimated	-	1725
<i>Municipal use (City of Moab)</i> Measured	-	2200
<i>Domestic consumptive use</i> Estimated	-	150
<i>Sheley diversion</i> Measured	-	3665
<i>Mill Creek outflow at delta (including underflow)</i> Measured	-	8960
<i>Release from storage</i> Estimated	3995	-
TOTALS	21645	21645

**Table 4. Preliminary water budget estimates for GCMC hydrologic system under current (natural and anthropogenic) conditions (modified from Phase 2 report).**

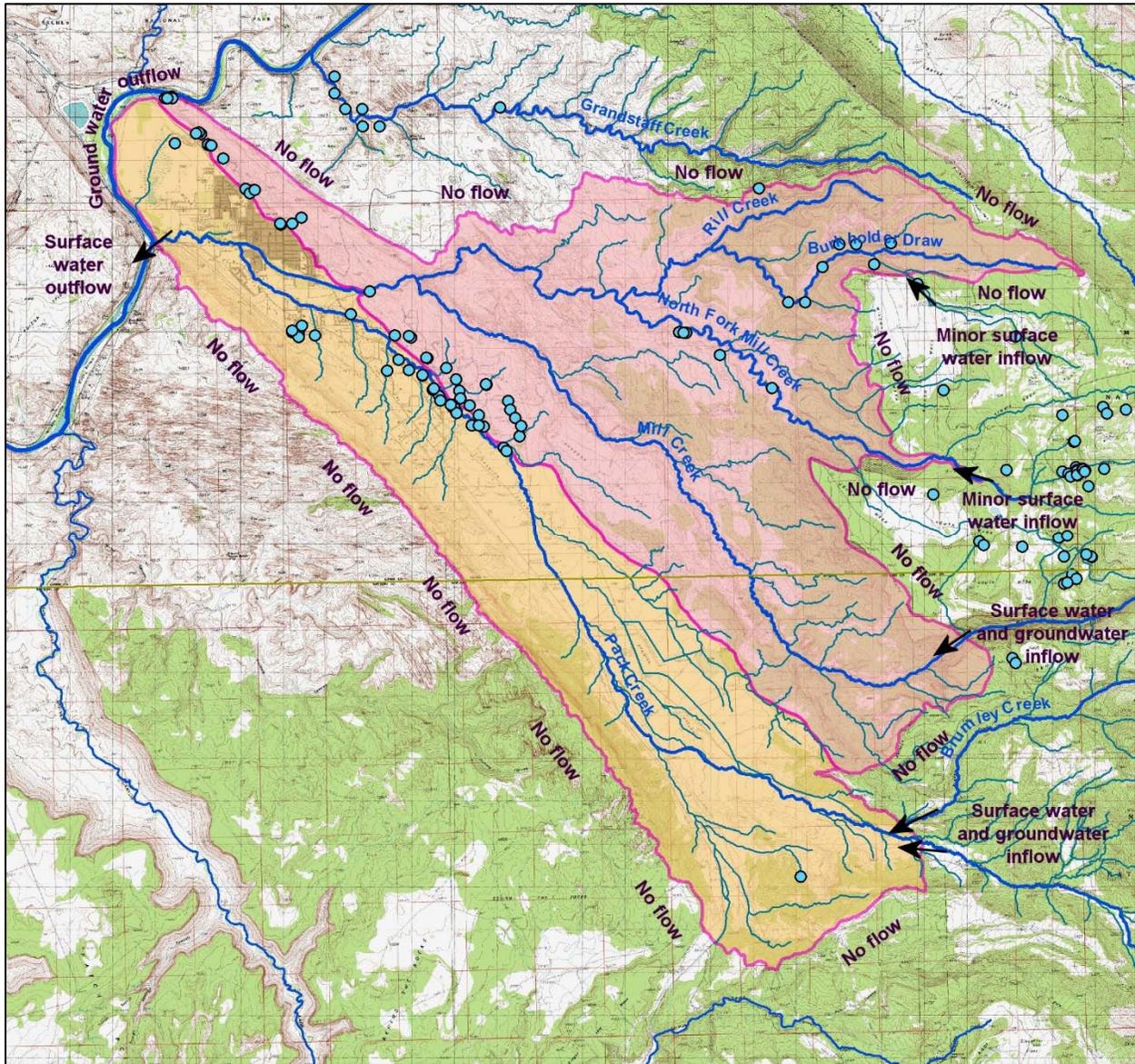
## 5.2 Preliminary Pre-Development and Post Development Water Budgets for the Entire GCMC/PCLA Hydrologic System

A preliminary water budget (PWB) is calculated based upon the information previously collected and analyzed by Kolm and van der Heijde (2018), Kolm and van der Heijde (2019), the HESA-based conceptual model of the GCMC hydrologic system determined in Phase 1, and the HESA-based conceptual model of the PCLA hydrologic system determined in Phase I and refined in Task 1 of this Phase (4) project. The area for the combined GCMC and PCLA hydrologic systems for which the water budget is determined is based, in part, on 1) the locations of various stream gages on Pack Creek and Mill Creek (Blanchard, 1990; USGS Surface-Water Dailey Statistics, Mill Creek at Sheley Tunnel Sites, 2019); 2) the location of most anthropogenic activities (diversions, domestic and agricultural water use); 3) the natural boundaries of the GCMC and PCLA hydrologic systems including Pack Creek and tributaries and Mill Creek and tributaries; and 4) the hydrogeologic and hydrostructural boundaries of the Pack Creek Alluvium Aquifer and Glen Canyon Group Aquifer as determined by HESA (Figure 16). The water budget area is outlined in Figure 16 and is bounded by the Glen Canyon Group Grandstaff Creek Subsystem (GCGC) to the northeast and east; the Morrison Formation to the east and southeast; the La Sal Mountain Upper Alluvial Subsystem (LSMA-P) Pack Creek Headwaters to the southeast; the Moab Rim and Kane Creek hydrological divides to the south, southwest, and west; and the Colorado River to the northwest (Figure 16). The PWB area used in this report covers almost all of the PCLA and GCMC hydrologic systems.

The surface and subsurface hydrologic systems or storage components and the hydrologic exchange processes or fluxes considered relevant for the PWB of the combined GCMC and PCLA hydrologic systems were derived from the conceptual models developed in the Phase 1 HESA as illustrated in Figure 16 (with boundary conditions). The significant inputs of the PWB are: 1) direct runoff of precipitation to streams; 2) recharge by infiltration of precipitation (rain and snow) across the entire PWB area using the concept of *hydro zones* explained earlier in this report and in Kolm and van der Heijde (2019); 3) Mill Creek groundwater flux, called groundwater underflow, at the upper Mill Creek boundary (inflow through Mill Creek fracture zone); 4) Pack Creek groundwater flux, called groundwater underflow, in the Quaternary hydrogeologic units (Qal) at the SE corner of the water budget area; 5) Brumley Creek groundwater flux, called groundwater underflow, in the Quaternary hydrogeologic units (Qal) at the SE corner of the water budget area; 6) Mill Creek inflow above later location of Sheley diversion; 7) Upper North Fork Creek and Burkholder Draw inflow from Mesas; 8) Pack Creek surface water inflow above the later ditch diversion in the SE corner of the water balance area; and 9) Brumley Creek surface water inflow to Pack Creek in the SE corner of the water balance area. 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 earlier sections of this report.

The outputs of the combined PWB are: 1) consumptive use crops; 2) evapotranspiration or consumptive use by native phreatophytes (cottonwoods, willows, tamarisk, and other riparian species) (Figure 13 and Figure 12 in Kolm and van der Heijde (2019)); 3) evaporative loss open water; 4) net municipal use GWSSA minus losses/return flow City of Moab Water; 5) domestic consumptive use by private wells (Figure 12 and Figure 10b in Kolm and van der Heijde (2019)); 6) groundwater discharge to the Colorado River; 7) Mill Creek surface water outflow at the

northern end of Spanish Valley to the Colorado River, and 8) release from groundwater storage in the post-development (current) PWB, primarily in the GCMC PWB area.



**Figure 16. Map showing the location of the Preliminary Water Budget (PWB) area of the combined GCMC and PCLA hydrologic systems with boundary conditions, and spring locations.**

WATER BUDGET COMPONENT	IN (ac-ft/yr)	OUT (ac-ft/yr)
<i>Direct runoff to streams</i> Estimated (section ...)	5925	-
<i>Recharge</i> Calculated (section ...)	8410	-
<i>Groundwater underflow at upper Mill Creek boundary (inflow through Mill Creek fracture zone)</i> Calculated (section...)	900	-
<i>Groundwater underflow at upper Pack Creek boundary</i> Calculated (section ...)	100	-
<i>Groundwater underflow at Brumley Creek</i> Calculated (section ...)	25	-
<i>Mill Creek inflow above later location of Sheley diversion</i> Measured (section...)	7545	-
<i>Upper North Fork Cr. and Burkholder Draw inflow from mesa's</i> Estimated (section ....)	minor	-
<i>Pack Creek inflow above later ditch diversion</i> Measured (section ...)	1845	-
<i>Brumley Creek flow into Pack Creek</i> Estimated (section ...)	1100	-
<i>Consumptive use crops</i> Not present (section ...)	-	0
<i>Consumptive use riparian vegetation</i> Calculated (section ...)	-	11190
<i>Evaporative loss open water</i> Calculated (section ...)	-	1460
<i>Municipal use (City of Moab and GWSSA)</i> Not present (section ...)	-	0
<i>Domestic consumptive use</i> Not present (section ...)	-	0
<i>Groundwater discharge to Colorado River</i> Estimated (section ...)	-	750
<i>Mill Creek outflow to Colorado River</i> Measured (section ...)	-	12450
<i>Release from storage</i> Naturally balanced system (section...)	-	0
TOTALS	25850	25850

**Table 5. Preliminary water budget estimates for the combined PCLA and GCMC hydrologic systems under natural (pre-development) conditions.**

WATER BUDGET COMPONENT	IN (ac-ft/yr)	OUT (ac-ft/yr)
<i>Direct runoff to streams</i> Estimated (section ...)	5950	-
<i>Recharge</i> Calculated (section ...)	8050	-
<i>Groundwater underflow at upper Mill Creek boundary (inflow through Mill Creek fracture zone)</i> Calculated (section...)	900	-
<i>Groundwater underflow at upper Pack Creek boundary</i> Calculated (section ...)	100	-
<i>Groundwater underflow at Brumley Creek</i> Calculated (section ...)	25	-
<i>Mill Creek inflow above Sheley diversion</i> Measured (section...)	6815	-
<i>Upper North Fork Cr. and Burkholder Draw inflow from mesa's</i> Estimated (section ....)	Minor	-
<i>Pack Creek inflow above ditch diversion</i> Measured (section ...)	1755	-
<i>Brumley Creek flow into Pack Creek</i> Estimated (section ...)	1100	-
<i>Consumptive use crops</i> Estimated (section ...)	-	3600
<i>Consumptive use riparian vegetation</i> Calculated (section ...)	-	8845
<i>Evaporative loss open water</i> Calculated (section ...)		1460
<i>Municipal use (City of Moab and GWSSA)</i> Measured (section ...)	-	2855
<i>Domestic consumptive use</i> Estimated (section ...)	-	350
<i>Groundwater discharge to Colorado River</i> Estimated (section ...)	-	750
<i>Mill Creek outflow to Colorado River</i> Measured (section ...)	-	10830
<i>Release from storage</i> Calculated (section...)	3995	
TOTALS	28690	28690

**Table 6. Preliminary water budget estimates for the combined PCLA and GCMC hydrologic systems under current (natural and anthropogenic) conditions.**

Table 5 and Table 6 present a preliminary pre-development water budget and a preliminary post-development water budget for the combined GCMC and PCLA hydrologic systems. 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 scenario, this closing term represents the term for direct runoff to streams and amounts to 5950 ac-ft/yr (Table 5). The post-development scenario presented in Table 6 incorporates among other human activities, the Sheley Diversion intake of 3665 ac-ft/yr, but the water budget treats that as an internal process, which doesn't appear on either table. However, due the diversion, and the increase water use by human activity, the closing term is release from groundwater storage in the GCMC part of the combined system of 3995 ac-ft/yr, which is approximately 14% of the total yearly budget. The deficit may be reduced over time by increased recharge in above average precipitation years, or as increased flow to Mill Creek into the GCMC hydrologic systems upgradient due to increased groundwater release in upgradient groundwater systems, or increased runoff from higher than average snowpack. This depletion of upgradient storage or mining of groundwater is also a concern for the sustainability of both the City's and the PCLA water supply.

### 5.3 PWB and the GCMC/PCLA Hydrologic System: Significance

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 GCMC and PCLA hydrological systems from the La Sal Mountain systems, or in percentages of pre-development input into the GCMC/PCLA hydrologic system: surface water and groundwater derived from the La Sal Mtns is 11,515 ac-ft/yr and counts for approximately 45%, and local recharge from precipitation counts for 33%. This means that the La Sal Mountain climate regimes can affect directly 78% of the water supply. Note that a combined consumptive use riparian vegetation and evaporative loss open water accounts for 49% of the total water budget out (almost one-half!), and the remainder of 51% is subsurface and surface discharge to the Colorado River. By comparison, in the post development time period, the development of the Sheley diversion to the overall redistribution of the water supply plus the increase in municipal use and consumptive use becomes more of a factor, or in percentages of post development change into the GCMC/PCLA hydrologic system: consumptive use crops accounts for 13%, municipal use and domestic consumptive use accounts for 11%, and groundwater released from storage accounts for approximately 14%. The Sheley diversion yearly amounts is almost entirely accounted for in the consumptive use of crops and domestic consumptive use. The most notable decline is the amount of Mill Creek outflow to the Colorado River of 1,620 acre-ft/year or 13%.

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/PCLA 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, Pack Creek and Brumley Creek at the east and southeast end of the GCMC/PCLA hydrologic system. Increased consumptive use would result from increased urbanization (more wells, non-native vegetation) or increased irrigation.

#### 5.4 PWB and the GCMC/PCLA Hydrologic System: Sustainability Concerns

There are a number of potential threats to the sustainability of the GCMC/PCLA hydrologic system and thus to the water supply of the City of Moab and Grand County, 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/PCLA hydrologic system, will result in decreased surface water flows and groundwater recharge from losing streams. Impacts on the GCMC/PCLA 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, Pack Creek and Brumley Creek at the east and southeast end of the GCMC/PCLA 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/PCLA hydrologic system will result in further decline of outflows such as at Mill Creek, Pack Creek and Brumley Creek in the eastern and southern part of the study area and various springs, and will likely lead to decline in storage and subsequent lowering of groundwater levels and groundwater availability for phreatic consumption.

## 6. CONCLUSIONS AND RECOMMENDATIONS

The Pack Creek Lower Alluvium (PCLA) hydrologic system is a complex mix of Alluvium and Alluvial Fan sediments overlying or adjacent to fractured and faulted Glen Canyon Group rock, and hydro-structures (fault and fracture zones that are either conductive or a barrier to groundwater flow). A preliminary (global) water budget (PWB) has been developed for the PCLA hydrologic system, focused on the external inputs (inflows) and outputs (outflows), and an analysis was made of the storage capacity of the PCLA aquifer in the PWB area. The most significant anthropogenic change in conditions happened in the early 1980s, the start of the Sheley diversion, together with the initiation of a steady increase in municipal and domestic water use that represents a significant increase in the anthropogenic withdrawals from the PCLA hydrologic system that continues to the present day. The “best” estimate for recharge in both periods amounts to about 16-17 % of overall precipitation in the PWB area. Direct runoff of precipitation to streams amounts to 815 ac-ft/yr. This term, corrected for the decline in precipitation between the two climate periods and the increase of direct runoff in buildup/urbanized areas amounting to a total of 1300 ac-ft/yr, is used in the post-development scenario. Direct evapotranspiration (ET) in the PWB area (excluding riparian vegetation), calculated as precipitation minus groundwater recharge and direct runoff to streams, amounts to about 14,525 ac-ft/yr for the pre-development period and to 13,565 ac-ft/yr for the post-development period, or about 75-78% of total precipitation, based on 30-year averages for the two climate periods. The total water budget of the PCLA amounts to 20,325 ac-ft/yr predevelopment, and 21,395 ac-ft/yr post-development/current conditions.

The primary significance of the PWB is that there is a significant amount of surface water and groundwater contributed to the PCLA hydrological system from the La Sal Mountain and GCMC hydrological systems: surface water and groundwater derived from the GCMC hydrologic system (Mill Creek + groundwater underflow at the Mill Creek delta + springs at eastern PWB boundary from GCMC system) is 13,270 ac-ft/yr and counts for approximately 65%; local recharge from precipitation and direct runoff from precipitation to streams counts for 20%; and directly linked groundwater inflow and surface water inflow (Pack Creek and Brumley Creek) from the La Sal Mountains hydrological subsystems counts for 15%. The La Sal Mountain and GCMC subsystems contribute more than 80% of the total inflow in the PWB area. A combined consumptive use riparian vegetation and evaporative loss open water accounts for 35% of the total water budget out, and remainder is subsurface and surface discharge to the Colorado River. By comparison, in the post development time period, the contribution of the Sheley diversion to the overall input becomes more of a factor, or in percentages of post development input into the PCLA hydrologic system: surface water (Mill Creek + Pack Creek + Brumley Creek) counts for approximately 55%; local recharge from precipitation and direct runoff to streams for 19%; groundwater inflow from the GCMC hydrological subsystems counts for about 9%; and the Sheley diversion provides 17% of the total inflow to the PCLA hydrologic system and has resulted in a 17% reduction of Mill Creek inflows towards Spanish Valley under base flow conditions and 31% reduction of springs and seeps discharge in the most likely scenario. Therefore, any decline in upstream total average flows in Mill Creek, Pack Creek, or Brumley Creek from natural or man-made causes will have an immediate and significant impact on the various outflows of the PCLA hydrologic system and poses a potential threat to the sustainability of the City of Moab’s and the County’s water supply.

The Quaternary alluvium and fan gravels, and the fractured Glen Canyon Group groundwater system is mostly unconfined, has a readily fluctuating water table, and the aquifer specific yield of the alluvium and alluvial fan gravels matrix is estimated at 10 – 30%, and the fractured/faulted Glen Canyon Group bedrock has a fracture specific yield estimated range from 10.0 – 40.0%. The results of GIS-based calculations show that the PCLA groundwater system has a variable storage low of 38,375 ac-ft, and a variable storage high of 101,400 ac-ft. The Quaternary alluvial deposits, designated storage zone 1, had the largest amount of variable storage with a range of 24,850-74,550 ac-ft. The current City of Moab source protection plans identify some of these hydro zones as critical, and an update to these plans will be completed in Phase 3 of this project.

In order to develop a preliminary water budget of the combined Pack Creek Lower Alluvium (PCLA) and Glen Canyon Group Mill Creek (GCMC) Subsystems of the MCSW study area, the true PWB of the Pre-development natural conditions of the GCMC subsystem and the updated PWB of the post development (current) conditions of the GCMC subsystem were evaluated. Then, this PWB was combined with the PWB for the PCLA hydrologic system to provide estimates for the entire City of Moab hydrologic system for water rights and water management purposes. In the combined GCMC/PCLA pre-development scenario, the water budget amounts to 25,850 ac-ft/yr, and the water budget closing term represents the term for direct runoff to streams and amounts to 5950 ac-ft/yr. The combined GCMC/PCLA post-development scenario, which amounts to 28,690 ac-ft/yr, incorporates human activities, such as the Sheley Diversion intake of 3665 ac-ft/yr, but the water budget treats the diversion as an internal process, which doesn't appear in the PWB. However, due to the diversion, and the increase water use by human activity, the closing term is release from groundwater storage in the GCMC part of the combined system of 3995 ac-ft/yr, which is approximately 14% of the total yearly budget. The deficit may be reduced over time by increased recharge in above average precipitation years, or as increased flow to Mill Creek into the GCMC hydrologic systems upgradient due to increased groundwater release in upgradient groundwater systems, or increased runoff from higher than average snowpack. This depletion of upgradient storage or groundwater mining is also a concern for the sustainability of both the City's and the PCLA water supply.

The primary significance of the combined PWB is that there is a large amount of surface water and groundwater contributed to the GCMC and PCLA hydrological systems from the La Sal Mountain systems totaling 11,515 ac-ft/yr and counts for approximately 45%, and local recharge from precipitation counts for 33% or the La Sal Mountain climate regimes can affect directly 78% of the water supply. A combined consumptive use riparian vegetation and evaporative loss open water accounts for 49% or one-half of the total water budget out, and the remainder of 51% is subsurface and surface discharge to the Colorado River. By comparison, in the post development time period, the development of the Sheley diversion to the overall redistribution of the water supply plus the increase in municipal use and consumptive use becomes more of a factor, or in percentages of post development change into the GCMC/PCLA hydrologic system: consumptive use crops accounts for 13%, municipal use and domestic consumptive use accounts for 11%, and groundwater released from storage accounts for approximately 14%. The Sheley diversion yearly amounts is almost entirely accounted for in the consumptive use of crops and domestic consumptive use. The most notable decline is the amount of Mill Creek outflow to the Colorado River of 1,620 acre-ft/year or 13%.

There are a number of potential threats to the sustainability of the GCMC/PCLA hydrologic system and thus to the water supply of the City of Moab and Grand County, 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/PCLA hydrologic system, will result in decreased surface water flows and groundwater recharge from losing streams. Impacts on the GCMC/PCLA 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, Pack Creek and Brumley Creek at the east and southeast end of the GCMC/PCLA 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/PCLA hydrologic system will result in further decline of outflows such as at Mill Creek, Pack Creek and Brumley Creek in the eastern and southern part of the study area and various springs, and will likely lead to decline in storage and subsequent lowering of groundwater levels and groundwater availability for phreatic consumption.

Based upon associated uncertainties with estimates, better monitoring via gaging stations at Mill Creek (Powerhouse, Junction with Pack Creek, Colorado River), Pack Creek (City Springs and Perennial Flow locations, Pack Creek Bridge, Settlement of Pack Creek), and Brumley Creek that record daily, seasonal, and annual information would improve the measurements of the City of Moab and Spanish Valley 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. This Phase IV HESA revealed that the GCMC/PCLV groundwater system was complex being both matrix and fracture-type flow, and that the design, implementation, and calibration of a mathematical model can be done, but given the uncertainties with the data available, the results would still tend to be questionable. The PWB of the GCMC groundwater system in Phase II would provide inputs into a Spanish Valley model, and the HESA of the PCLV and GCMC groundwater systems would provide boundary conditions for that model.

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## APPENDICES

Object ID (from GIS)	Precipitation (inches)	Hydro Zone Description	Hydro Zone ID	Area (acres)	Average Annual Precipitation 1971-2000 Acre-ft	Recharge % of Precip	Recharge 1971-2000 Low Acre-ft/yr	Recharge 1971-2000 High Acre-ft/yr	Recharge 1971-2000 Average Acre-ft/yr
1	9	Stream alluvium and gravels	2	2098.48	1573.86	20-30	314.77	472.16	393.46
2	11	Stream alluvium and gravels	2	236.07	216.40	20-30	43.28	64.92	54.10
0	9	Stream alluvium and gravels	2	32.69	24.52	20-30	4.90	7.35	6.13
3	13	Stream alluvium and gravels	2	1310.28	1419.47	20-30	283.89	425.84	354.87
4	11	Stream alluvium and gravels	2	4904.19	4495.50	20-30	899.10	1348.65	1123.88
5	9	Stream alluvium and gravels	2	1855.63	1391.73	20-30	278.35	417.52	347.93
6	13	alluvial fans and slope deposits	3	1808.06	1958.73	10-20	195.87	361.61	293.81
7	11	alluvial fans and slope deposits	3	2100.81	1925.74	10-20	192.57	420.16	288.86
8	9	alluvial fans and slope deposits	3	429.26	321.94	10-20	32.19	85.85	48.29
9	13	bedrock	4	3046.31	3300.17	5	165.01	165.01	165.01
10	11	bedrock	4	1548.27	1419.25	5	70.96	70.96	70.96
11	9	bedrock	4	616.82	462.61	5	23.13	23.13	23.13
<b>Total</b>				19986.87	18509.92		2504.04	3863.17	3170.43

### Appendix A. Recharge calculation: Pre-development (natural)

Object ID (from GIS)	Precipitation (Inches)	Hydro Zone Description	Hydro Zone ID	Area (acres)	Average Annual Precipitation 1981-2010 Acre-ft	Recharge % of Precip	Recharge 1981-2010 Low Acre-ft/yr	Recharge 1981-2010 High Acre-ft/yr	Recharge 1981-2010 Average Acre-ft/yr
1	8	buildup area	1	594.32	396.22	10	39.62	39.62	39.62
2	9	buildup area	1	1521.77	1141.33	10	114.13	114.13	114.13
3	10	buildup area	1	218.45	182.05	10	18.20	18.20	18.20
0	8	Stream alluvium and gravels	2	27.70	18.47	20-30	3.69	5.54	4.62
4	8	Stream alluvium and gravels	2	993.21	662.14	20-30	132.43	198.64	165.54
5	9	Stream alluvium and gravels	2	917.86	688.40	20-30	137.68	206.52	172.10
6	10	Stream alluvium and gravels	2	2177.16	1814.30	20-30	362.86	544.29	453.58
7	11	Stream alluvium and gravels	2	2626.59	2407.71	20-30	481.54	722.31	601.93
8	12	Stream alluvium and gravels	2	851.91	851.91	20-30	170.38	255.57	212.98
9	13	Stream alluvium and gravels	2	503.37	545.32	20-30	109.06	163.59	136.33
10	8	alluvial fans and slope deposits	3	0.83	0.55	10-20	0.06	0.11	0.08
11	9	alluvial fans and slope deposits	3	434.11	325.58	10-20	32.56	65.12	48.84
12	10	alluvial fans and slope deposits	3	1053.40	877.84	10-20	87.78	175.57	131.68
13	11	alluvial fans and slope deposits	3	995.96	912.97	10-20	91.30	182.59	136.94
14	12	alluvial fans and slope deposits	3	1417.87	1417.87	10-20	141.79	283.57	212.68
15	13	alluvial fans and slope deposits	3	435.95	472.28	10-20	47.23	94.46	70.84
16	8	bedrock	4	8.64	5.76	5	0.29	0.29	0.29
17	9	bedrock	4	624.68	468.51	5	23.43	23.43	23.43
18	10	bedrock	4	499.57	416.31	5	20.82	20.82	20.82
19	11	bedrock	4	1120.93	1027.51	5	51.38	51.38	51.38
20	12	bedrock	4	2453.03	2453.03	5	122.65	122.65	122.65
21	13	bedrock	4	504.55	546.60	5	27.33	27.33	27.33
<b>Total</b>				19981.88	17632.63		2216.20	3315.73	2765.97

### Appendix B. Recharge calculation: Post-development (current)

Storage Hydro Zone Number	Storage Hydro Zone Type	Hydro Zone Average Depth (ft)	Hydro Zone Area (acres)	Specific Discharge	Total Storage (acre-ft)	Available Storage 10% (acre-ft)
1	Stream Alluvium & Alluvial Gravels	175*	14220	10-30%	248500-745500	24850-74550
2	Alluvial Fans & Slope Deposits	-	5090	-	minor	minor
3a	Moab Rim Fault and Fracture Zone	500/2	1935	20-40%	96250-192500	9625-19250
3b	Kayenta Heights Fault and Fracture Zone Extension	500/2	760	20-40%	38000-76000	3800-7600
4	Exposed unfractured bedrock	-	5485	-	minor	minor
Total			27490		382750-1014000	38375-101400

\* Based on valley fill thickness published in Lowe and others 2007.

**Appendix C. Aquifer storage calculations.**