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UTAH
DNR
WATER RESOURCES

HB 429 GREAT SALT LAKE STORMWATER STUDY

(HAL Project No. 420.03.100)

NOVEMBER 2023

HANSEN ALLEN & LUCE INC
ENGINEERS

LimnoTech
Water Environment | Scientists Engineers

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State of Utah Division of Water Resources

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CHAPTER 1 – INTRODUCTION

PURPOSE & BACKGROUND

During the 2022 legislative session, the Utah legislature passed HB429, which specifies the completion of a wide-scale Great Salt Lake Watershed Integrated Water Assessment. Among the bill's provisions is a specific component addressing the effect of Low Impact Development (LID) storm water permit requirements that states:

> *"As part of the integrated water assessment, the division shall study the impact of low impact development best management practices associated with post-construction retention stormwater permit requirements on the water budget of the Great Salt Lake.[1]"*

One of the important aspects of the Integrated Water Assessment is the development of "*a water budget for the Great Salt Lake and the Great Salt Lake's associated wetlands, including water flows needed to maintain different lake levels under different scenarios, taking into consideration water quality, ecological needs, economic benefits, and public health benefits of the Great Salt Lake.*"[2] This study addresses questions which have been raised about the impact of stormwater management LID on flows to the Great Salt Lake.

DEFINITION AND USE OF LID

LID is a generic term for a type of stormwater management practice. It is also interchangeably referred to as Green Infrastructure. As defined in Utah DEQ's Guide to Low Impact Development within Utah (Utah DEQ, revised 2020), LID refers to "*engineered systems, either structural or natural, that use or mimic natural processes to promote infiltration, evapo-transpiration, and/or reuse of storm water as close to its source as possible to protect water quality and aquatic habitat. LID practices at the regional and site specific level preserve, restore, and create green space using soils, vegetation, and rainwater harvesting techniques. These systems and practices are referred to as Best Management Practices (BMPs).*" Because the purpose of LID is to "promote infiltration and evapotranspiration…of storm water," LID mimics the undeveloped water flows within a watershed which reduces the volume of runoff and the volume flowing through conveyances thereby improving water quality of stormwater.

A full discussion of the regulatory requirements impacting the implementation of LID is included in **Appendix A**. A literature review focused on the different types of LID is found in **Appendix B. Appendix C** summarizes data collected on what types of LID BMPs are being used locally.

PROJECT GOAL

Per the project's Scope of Work, this project was designed to evaluate "*the impact of LID BMPs associated with post-construction retention stormwater permit requirements on the water budget of the Great Salt Lake…The primary outcome of the study will be the methodology or methodologies for quantifying the impacts of LID BMPs on surface and groundwater flows and deliveries to GSL.*" Simply stated, the goal of this project was to evaluate the impact of LID on overall flows to the Great Salt Lake (GSL). The project was also designed to evaluate the impact of increasing LID usage due to community growth.

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[1] Utah DEQ Post-construction Stormwater Study Attachment B: Scope of Work.

[2] Utah DEQ Post-construction Stormwater Study Attachment B: Scope of Work.

METHODOLOGY

To address the project goals, the HAL/LimnoTech team developed a linked surface water-groundwater modeling approach to determine the effects on water flow volumes due to the implementation of LID. The models and modelling area are described in full detail in **Appendix D**. The following simulations were compared and evaluated to track changes in flows throughout the water cycle to determine how LID impacts flows to the Great Salt Lake.

- Baseline simulation representing existing conditions including large undeveloped areas within the study area.
- Development without LID simulations that represent future conditions where new developments do not implement LID strategies.
- Developed with LID simulations that represent future conditions where new developments implement LID strategies.

The ultimate evaluation included comparisons of the volumes of stormwater reaching the Great Salt Lake in the different scenarios through both surface runoff and through groundwater flow paths (i.e., the difference between groundwater entering the lake in the undeveloped scenario vs. the groundwater going to the lake in each of the developed/ growth scenarios). An estimate of the changes in stormwater-runoff-based surface flows to the lake was also part of this evaluation.

The basic components of the water cycle in the region are shown in **Figure 1** below. In a "natural" (i.e., undeveloped) area, precipitation (rainfall and snowmelt) can infiltrate into the groundwater or run off directly into surface waters and eventually reach the Great Salt Lake. Processes including evaporation from impervious surfaces, uptake by plants, evaporative losses from soil and plants (evapotranspiration or ET) and evapotranspiration from groundwater as it discharges from the aquifer reduce the amount of water that reaches the lake. In urban or other developed areas, stormwater management from impervious surfaces alters surface water runoff and groundwater flow contributions. Generally, impervious surfaces in urban development result in increased surface water runoff and decreased groundwater flow. However, implementation of LID intercepts some of the surface flows resulting in increased infiltration into the deep groundwater, increased infiltration into shallow soils and eventual evaporation, and increased uptake into plants. Flows exceeding the LID capture volume are bypassed and flow to the lake. The impact of LID on surface flows, infiltration and ET was considered in the modeling effort (for more details see **Appendix D**).

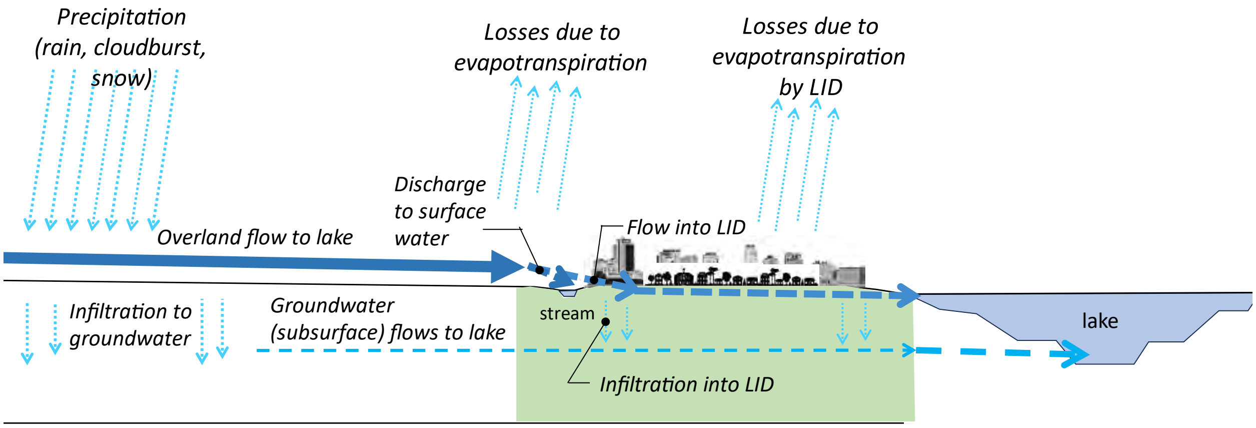


Figure 1. Water Cycle in an Urban Area with LID.

While the conceptual flow balance underlying this project is very simple, the details are complex because of the large number of flow pathways and the physical and biological processes. The modeling was developed taking these factors into account. Technical details for the modeling set up and execution are provided in **Appendix D**.

CHAPTER 2 – MODELING SUMMARY

SURFACE WATER MODELING

The SWMM surface model of MS4 municipalities along the Wasatch Front that drain to the Great Salt Lake encompasses 736,831 total acres, and includes about 18% impervious surface. Simulated scenarios included the baseline (current) condition, future-development scenarios without LID implementation, and future-development scenarios with LID added to capture runoff. The 100% future-development scenario is the 'full buildout' scenario that estimates the maximum number of development acres added to the model within the USGS defined primary and secondary recharge areas beyond current conditions, given long-term planning projections. The 50% development represents half of that added acreage. See **Appendix D** for the area considered by the SWMM model, the input data and modelling approaches, and the model validation. **Table 1** summarizes the physical attributes of each of the scenarios.

Table 1. Summary of SWMM Surface Model Scenarios.

Scenario	Impervious Land Cover (%)	Pervious Land Cover (%)	Future Development Area (acres)*	LID practices total footprint (acres)
Baseline (current conditions)	17.7%	82.3%	0	n/a
50% Future Development	20.2%	79.8%	35,598	n/a
50% Future Development with LID	20.1%	79.9%	35,598	420
100% Future Development	22.6%	77.4%	71,197	n/a
100% Future Development with LID	22.5%	77.5%	71,197	840

** future development acres are assumed to be 50% impervious*

The period from 1980 to 2022 was simulated in SWMM for all five scenarios. This 43-year period was chosen because of long-term precipitation data availability and reflects a variety of precipitation years.

Table 2 summarizes surface model results in both total annual volumes and percentages of total precipitation for each model output type (values are rounded to the nearest hundred acre-feet (AF)). The infiltration to groundwater volume is an offline calculation that accounts for the fact that most infiltration from precipitation does not reach groundwater aquifers due to evaporative losses from the soil/sub-surface and uptake by vegetation. LID-linked contributions to groundwater recharge are more substantial, with fewer losses, because of the more direct pathway from LID infiltration structures to groundwater.

Table 2. Summary of SWMM Surface Model Results.

Average annual precipitation, all scenarios (acre-ft / year):				1,418,200
			Total Infiltration	
Scenario	Evaporative losses from surface (ac-ft/yr)	Surface runoff (ac-ft/yr)	ET, plant uptake & evaporative losses from soil (ac-ft/yr)	Infiltration to Groundwater (acre-ft / year)
Baseline (current conditions)	65,800 *(4.6%)*	200,000 *(14.1%)*	1,089,800 *(76.8%)*	62,600 *(4.4%)*
50% Future Development	+8,400 *(5.2%)*	+21,200 *(15.6%)*	-27,000 *(74.9%)*	-2,600 *(4.2%)*
50% Future Development with LID	+8,400 *(5.2%)*	+100 *(14.1%)*	-18,300 *(75.6%)*	+9,800 *(5.1%)*
100% Future Development	+17,200 *(5.9%)*	+42,000 *(17.1%)*	-54,100 *(73.0%)*	-5,100 *(4.1%)*
100% Future Development with LID	+17,100 *(5.8%)*	+300 *(14.1%)*	-36,800 *(74.2%)*	+19,400 *(5.8%)*

When comparing results from **Table 2**, the scenario of 100% development with LID leads to slightly greater runoff than the current-conditions baseline scenario, and slightly less infiltration than the baseline. Those differences are due to the LID having been set up in the model to capture all the future-development runoff up to the 80th-percentile precipitation event (about 0.5”). For rainfall events larger than 0.5”, the LID will still function, but will eventually reach its maximum infiltration rate with the excess running off as surface water flow.

Figure 2 plots the runoff flows for a single 0.85” rain event in October 2018, for a single 1,355-acre, 47% impervious SWMM model shed located in the Magna area of Salt Lake County. The current-conditions baseline, 100% future development, and 100% future development with LID scenarios are compared. Runoff peak flows and overall volumes are reduced in the LID scenario, as infiltration rates increase due to the addition of LID that is capturing runoff and allowing it to infiltrate. Note that the LID-driven infiltration continues near the tail end of the event, with a substantial portion of infiltration occurring after the final flow peak on October 5. LID scenario runoff is roughly equivalent to the current-conditions baseline runoff for this shed. This plot shows LID reducing runoff for a very large rain event within a highly-impervious shed.

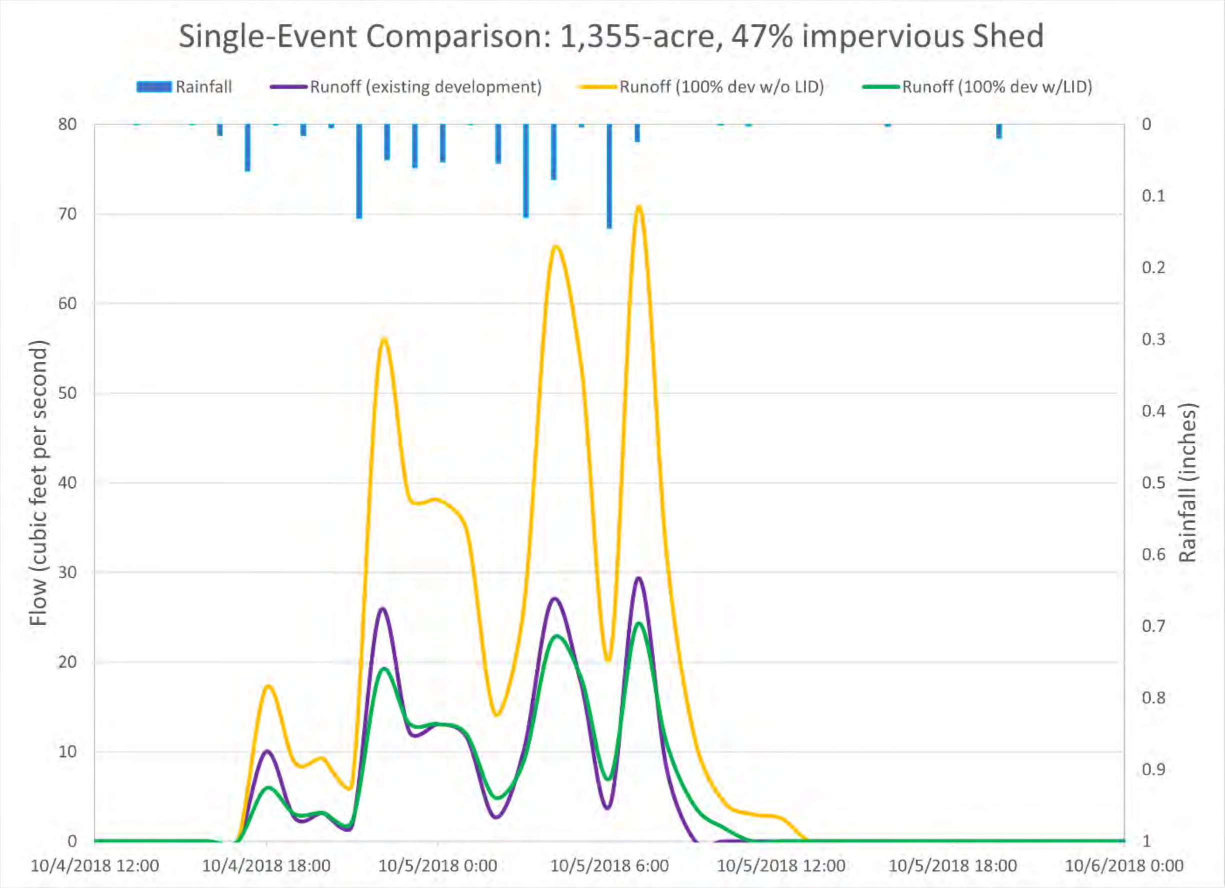


Figure 2. SWMM Surface Model Single-Event Flow Comparison.

GROUNDWATER MODELING

MODFLOW groundwater models of the aquifer systems developed by the U.S. Geological Survey (USGS) cover a similar geographical extent compared to the SWMM models and include the recharge areas provided by the SWMM model (**Appendix D**). The changes in infiltration to groundwater from **Table 2** for the Baseline and 100% Future Development scenarios (with and without LID) were simulated in the groundwater models to determine the changes in discharge from the groundwater models. The changes to the modeled recharge inputs are shown in **Table 3**.

Table 3. Summary of Differences in Groundwater Recharge from Development with and without LID.

Scenario	Change in Infiltration to Groundwater in Groundwater Model Domain (acre-ft / year)
Baseline (current conditions)	0
100% Future Development	-5,100
100% Future Development with LID	+19,500

The changes in modeled recharge with development lead to corresponding changes in outflows from the groundwater system, including evapotranspiration and outflow to lakes, rivers, and other surface waters. The cumulative changes in the groundwater models are summarized in **Table 4**.

Table 4. Summary of Changes in Groundwater Discharge Based on MODFLOW Groundwater Model Results.

Scenario	ET (acre-ft / year)	To GSL (acre-ft / year)
Baseline (current conditions)	90,500	325,400
100% Future Development	89,400 *(-1,100)*	321,400 *(-4,000)*
100% Future Development with LID	93,700 *(+3,200)*	341,600 *(+16,200)*

Compared to the baseline, the 100% Future Development scenario results in more runoff flowing to GSL which results in less infiltration to groundwater (5,100 less AF per year, **Table 3**) and therefore less discharge from groundwater to GSL (4,000 less AF per year, **Table 4**) but less loss of groundwater to ET (1,100 less AF per year, **Table 4**). In contrast the 100% Future Development with LID scenario results in more recharge to the aquifer (19,500 more AF per year, **Table 3**) and therefore more discharge from groundwater to GSL (16,200 more AF per year, **Table 4**) but also more loss of groundwater to ET (3,200 AF per year, **Table 4**).

Routing storm water flows through the groundwater system, as in the case of the 100% Future Development with LID scenario, creates a delay in the water reaching the Great Salt Lake. It is difficult to quantify the timing of the delays because development occurs gradually. Based on preliminary groundwater modeling using transient versions of the USGS MODFLOW models, it could take up to 50 years for groundwater discharges to balance with any change in groundwater recharge. This is primarily due to the vast storage capacity of, and the slow movement of water through, the aquifer system.

GREAT SALT LAKE WATER BALANCE

The modeling results must be understood in the context of the Great Salt Lake system. The maximum observed volume of the Great Salt Lake is over 30 million acre-ft when at its highest recorded water level, with a maximum surface area of 1.5 million acres (Bouchard, 2022). It is the largest lake in the United States west of the Mississippi River. The last 20 years of drought have culminated in the lake dropping to its lowest level ever recorded in 2022, with a surface area of only 0.6 million acres, or about 40% of the record-high surface area of the lake. **Figure 3** compares the lake at its highest and lowest recorded water levels.

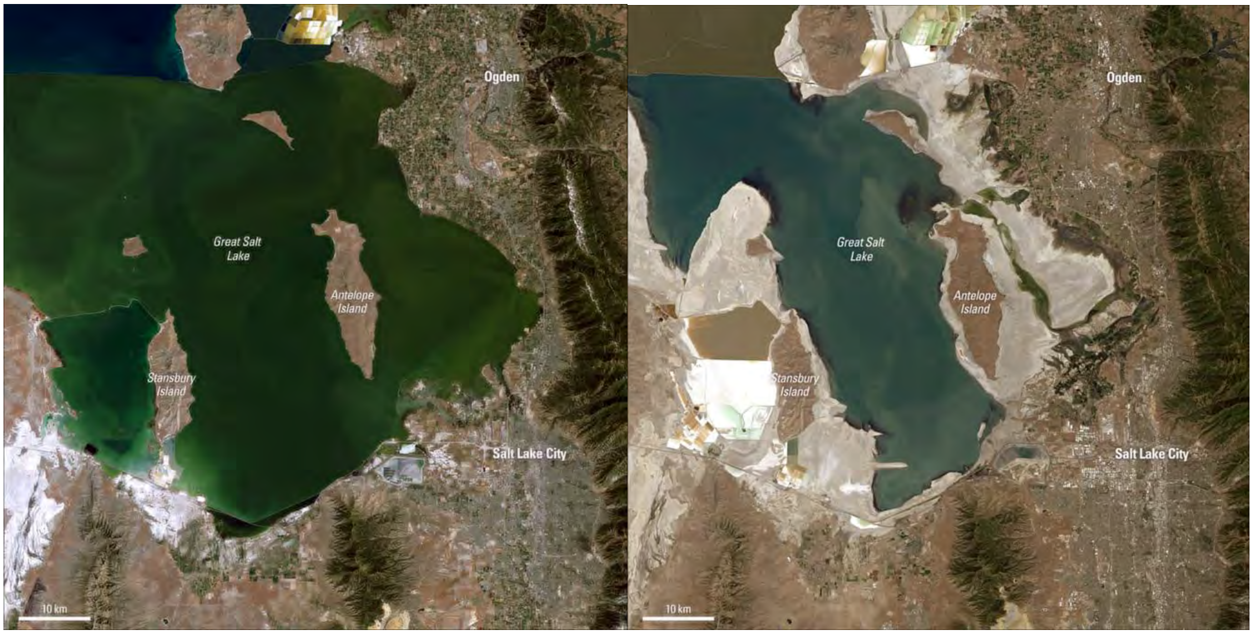
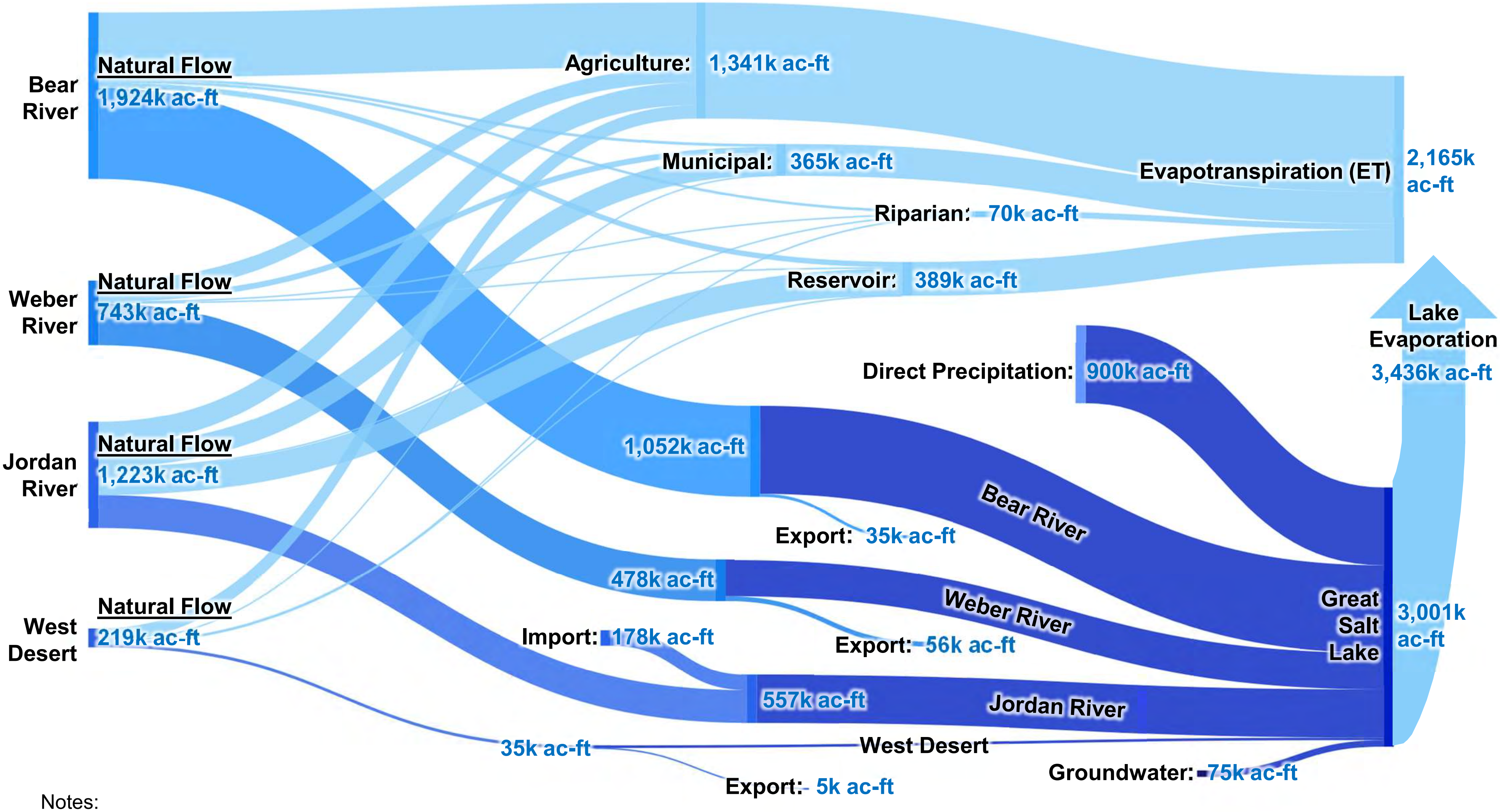


Figure 3. Satellite Photos of the Great Salt Lake in 1986 Near Capacity (left) and in 2022 at a Record Low (right) (Bouchard, 2022).

This record-high to record-low drop in water level has been documented by a water balance of the lake inflows, outflows (evaporation), and water diversions from tributaries upstream of the lake by the Utah Division of Water Resources (2023). The analysis demonstrated that the average volume of the Great Salt Lake has had a deficit of 435,000 acre-ft per year (**Figure 4**) from 1989 through 2020. It should be noted that in 1989 the lake was near its highest level following essentially the wettest 10 years on record within the basin. This is compared to 2020 which is near the end of the driest 20 years on record. **Figure 5** shows the full history of Great Salt Lake water elevation as recorded by the USGS. Figure 5 shows that the lake has historically fluctuated significantly and will likely continue to do so. Available precipitation compared to the consumptive (or evaporative) processes throughout the Great Salt Lake Basin is the most important factor for the quantity of water reaching the Great Salt Lake each year. Although available precipitation cannot be controlled, some practices can be implemented that can reduce the amount of evaporation and consumption that occurs as water moves through the basin.



Notes:

- Evaporation from the Great Salt Lake resulted in an annual net lake deficit of 435k ac-ft from 1989 through 2020.
- Based on modeling performed for this study, stormwater contribution to surface water flows to GSL are less than 10%.

Made with SankeyMATIC

Figure 4. Water balance of Great Salt Lake 1989-2020 Sankey Diagram, including natural flows to the lake, diversions, and natural evaporation pathways (DWR, 2023).

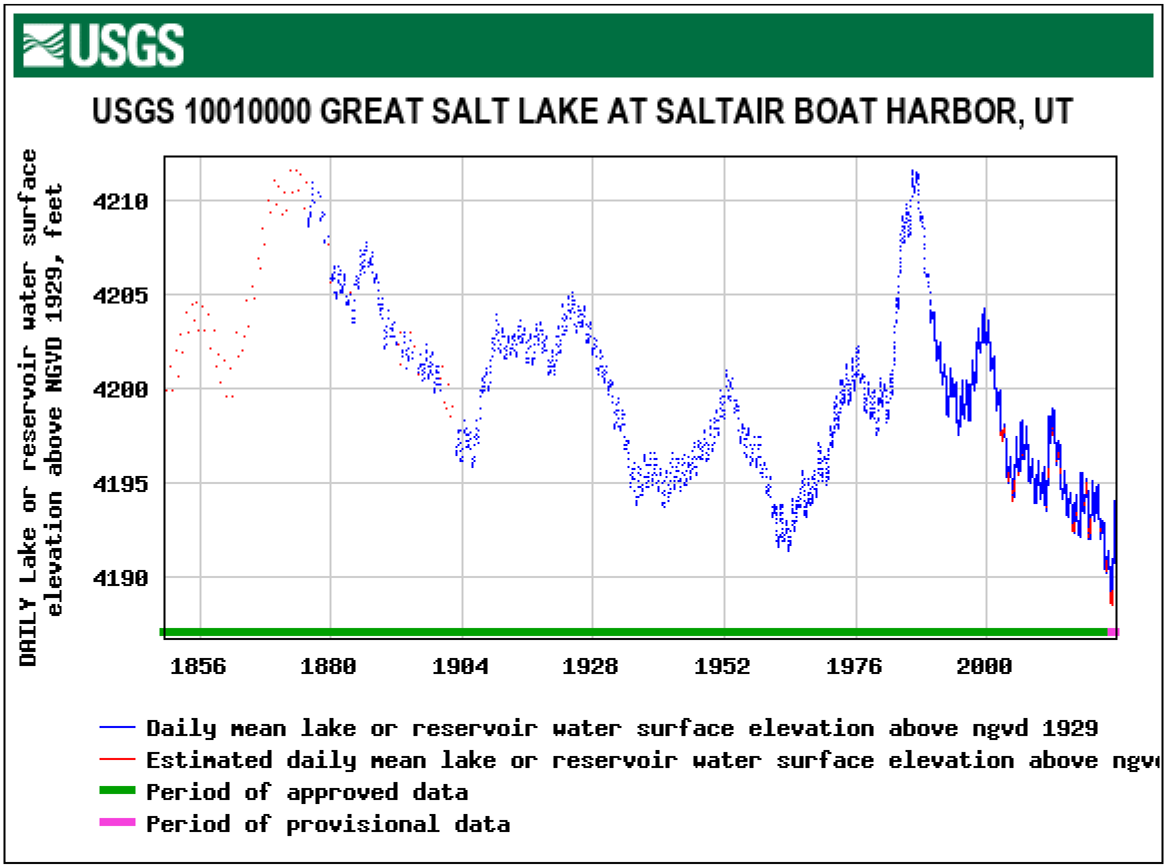


Figure 5. Great Salt Lake Elevation over the Period of Record.

Contribution of Stormwater

Surface water modeling of current conditions completed for this study estimated that stormwater contributes approximately 200,000 acre-ft per year[3] to the Great Salt Lake. That volume is about 7% of the average total water that naturally flows to the Great Salt Lake each year (3.001 million acre-ft, **Figure 4**). As discussed in the modeling summary section (**Table 2** and **Table 4**), future scenarios with LID will contribute an additional 16,700 acre-ft (compared to existing conditions from surface water and groundwater flows), and future development without LID will contribute approximately 37,700 more acre-ft. These values represent an additional 0.5 to 1% of the average annual flows to the Great Salt Lake. Alternative methods for treating water from impervious areas would need to be implemented if development without LID occurs. Overall, surface and groundwater flows to the Great Salt Lake are dominated by the size of the annual snowpack, and not by stormwater runoff. Future development with or without LID will likely have a relatively small future impact (0.5%) on the lake water balance.

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[3] This is from the four largest MS4 counties that expect to have the most development over the next 40 years.

CHAPTER 3 – CONCLUSIONS AND RECOMMENDATIONS

PROJECTED IMPACTS TO GSL WATER BALANCE CONCLUSIONS

Predicting where and how much future development (from the present day) will occur is uncertain and difficult. The Great Salt Lake drainage area is expansive and modeling all potential development was beyond the scope of this project. Therefore, development estimates have been made within each county based on a combination of data sources including present conditions (National Land Cover Dataset) and future plans and projections (Wasatch Front Regional Council, Kem C. Gardner population projections, and county level planning documents). Details about the approach used for estimating these areas, and the changes to runoff and groundwater recharge as a result of development, are summarized in **Appendix D.**

The assumptions for the future developed area and the percentage of that area that is impervious (i.e. roads, driveways, parking lots) are major factors in the reported results. A review of modeling results for various model inputs showed that reasonable estimates can be made by scaling the results to a smaller unit area (See Appendix D SWMM Output Scalability section). SWMM and groundwater modeling results were scaled to represent a 100-acre development with 50% impervious area. This allows for the results to be more easily applied to various future development scenarios outside of the modeled area by applying the results in 100-acre increments or units. **Figure 6** provides three Sankey diagrams (Baseline, LID, and No LID) to help visualize the magnitude and pathway of stormwater assuming average precipitation over 100-acres. The Baseline scenario for the 100-acre development represents a completely undeveloped condition with essentially zero impervious area. **Table 5** summarizes the general trends in the results when compared to Baseline conditions from these scaled results.

Table 5. Percent Change in Flow Compared to Undeveloped Condition.

Scenario	Surface Runoff	Total ET	Groundwater Recharge to GSL	GSL Inflows	Water Quality Impacts
100% Future Development No LID	3,933% ⬆	30% ⬇	36% ⇩	292% ⬆	Water quality degrades as development occurs (Hertzman 2016). Alternative treatment is required.
100% Future Development with LID	33% ⇧	13% ⇩	138% ⬆	129% ⇧	Water quality degrades as development occurs. LID filters runoff through the soil (Gautam et al. 2010, See Appendix B).

Note: Comparisons are to the undeveloped conditions that become developed with 50% impervious cover.

Table 6 summarizes the total area modeled, total area where projections were used, and the resulting runoff increases compared to the Baseline condition for the LID and No LID scenarios through the 2060 projection. High and low range estimates are provided in parentheses.

It should be noted that the results from this study are estimates and the uncertainty involved in these types of predictions is high. The results from our analysis can help guide decision-making, as they should help to explain the complex physical processes and connections between LID and groundwater flow to the Great Salt Lake.

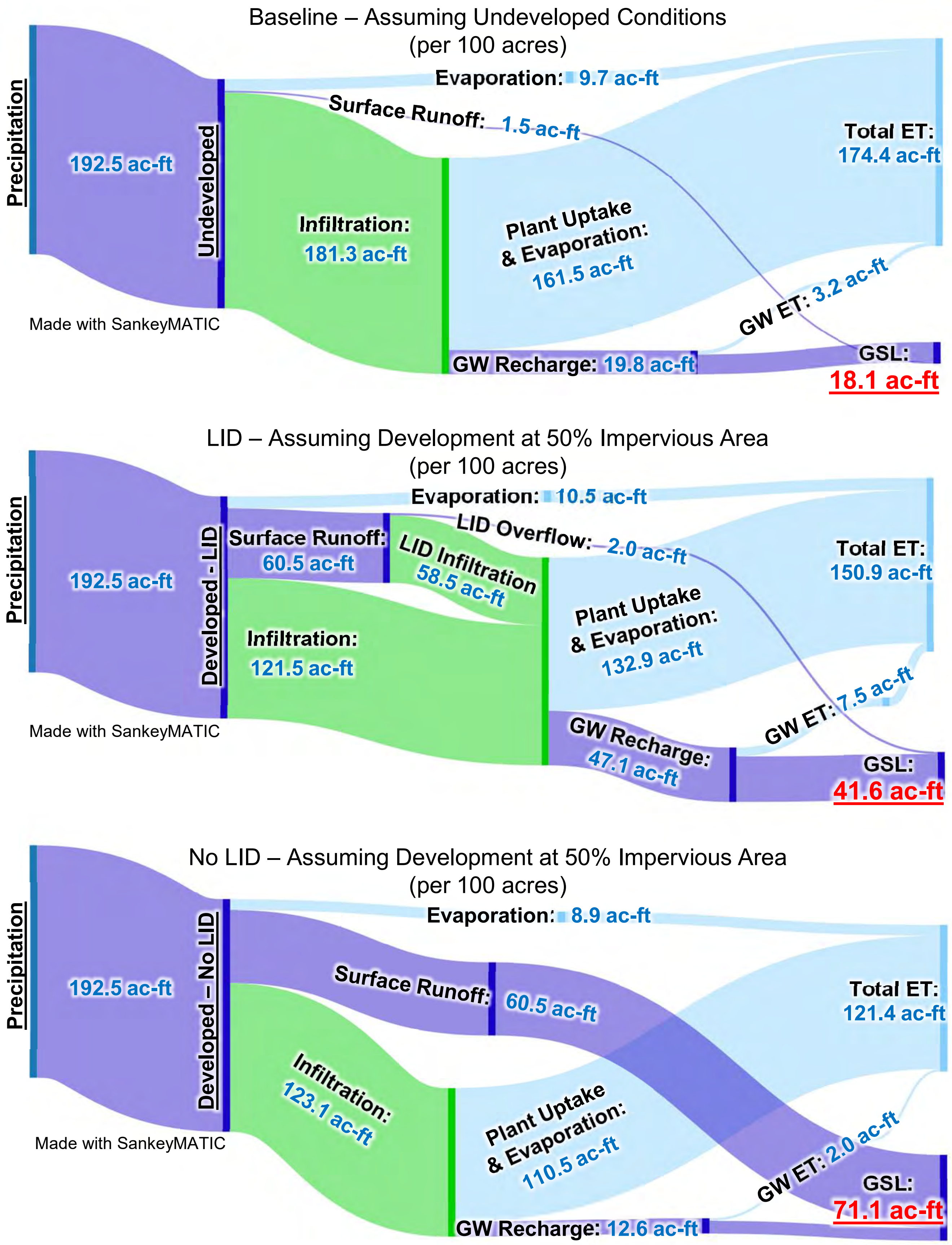

Figure 6. Sankey Diagrams showing Baseline, LID, and No LID Scenarios for 100 acres of Development

This analysis provides a summary of expected hydrologic impacts of projected 2060 future development to the GSL with and without LID implementation. The analysis suggests that more water would reach the lake for all future development scenarios. Future development without LID contributes more to GSL than development with LID.

Table 6. Summary of Additional Volume to GSL Compared to Baseline through 2060.

Description	Modeled Areas	Areas Not Modeled	Totals
Developed Area (acres)	**71,200** (64,100-78,300)	**62,100** (55,900-68,300)	**133,300** (120,000-146.600)
Impervious Surface (acres)	**35,600** (25,800-49,900)	**17,400** (11,400-21,200)	**53,000** (37,200-,71,100)
Additional Volume to GSL (LID) (acre-ft)	**16,700** (12,100-23,400)	**8,200** (5,400-10,000)	**24,900** (17,500-33,400)
Additional Volume to GSL (No LID) (acre-ft)	**37,700** (27,300-52,800)	**18,400** (12,100-22,400)	**56,100** (39,400-75,200)

1.Tooele County has been excluded from these numbers based on findings from the Stolp & Brooks (2009) study that shows little to no water from Tooele County enters the GSL.

The difference between the LID and No LID scenarios through the year 2060 was estimated to be 31,200 ac-ft (56,100 – 24,900 ac-ft from Table 6) per year. As noted in Figure 4, the total average inflow to the GSL from 1989 to 2020 has been approximately 3,001,000 ac-ft annually. The relative difference between future development with LID and without LID represents approximately 1% of the total annual inflow to the GSL as shown on Figure 7.

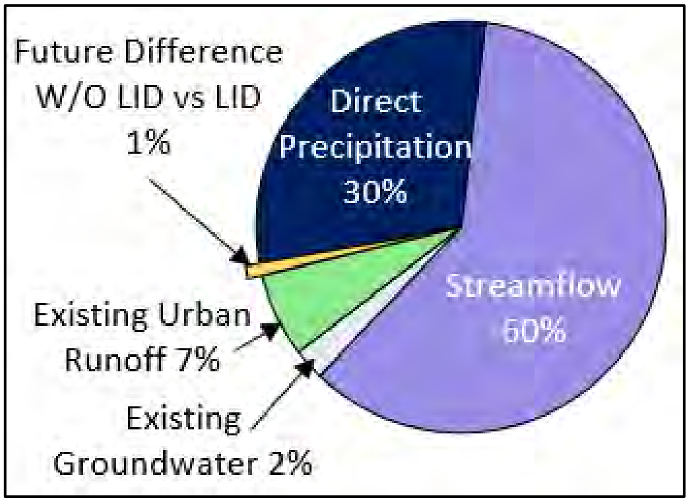

Figure 7. Sources of Annual Inflows to GSL.

GENERAL OBSERVATIONS

Table 7 summarizes some general observations made concerning future development within the GSL Basin as it relates to LID implementation within future developments.

Table 7. General Observations Regarding Future Development and LID Implementation.

	Overall Development	Without LID	With LID
Benefits	Increases water to the GSL	• More water to GSL than with LID • Water reaches GSL faster (days)	• Improved water quality • Increases groundwater recharge
Drawbacks	Impairs water quality	• Reduces groundwater recharge • Requires alternative water quality treatments	• Water reaches GSL slower (years) • Increased ET resulting in less water to GSL than without LID

RECOMMENDATIONS

The main purpose of LID infrastructure is to improve the water quality of stormwater runoff rather than to enhance aquifer recharge or increase water levels in the Great Salt Lake. If the “No- LID” development scenario were realized, this water would still need to be treated before entering the tributaries of the lake. To better understand the pros and cons of the two approaches we recommend the following additional work be completed.

- Use the models prepared as part of this study to quantify the water quality benefits that LID techniques provide. Water Quality is built into the SWMM surface water model, and can be added to the analysis. The model could be used to create scenarios to simulate the benefits of alternative BMPs from a water quality perspective to estimate their impacts on water quality. The quantity of water that reaches the Lake via these methods could also be evaluated.
- This study’s modeling also required multiple assumptions – including LID practice types, LID performance, and runoff capture rates – that may not be applicable for all real-world applications of LID; future modeling would enable exploration of these assumptions and testing of additional LID performance parameters.
- Develop a cost/benefit analysis for LID and non-LID techniques. The costs for non-LID techniques would include alternative water quality treatment to meet MS4 requirements for comparison to the LID requirement costs.
- Develop regionalized planning cost estimates for implementing LID and various types of other stormwater infrastructure. This analysis should evaluate the most cost-effective ways to improve stormwater water quality while also minimizing evapotranspiration before the water reaches the Great Salt Lake.

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APPENDIX A

Regulatory Requirements for Stormwater Retention

APPENDIX A - SUMMARY OF REGULATORY REQUIREMENTS FOR STORMWATER RETENTION

This section summarizes the regulatory requirements for stormwater retention in Utah, as well as retention requirements in neighboring and/or states with similar climatic conditions. Compliance with stormwater retention requirements is a major driver of LID implementation in Utah.

Regulatory Requirements for Stormwater Retention in Utah

Utah MS4 permits include a Post-Construction Retention Standard that regulates "construction sites with a land disturbance of greater than or equal to one acre, including projects less than one acre that are part of a larger common plan of development or sale which collectively disturbs land greater than or equal to one acre…" The permits state that "by July 1, 2020 all new development projects meeting the applicable threshold, to manage rainfall on-site, and prevent the off-site discharge of runoff associated with precipitation less than or equal to the 80th percentile rainfall event. The 80^{th} percentile rainfall event is the event whose precipitation total is greater than or equal to 80 percent of all storm events over a given period of record. This requirement also regulates re-development, and states "By July 1, 2020, redevelopment projects meeting the applicable threshold that increase the impervious surface by greater than 10%, shall manage rainfall on-site, and prevent the off-site discharge of the net increase in the volume associated with the precipitation from all rainfall events less than or equal to the 80th percentile rainfall event. Projects subject to the requirements above must manage stormwater through a Low Impact Development (LID) approach which promotes the implementation BMPs that allow storm water to infiltrate, evapotranspire or harvest and use storm water on site to reduce runoff from the site."

Stormwater Retention Requirements in States with Climactic Conditions Similar to Utah

This table includes other states in U.S. EPA Region 8 (except for South Dakota and Wyoming, because their permits have been administratively extended because they have not yet adopted stormwater retention requirements), plus several other states with climactic conditions similar to Utah.

Table 1: Stormwater Retention Requirements in States with Climactic Conditions Similar to Utah

State	Stormwater Retention Requirement	Reference	Additional Notes
Colorado	The permittee must implement a program to reduce the discharge of pollutants to the MS4 from applicable development sites. "Applicable development sites" are those that result in land disturbance of greater than or equal to one acre, including sites less than one acre that are part of a larger common plan of development or sale, unless excluded per the regulations. The permittee must provide treatment and/or infiltration of the WQCV at 100% of the applicable development site (with exceptions). The control measure(s) must be designed to treat at a minimum the 80th percentile storm event. The control measure(s) shall be designed to treat stormwater runoff in a manner expected to reduce the event mean concentration of total suspended solids (TSS) to a median value of 30 mg/L or less.	https://oitco.hylandcloud.com/pop/docpop/docpop.aspx	
Montana	Applicable to MS4 permittees. For new development or redevelopment projects greater than or equal to one acre, the program shall include a process, where such practices are practicable, to require the implementation of low-impact development practices that infiltrate, evapotranspire, or capture for reuse the runoff generated from the first 0.5 inches of rainfall from a 24-hour storm preceded by 48 hours of no measurable precipitation	https://mdt.mt.gov/pubinvolve/stormwater/docs/MTR040000-GENERAL-PERMIT-2010.PDF	

North Dakota	MS4 Permittees must develop, implement, and enforce a program to reduce pollutants in stormwater runoff from new development and redevelopment projects within the jurisdiction of the MS4 for projects that disturb one or more acres, including projects that disturb less than one acre that are part of a larger common plan of development or sale that disturbs one or more acres.	https://deq.nd.gov/publications/wq/2_NDPDES/Stormwater/MS4/NDR04per20210401F.pdf	
Arizona	Level 1 Single Commercial Lot): storage of the entire 1-hour, 100-year rainfall falling on the project site	https://new.azwater.gov/sites/default/files/SS8-99Detention_Retention.PDF	
	Level 2 (Small Subdivisions, <160 acres): storage of a portion of the 1-hour, 100-year rainfall falling on the project site to maintain the 100-year pre-development runoff rate from the site		
	Level 3 (Large Subdivisions >160 acres and Planned Communities): Where possible, stormwater detention/retention should be implemented on a regional basis by the governing authority/district. The stormwater detention/retention program should utilize regional detention/retention based on a watershed-wide assessment of the effects of urbanization and planning and development of facilities at the most effective locations to minimize those effects. Where the implementation of a regional program is not possible or practical, stormwater detention should be provided to the extent necessary to ensure that postdevelopment peak discharges from a project site are no greater than predevelopment peak discharge rates for the 2-, 10- and 100-year events		
Idaho	MS4 permittees are required to use permanent stormwater controls that are sufficient to retain onsite the runoff volume produced from a 24-hour, 95th percentile storm event; or sufficient to provide the level of pollutant removal greater than pollutant removal expected by using onsite retention of runoff volume produced from a 24-hour, 95th percentile storm event.	https://www.epa.gov/sites/default/files/2021-01/documents/r10-npdes-itd3-ms4-ids028177-final-permit-2021.pdf	
New Mexico	MS4 permittees must develop, revise, implement, and enforce a program to address stormwater runoff from new development and redevelopment projects that disturb greater than or equal to one acre, including projects less than one acre that are part of a larger common plan of development or sale, that discharge into the MS4. MS4 permittees must develop and incorporate a stormwater quality design standard that manages on-site the 90'" percentile storm event discharge volume associated with new development sites and 80'" percentile storm event discharge volume associated with redevelopment sites, through stormwater controls that infiltrate, evapotranspire the discharge volume, except in instances where full compliance cannot be achieved, as provided in Part I.D.5.b.(v).	https://www.epa.gov/sites/default/files/2018-10/documents/r6-npdes-middle-rio-grande-ms4-nmr04a000-final-permit-2014.pdf	New Mexico also has specific guidance for the implementation of Green Infrastructure at https://www.env.nm.gov/wp-content/uploads/sites/25/2017/06/notice-2017-05-01_Green-Infrastructure-FAQs_Final.pdf

APPENDIX B

Great Salt Lake Stormwater Study, Task 1: Literature Review

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Memorandum

From:	LimnoTech	**Date:**	14 March 2023
		Project:	UTAHGSLLID
To:	Jim Harris, Utah DEQ-DWQ DWQ & DWRe Staff	**CC:**	Hansen, Allen, & Luce

SUBJECT: **Great Salt Lake Stormwater Study, Task 1: Literature Review**

Background and Purpose

The State of Utah has identified the need to evaluate the impact of Low Impact Development (LID) – also known as Green Infrastructure (GI) - on the water budget of the Great Salt Lake. In order to do this, the project will develop and implement a conceptual model of the water flows within the basin to visualize and quantify (at a high level) the various component flow types and pathways (i.e., precipitation, overland flow, infiltration to groundwater, evapotranspiration) and to evaluate how LID impacts these flow components.

Task 1 under this project is to complete a technical review of current relevant literature, research, and studies that have evaluated the effects of on-site stormwater retention practices on groundwater and surface water quantity. To do this, we have sought out and compiled information on LID’s relative effects on surface water and groundwater hydrology, including retention, infiltration, and evaporation/evapotranspiration rates. Specifically, the studies and documents have been evaluated to identify information such as estimates of infiltration and evaporation under different design, precipitation, and climate conditions. This type of information will be useful when developing and parameterizing the conceptual model of flows within the basin and the impact of LID.

This document summarizes the studies that have been evaluated. Within this review, we have prioritized studies and data based on their applicability to the semi-arid climatic conditions in Utah. We have also focused on the types of BMPs that are allowable, recommended, and/or prevalent under DEQ regulations.

Methodology

In order to conduct this literature review, two primary means for identifying relevant literature were used. These included:

- Internet searches; and
- Direct contact with identified potential experts.

Internet searches were used to identify research papers, academic documents, guidance, municipal plans, and other relevant information. Keywords such as “low impact development,” infiltration," "semi-arid western United States," "groundwater-surface water interaction," "aquifer recharge," and other terms and phrases were used in the searches. Once relevant papers were identified, they were compiled, and the sources cited in those papers were reviewed to determine if those sources should be reviewed as well. In addition, Google Scholar was used to follow research forward to determine if the papers we had identified had in turn been cited in other work.

Direct contact was also made with researchers in Utah, including academics at Utah State (Ryan Dupont) and the University of Utah (Sarah Jack Hinners). Contact was attempted, but not made, with an additional professor at Utah State (Erin Rivers).

A bibliography of source documents was compiled and the source documents were reviewed for information that could inform the remainder of the project. This literature review provides a summary of relevant information, as well as the source of that information.

Literature Review Results

Stormwater Best Management Practices (BMPs) and LID have been used for several decades to control stormwater, protect against flooding, and meet regulatory requirements for reducing runoff and pollutant loading to surface waters. Traditional stormwater BMPs, such as wet and dry detention ponds, retention ponds, and filters, as well as more recently developed LID, such as bioretention, green roofs, and other systems that attempt to reproduce more natural hydrologic conditions, detain or retain stormwater runoff, reducing peak flows and controlling the total volume of runoff. Some of these BMPs detain water before releasing it back into the storm sewer system, thereby reducing issues related to high flows, such as stream erosion and first flush pollutant loading. Other BMPs – particularly LID – retain and infiltrate storm flows using specialized media and plants. These LID practices can also infiltrate stormwater back into the groundwater.

Other types of stormwater management practices, collectively known as rainwater harvesting, specifically collect and retain stormwater runoff for the purposes of beneficial reuse, such as irrigation, domestic use, cooling, or even drinking.

Municipalities in Utah use these types of BMPs and LID to control stormwater runoff for the purposes of controlling peak discharges, minimizing erosion, improving water quality, and mitigating flooding. Many municipalities have specific regulatory requirements to implement stormwater management programs. Stormwater BMP design manuals have been prepared by multiple municipalities, state agencies, and other entities to prescribe designs that will maximize the impact of these BMPs, as well as meet regulatory requirements for stormwater control. The specific design requirements of BMPs approved for use in Utah are an important component of this study, because those design factors impact the effectiveness of those BMPs at intercepting, storing, and infiltrating flows from stormwater runoff.

Research on LID in Semi-Arid Environments

Most BMP and LID research in the United States has been undertaken in temperate, humid, or cold climates – much of it in the mid-Atlantic or Upper Great Lakes regions. However, conditions in Utah are very different than in these areas – the climate is drier and is characterized by lower frequency storms.

BMPs and LID have been studied in arid and semi-arid conditions similar to those in Utah, including studies in Albuquerque, NM (Hertzman, 2016), the Las Vegas Valley (Sun, et. al., 2016), Phoenix, AZ (Meerow, et. al., 2021), the Middle Rio Grande watershed in New Mexico (Thomson, 2021; Regier, et. al., 2020) and Colorado (Topper, 2009). International studies have been conducted in locations such as Iran (Heidari and Kavianpour, 2021; Jamali, et. al., 2021) and Mexico (Lizarraga-Mendiola, et. al., 2017). There has also been some research in Utah itself (Ahmed, 2007; Heiberger, 2013).

Many of the papers written on BMPs in arid and semi-arid climates focus on stormwater quality and pollutant removal (e.g., Jiang, et. al. 2015; Regier, et. al. 2020; Gupta, 2022). Others focus on generalized impacts and benefits of stormwater management. For example, Meerow, et.al., (2021) summarize the hydrologic, water quality, urban heat, and air quality benefits of GI in Phoenix, Arizona while Jamali et. al. (2021) evaluate the prioritization of areas for implementing GI in Tehran, Iran, based on reducing the urban heat island impact and controlling runoff. Other papers focus on surveying practitioners in the field. For example, as part of his master's thesis at the Utah State University, Ahmed (2007) interviewed municipal stormwater managers to evaluate the perceived effectiveness of structural stormwater BMPs (in terms of reductions in runoff and reduced pollutant loading) for BMPs installed on municipal sites in northern Utah. Similarly, Heidari (2022) focuses on stakeholder perceptions of various practices to address their primary concerns. As part of a proposed a methodology for selecting the “best” LID practices, Heidari evaluated the priorities of different stakeholders, including municipal governments; building and land developers; planners; private homeowners; local business owners; and non-profit organizations [NGOs]. Of particular relevance to this study is his conclusion that municipalities and NGOs are more concerned about groundwater recharge issues compared to other stakeholders.

A large focus of the literature is the effectiveness of BMPs in semi-arid environments. Gautam et. al., (2010) evaluated the effectiveness of BMPs in the desert Southwest through a review and evaluation of the available studies and data. One premise of the study is that “water availability, management, and sustainability issues in the Desert Southwest are unique from the rest of the country and thus stormwater BMPs must also be different.” The authors summarize hydro-meteorological factors that make the desert Southwest different from other areas, including:

- Despite low average and annual total precipitation compared to other regions of the country, the extreme value of rainfall depth and intensity can be significant;
- A large inter-storm duration period due to the low number of days of rainfall per year;
- The significant impact of urbanization and land development through water use, return flow, and flooding; and
- A very high potential evapotranspiration rate.

The authors also note that “sparse vegetation, sprawling and rapid land development, and general geology can contribute to relatively higher runoff Curve Numbers” in the desert Southwest compared to other areas. Their data compilation for Curve Numbers for southwestern cities (cited by the authors through a separate source) range from 86 in Dona Ana County, NM and Tucson, AZ to 91 in Badger Wash, CO. While the authors do not provide Curve Numbers for other areas, these numbers are generally…indicative of impervious land cover, open space in poor condition with low-infiltration underlying soils, or residential areas with low-infiltration soils (USDA, 1986).

The authors summarize the implications of hydroclimatic characteristics of arid regions on BMP design in the desert southwest compared to other areas, including:

- A much smaller storage area is needed to treat for water quality and quantity.
- Common structural BMPs that are often used in humid regions (e.g., wet detention ponds) may be unsuitable for the arid regions because of the high evaporation rate combined with the demands of sustainable water use.
- The increased flow rates compared to natural conditions that are caused by rapid urban growth can increase erosion in the natural washes that are often used as flood conveyance facilities.
- Runoff from landscape irrigation and other outdoor uses can impact BMPs that rely on recharge as a treatment mechanism. This can also change ephemeral channels into perennial streams. The authors cite the Las Vegas Wash as an excellent example of this issue.
- Given the low frequency of storms in arid regions, the build-up of pollutants can increase over longer periods of time, which may result in high concentrations of pollutants in the "first flush" compared to other areas.

In addition, the authors note that it may be difficult to convince stakeholders of the need for implementation of BMPs because of the overall low annual totals of precipitation.

Noting that since water quantity is a dominant priority in arid regions, the authors summarize that "the best strategy for effective BMPs for the arid Southwest should be developed based on stormwater conservation and water reuse. Such conservation practices should be based on rainwater harvesting, local groundwater infiltration when feasible, and minimization of evapotranspiration losses." They cite four principles from (Caraco, 2000):

- Stormwater practices should be carefully selected and adapted for arid watersheds.
- Stormwater practices should avoid irrigation needs.
- Ground water resources need to be protected from contamination and augmented through recharge practices where feasible.
- Channel erosion and sediment generation in the watershed should be minimized.

Many papers focus on the specific design of BMPs and LID to address local conditions in a semi-arid environment (Lizarraga-Mendiola, et. al., 2017; Heiberger, 2013). For example, as part of his master's Thesis at the University of Utah, Heiberger (2013) examined the performance of bioretention cells on the University of Utah campus in Salt Lake City. His conclusion was that, with proper design and sizing, nearly all annual runoff volume can be controlled on site and either infiltrated or utilized by native plant species. As measured infiltration data were limited to the vadose zone, the infiltrated volume was considered potential recharge. He noted that future work may include modeling and installation of deeper sensors as a means of approximating recharge.

Lizarraga-Mendiola, et. al. (2017) evaluated the design of a bioretention cell and an infiltration trench in a semi- arid micro watershed. One concern was whether the bioretention cell design would require irrigation, which can be a drawback in a water-scarce environment. Results showed that the cell required irrigation in some of the dry months (November and December), even in years characterized by abundant rainfall. However, the plants recovered during rainy months, which the authors interpret as indicating that well-designed BMPs with appropriate plant regimes can succeed in these types of environments.

In their paper entitled "Assessing the Applicability of Low Impact Development Techniques in Arid and Semi-arid Regions," Heidari and Kavianpour (2021) evaluated LID techniques in Varamin, Iran – an area with low slope regions with arid and hot climate. The authors evaluated the effectiveness of three BMP types (rainwater tanks, bioretention and pervious pavement) on stormwater quality and quantity management and found that the rainwater harvesting systems had the greatest impact on the surface water collection system in terms of both stormwater quality and quantity management. The authors also note that rainwater harvesting can be ideal for these types of climates because it can enhance water available for reuse, which is an important consideration in areas of water scarcity.

Considerations/Challenges in Using LID to Recharge Groundwater Sources in the Arid West

In his paper entitled "Stormwater Capture in the Arid Southwest: Flood Protection Versus Water Supply," Thomson (2021) discusses the challenges of capturing stormwater to augment urban water supplies in the arid southwest, focusing on the Middle Rio Grande watershed in central New Mexico. His focus is on non-economic factors and his goal is "to identify the issues that must be addressed when considering urban stormwater runoff as a source water supply." His paper considers the following challenges to in capturing and using stormwater capture in the southwest:

- Regulatory challenges, especially water rights and downstream delivery requirements;
- Hydrologic challenges associated with the transient nature of storms in arid environments and the limited volume of water generated;
- Engineering and infrastructure challenges required to capture, store, treat, and transport stormwater to potential users;
- Water quality challenges due to the poor quality of runoff from urban watersheds.

Based on these challenges, Thomson concludes that "instead of community-scale stormwater retention and reuse, onsite retention and reuse may be a more realistic strategy for urban stormwater capture." He continues to state that "although large-scale stormwater capture and reuse concept has public appeal, the regulatory and infrastructure challenges are so great that a project to recover the comparatively small volume of water available is not likely to be feasible."

Research on Infiltration and Groundwater Recharge in Semi-Arid Environments

There has been an abundance of research on the impacts on how infiltration of stormwater runoff through BMPs can impact the subsurface. For example, in their research in the Upper Midwest on how stormwater runoff intercepted by GI can reach surface waters through rainfall-derived inflow and infiltration, Zhang and Parolari (2022) evaluated partitioning of various subsurface flows from infiltration through stormwater BMPs. The authors state that "stormwater infiltration aims to replenish soil moisture and recharge groundwater to promote slow hydrologic flowpaths, evapotranspiration and baseflow, while reducing rapid overland flow." With respect to rainfall-derived infiltration and inflow, "sensitivity analysis indicated that the surface direct inflow was controlled more by precipitation/ evapotranspiration ratio and the subsurface infiltration was controlled more by groundwater table depth and sanitary sewer defect density. The largest effect of GI was to shift surface runoff to evapotranspiration and reduce peak flow in urban sewer systems." The authors modeled the impact of disconnecting downspouts on the relationships and partitioning of water infiltrated through GI. The concluded that the "partitioning of water infiltrated through GI between evapotranspiration, groundwater recharge, and RDII, impacts how effective GI is at redirecting stormwater flows from fast to slow pathways." Citing Lizarraga-Mendiola et. al. (2017) and Ebrahimian et. al. (2019), the authors state that "for more arid areas or drier periods with lower precipitation / PET ratios, although there is smaller hydrologic input to GI, the relative change in water budget partitioning by GI may be greater because a larger proportion of enhanced infiltration by GI can be lost via ET and less can be routed as quick flow into the system." This supports other findings that ET is an important factor for water balances in semi-arid environments.

While infiltration and its impact on groundwater discharge are acknowledged as important in arid and semi-arid climates, there has been a paucity of research on this topic. In its report titled *Identifying Key Areas in the City of Phoenix for Infiltration and Retention Using Low Impact Development* (Tosline, et.al., 2022) conducted a literature review, but they found no studies that focused on water retention/ recharge.

While there has been a good deal of research on subsurface interactions in humid climates, very little has been done for the arid and semi-arid west. Carraco (2000) also notes the importance of groundwater in arid and semi-arid communities. The author notes that "in many arid communities, protection of groundwater resources is the primary driving force behind stormwater treatment. Ironically, early efforts to use stormwater to recharge groundwater have resulted in some groundwater quality concerns. In Arizona, for example, stormwater was traditionally injected into 10 to 40 foot deep dry wells to provide for groundwater recharge. Concerns were raised that deep injection could increase the risk of localized groundwater contamination, since untreated stormwater can be a source of pollutants, particularly if the proposed land use is classified as a stormwater hotspot." Similarly, in their study on integrated stormwater and groundwater management in urban areas within semi-arid regions, Naeimi and Safavi (2018) state, "in arid and semi-arid regions, groundwater resource is generally the only source of water and also the vulnerable one which is prone to be polluted and depleted. Hence, taking this significant component into account in the hydrologic cycle is of great importance." Citing Bouwer (2002), Naeimi and Safavi go on to state that whereas in Mediterranean and humid climates, 15–40% of the precipitation infiltrates into the groundwater resources. In a dry climate, normal or natural recharge is 0–2% of the precipitation, the lowest amount compared to other climates.

Gabor et. Al. (2017) worked in Red Butte Creek in Salt Lake City to evaluate whether "subsurface water drives surface water chemistry," focusing on how the infiltration of pollutants from urban runoff into groundwater eventually increases pollutant loads into surface waters. Using conservative tracers of urban runoff (chloride, nitrate), these researchers concluded that "the urban aquifer drives urban impacts to water quality." They continue on to say that "overall, these results indicate larger-scale hydrogeologic controls on surface water– groundwater interactions in urban catchments that operate on a scale of kilometers in space and months to decades in time...Our evidence of exchange occurring over larger space and time scales necessitates a consideration of subsurface exchange not just with the hyporheic but with a larger alluvial zone (see graphical abstract). This highlights the importance of the vertical dimension, as described in the urban watershed continuum."

Several studies do focus on groundwater recharge in arid and semi-arid environments. In a study for Clear Creek County, in the Front Range of Colorado, Topper (2009) focused on identifying "passive absorption and infiltration best management practices that target the development induced runoff from frequent, smaller volume storms that would not have produced runoff in the native environment." He notes that "in Colorado's semi-arid climate, most of the precipitation that falls on the land surface is lost to evapotranspiration. The remaining water is: 1) absorbed by the soil to increase soil moisture and when saturated infiltrates into the subsurface and/or 2) flows overland to become runoff. It is not until excess soil moisture conditions exist that water moves downward by gravity to reach the water table recharging the aquifer. Natural recharge occurs when precipitation percolates into the ground (infiltration) and reaches the water table. Natural recharge rates in Colorado are highly variable." He then cites Poeter et. al. (2003) and states that "in the mountainous regions of the Front Range it is estimated that only 6-8 percent of total precipitation contributes to recharge of long-term groundwater storage." The author then goes on to state that "reduced infiltration causes a reduction of natural recharge that in combination with increased withdrawals through well pumping can cause a decline in water levels. Absent other sources of recharge, declining water levels also leads to a reduction of baseflow in streams."

Topper notes that "enhanced recharge has historically consisted of vegetation management, where deep-rooted, hydrophilic or "water-loving" vegetation are replaced by shallow-rooted water-conserving vegetation or bare soil. Enhanced recharge can also be achieved by selective management of runoff." The paper looked at natural recharge potential based on geology, slope, soil type, and precipitation. The study concludes by suggesting avoiding development in areas with high infiltration potential. However, if they are developed, the author suggests siting infiltration BMPs in these areas to enhance groundwater recharge.

In their study in Isfahan - the third-largest city in Iran - Naeimi and Safavi (2018) found that the potential recharge volumes by BMPs were 2.4, 11.1 and 37.5 million cubic meters per year (MCM/year) for dry, normal and wet years, respectively. The authors used the Soil Conservation Service Curve Number (SCS CN) method and a GIS application to calculate runoff volume based on CN classes over a 410 km^2 urban area in dry, normal and wet conditions. The authors evaluated multiple BMP types for inclusion in the model based on their capacity for groundwater recharge; their space requirements given that they were going to be installed in public areas; and their need for pretreatment. The ability to control rooftop runoff and to be used in public parking lots were also evaluated. The authors chose dry wells, gravel trenches and pervious pavement for high, average and low flooding areas ("zones"), respectively. These practices have different infiltration capabilities to transfer runoff into the groundwater, and these differences were addressed through the assignment of different infiltration coefficients. These BMPs were then modeled as a source control method to infiltrate the calculated runoff to the zones as potential recharge. In the area with the lowest flooding potential, zone 1, with the minimum flooding level, pervious pavement was chosen as an appropriate BMP to increase surface perviousness and control runoff volume and velocity. The authors notes that pervious pavement has high volume reduction capability, and can be useful in public or private parking lots and areas with pedestrians. For zone 2, where flooding potential is moderate, the authors modeled gravel trenches. Gravel trenches require large amounts of space, but can be appropriate for use near the roads and parking lots in public areas. In zone 3, which consisted of high-densely populated residential areas and had the highest imperviousness and insufficient drainage areas, a high-efficiency method that required less space was necessary. The authors modeled dry well implementation for zone 3 to lower the volume and transfer rooftop runoff with a low level of contamination in this zone. The results suggested that the aquifer volume was extensively influenced by the stormwater infiltration applied followed by using the BMPs in the model.

Voter and Loheide II (2021) evaluated the effects of LID practices on long-term surface runoff, deep drainage, and ET. The authors state that "while event-scale performance is critical for mitigating flood risk, an understanding of the long-term partitioning of hydrologic fluxes is also needed to assess impacts on other ecosystem services that are controlled by deep drainage (DD) and evapotranspirative fluxes." They further state that "partitioning of increases in DD vs increases in ET due to infiltration-based LID is controlled by PET:P and total precipitation, with LID practices mostly increasing DD in humid areas but mostly increasing ET in arid and semi-arid areas." They note that "the role of energy availability and well-known ecological frameworks based on the aridity index (ratio of potential evapotranspiration (ET) to precipitation, PET:P) … are almost entirely absent from the LID scientific literature. Furthermore, it has not been tested whether these natural system frameworks can predict the fate of water retained in the urban environment when human interventions decrease runoff."

The authors utilized a process-based hydrologic model of a baseline single-family parcel and a parcel with infiltration-based LID practices. Statistical analysis of the model evaluated the effects of LID practices on long-term surface runoff, deep drainage, and ET. The results indicate that long-term surface runoff, deep drainage, and ET are controlled by the relative balance and timing of water and energy availability and measures of precipitation intermittency. In their discussion, the authors note that humid cities like Baltimore, MD and Madison, WI experience "increased DD near disconnected impervious features and little sign of increased ET" and cities with more moderate climates (such as Oklahoma city, OK) have about equal increases in DD and ET, "the more arid cities of Phoenix, AZ and El Paso, TX (PET:P of 8.1 and 29.5, respectively) instead show strong hot spots of increased ET with little increase in DD." The authors conclude that in arid environments, "the wetting fronts at impervious-pervious interfaces… [that]…can regularly penetrate past the root zone and result in strong hot spots of DD… are not strong enough to do the same in more arid locations where infiltrated water instead remains in the root zone until transpired by vegetation." The authors go on to say that "if managers in arid locations desire increased DD, we suggest concentrating runoff from a larger impervious source area than exists on this example single-family parcel, e.g., by using focused infiltration basins which collect runoff from several residential parcels."

As part of the Los Angeles Water Augmentation Study (U.S. Bureau of Reclamation, 2010) the U.S. Bureau of Reclamation and the Los Angeles & San Gabriel Rivers Watershed Council focused on evaluating "the potential benefits to water quality and supply from using stormwater runoff, as well as barriers associated with such use." Among the goals of this study were:

- Develop an understanding of the land use, soil, and hydrogeological factors in capturing and infiltrating runoff;
- Assess the effectiveness of various infiltration techniques, particularly in removing pollutants;
- Quantify the amount of stormwater that could realistically be captured and infiltrated;

- Develop a framework of social, economic, and institutional factors that must be addressed in order to create a program to implement widespread infiltration; and
- Develop a region-wide implementation plan to deploy infiltration devices in appropriate locations and settings, along with guidelines for sustainability.

The project employed a groundwater model (the Groundwater Augmentation Model [GWAM]) and concluded that "The GWAM estimates that annually 16 percent of precipitation currently percolates to groundwater (about 194,000 acre-feet) in the Los Angeles Region, while 50 percent (approximately 601,000 acre-feet) becomes runoff that flows directly through the stormwater conveyance system to the ocean...Implementing a regional decentralized stormwater management where the first ¾" of each rain storm is captured and directed for infiltration on all parcels could add up to 384,000 acre-feet bringing the estimated total to 578,000 acre-feet of recharge per year, on average, to the groundwater basins – enough water for 1.5 million people."

Zhang and Peralta (2019) combined the Source Loading and Management Model (WINSLAMM) (which they used to estimate runoff from precipitation in areas with GI and the Soil Conservation Service (SCS) runoff curve method to estimate infiltration in the southwestern U.S. They applied the approach to a Salt Lake City residential area for current land use and three assumed runoff control practices and computed infiltration and runoff values enable to estimate the runoff reduction and infiltration increase due to alternative GI construction modes. The infiltration coefficients they generated are ratios (like runoff coefficients) that are useful for estimating infiltration volumes for specified area, land use, and rainfall. This is illustrated in Figure 1 below.

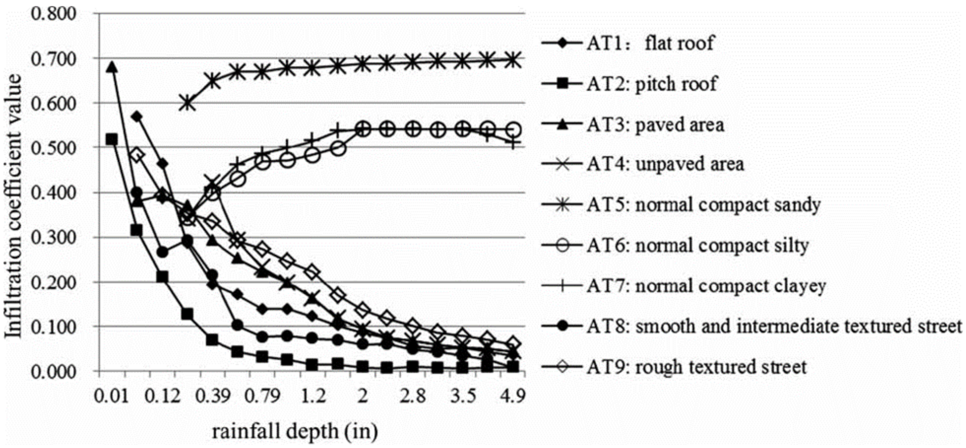

Figure 1. Infiltration Coefficient / Rainfall Ratios (Zhang & Peralta, 2019).

In a follow-up study, Dupont, et. al. (2021) set out to test the hypothesis that Managed Aquifer Recharge (MAR) via stormwater harvesting is technically feasible. They used the WINSLAMM model set up for Red Butte Creek watershed. The authors note that "when GI was applied to the full basin only a slight decrease in total annual discharge was observed. Application of GI within a more urbanized subbasin resulted in significantly reduced peak runoff and appreciably increased groundwater recharge." The authors then present a case study in the Salt Lake Valley near the Jordan River "to evaluate the potential for Spring runoff infiltration through shallow groundwater recharge coupled with Summer groundwater recovery for turf grass irrigation under Northern Utah climatic conditions (historical April, May, early June rainfall patterns). Results indicated a stormwater recovery effectiveness from 10.7% to 52.7% depending on irrigation scheduling, and a feasible constant recovery rate of shallow groundwater from 1.0 to 10.6 gpm." While the authors focus on recharge of the shallow aquifer, their methods and modeling could be useful in looking at recharge of the deep aquifer as well.

Evapotranspiration and Uptake of Water by LID Plantings in Semi-Arid Environments

One issue of specific focus in the literature on BMPs in semi-arid climates is how BMPs can function to enhance water retention to support plants. For example, Kauffman and Stropki (2022) evaluate whether soil moisture in rain gardens can sustain trees planted around those rain gardens, concluding that the rain gardens retained sufficient soil moisture to sustain surrounding vegetation, noting "the ease with which rain gardens refilled and maintained soil moisture bodes well for sustaining urban trees and offsetting irrigation costs in semi-arid climates with limited water resources." Similarly, Lizarraga-Mendiola, et. al. (2017) evaluate potential designs of a bioretention cell and an infiltration trench based on the site hydrology and the consumptive water use of plants able to tolerate the water stress characterizing these climatic regions. This study found that bioretention was "inefficient in some of the dry months (November and December), even in years characterized by abundant rainfall" and required irrigation during these months to maintain plant viability. Requirements for irrigation can be a major consideration in the semi-arid west, and can limit the viability of LID.

U.S. EPA (2012) and Tolderund (2010) focus on the design of green roofs in the semi-arid west, including the evaluation of plants that can survive in semi-arid conditions. While the focus of the EPA document is the sustainability of green roof systems, it does provide useful information about ET rates for plants recommended for use in LID in the semi-arid west. The study also evaluates soil moisture content. The Tolderund paper is more specifically focused on providing optimal green roof designs.

Evapotranspiration (ET) from stormwater BMPs and GI is a key component in the water cycle within the BMPs and can have major impacts on water's ability to infiltrate and recharge groundwater. Ebrahimian, et. al., (2019) conducted a literature survey focusing on ET in runoff volume reduction of green roofs and rain gardens The authors note that "evapotranspiration is mostly unaccounted in the design and crediting of GSI systems because of the complex interaction of soil, plants, and climate that makes its quantification difficult." The authors cite Eger et al. (2017) in reporting that the average and median ET portion of water budgets as 61% and 64%, respectively, in green roofs (N = 59) and 37% and 28%, respectively, in bioretention cells (N = 10). Their study of the literature indicates that the annual volume retention in green roofs (mostly due to ET) can range from 11% to 77% of the total rainfall volume (with a median of 57%) in different studies depending on meteorological conditions and green roof properties. The authors also found that the ET rates in green roofs and rain gardens in different climates and experimental setups are found to vary between 1 and 10 mm/day. However, most of these studies were not conducted in arid or semi-arid climates. In reviewing the locations of the study, one cited study (Feng, et. al. 2018) was conducted in Utah.

The study by Feng, et. al. 2018 focused on understanding the ET process as critical to evaluating the feasibility and sustainability of green roofs in semi-arid climates. The study notes that water needs to be evapotranspired to regenerate retention capacity between rainfall–runoff events. Evapotranspiration also cools roof surfaces in warm seasons, enhancing the green roof's ability to reduce the heat island effect.

LID Design in Utah: Addressing Semi-Arid Climates

The Utah Department of Environmental Quality, Water Quality department developed *A Guide to Low Impact Development within Utah.* The most recent update was released in 2020. The guide starts by listing various municipal stormwater ordinances around the state and provides instruction and examples of ways to both retrofit existing infrastructure and how to incorporate green infrastructure into planned projects. One of the main goals of LIDs is to recreate predevelopment environmental conditions for stormwater via retention of the volume of runoff in a 24-hour 80th percentile storm.

The guide lays out many of the different types of LID BMPs, how to evaluate their effectiveness, potential technical infeasibilities that might arise, maintenance concerns, and provides a BMP design flow chart. Vegetation selection and land use are discussed in detailed sections later in the guide. Finally, the guide concludes with both specific and general examples of different types of LID BMP projects.

The guide includes some specific recommendations for semi-arid climates. For example, the site considerations include assessment of the type of soil and the local groundwater conditions in consideration of the type of green infrastructure chosen. Only certain soils make LID feasible, and the guide links to the USDA soil survey map. The guide also provides three different USGS sources for local groundwater information. In the vegetation selection section, the guide recommends using vegetation that is suited to the semi-arid climate. Appendix E lists plants suitable for Utah's semi-arid climate.

Salt Lake City requires the use of Green Infrastructure and Low Impact Development, where feasible, to meet water retention and treatment standards (Salt Lake City. 2021). Projects where this is not feasible are required to provide a rationale documenting alternative design criteria and to quantify the infiltration, evapotranspiration, and rainwater harvesting in the site plan. Other control measures may be required to further protect water quality. Salt Lake City allows suitable BMPs from on *A Guide to Low Impact Development within Utah.* The city does not provide specific guidance for semi-arid green infrastructure, but the LID guide does (see above).

Salt Lake County provides a guide that provides a list of examples of different types of green infrastructure, low impact development, construction practices, and hydraulic structures. Each example provides a picture, description, applications, implementation, limitations, and maintenance (Salt Lake County Engineering and Flood Control. 2012). Many of the examples can be utilized in semi-arid climate conditions, and each example includes BMP limitations that can be used to assess whether they would perform well in semi-arid climate conditions.

Weber County has a brochure encouraging xeriscaping in the Utah desert. Xeriscaping would utilize native Utah plants to conserve water, reduce stormwater runoff, and decrease soil expansion.

Davis County has a guide to Stormwater BMPs that is focused on construction and reducing soil erosion. The guide lists BMPs to follow in numerous scenarios commonly experienced during construction activities. These BMPs are generalized and are not specific to semi-arid climates.

Groundwater Research in Utah

The groundwater system in the Great Salt Lake basin has been investigated by academic and government researchers for many decades. Over time, the understanding of groundwater and surface water as a single interconnected system has become more widely appreciated in Utah and elsewhere (Winter et al., 1998). The hydrogeologic framework of the Salt Lake Valley consists of fractured rock aquifers in the Wasatch Range to the east and in bedrock underlying the valley and in the Oquirrh Mountains to the west, as well as saturated basin fill composed of alluvial fan deposits and lakebed/lakeshore deposits that are interbedded in complex ways. The basin-fill sediments are zoned into roughly parallel north-south bands that are classified into three distinct areas: the primary recharge area (upper elevations), secondary recharge area (intermediate elevations), and the discharge area (lower areas, including wetlands and lower stream reaches) (Figure 2).

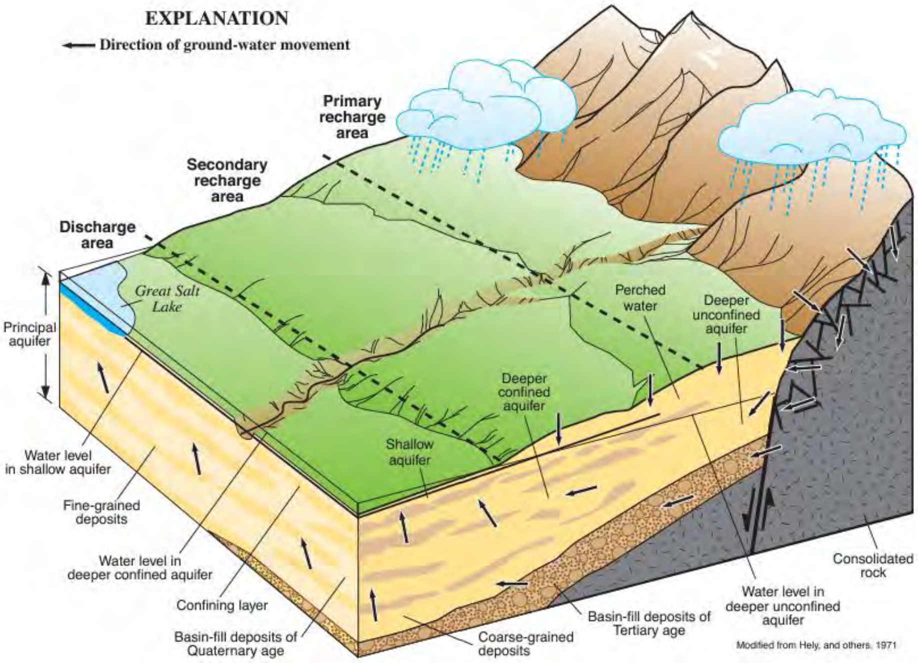

Figure 2. Schematic diagram showing the basin-fill deposits and hydrogeology of the Salt Lake Valley (Thiros, 2003, modified from Hely et al., 1971).

Groundwater has been historically exploited for agricultural irrigation in the valley, but there is increasing demand for use of groundwater for municipal water supply purposes (Utah DNR, 2002; Hogue and Downen, 2020). Regional groundwater modeling has been used for many years to relate groundwater recharge, extraction, and discharge in the valley's aquifers at regional scales and more local scales (Lambert, 1995).

Recent research on the groundwater system of the Salt Lake Valley has included satellite-based radar studies of spatial variation in fault-related and groundwater-related movements of the ground surface (Hu et al., 2018; Hu and Bürgmann, 2020). These studies found a long-term and seasonal correlation between surface uplift/subsidence and groundwater recharge/discharge, with net uplift of 15 mm/year southwest of Salt Lake City. Thaw et al. (2022) conducted a national-scale study that included Utah data and concluded that younger groundwater is found at greater depths in aquifers where groundwater extraction from wells is high. Young et al. (2021)

showed from a comparison of satellite and global positioning system (GPS) data that water loss from aquifers around Great Salt Lake was almost twice the amount of loss from the lake itself during an earlier drought period (2012-2016), and that this regional unloading of mass correlated with greater seismic activity during the drought period. Recent geochemical studies of water isotopes in and around Utah Lake were able to constrain the groundwater inputs of its tributary rivers and of the lake itself (Zanazzi et al., 2020), as well as evaporative fluxes, mixing, and residence times.

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APPENDIX C

Great Salt Lake Stormwater Study
LID Data Collection Summary

MEMORANDUM

DATE: November 27, 2023

TO:
James Harris, Assistant Director at Division of Water Quality
Division of Water Resources
1594 W. North Temple, Suite 310
Salt Lake City, UT 84116

FROM:
Kayson Shurtz, P.E.
Hansen, Allen & Luce, Inc. (HAL)
859 West So. Jordan Pkwy – Suite 200
South Jordan, Utah 84095

SUBJECT: Great Salt Lake Stormwater LID Data Collection Summary

PROJECT NO.: 420.03.100

BACKGROUND

As part of the Great Salt Lake (GSL) Stormwater Study, HAL reached out to communities within the GSL basin to get a better understanding of what types of existing Low Impact Development (LID) Best management Practices (BMPs) that have been implemented within each community. There are approximately 100 communities in the GSL watershed boundary. The goal for the data collection effort was to receive data for at least 15% of these communities in order to obtain a representative sample of typical LID practices in the GSL watershed.

DATA COLLECTION PROCESS

HAL reached out to 25 communities within the GSL watershed and received responses from 15 of them. Each community was asked for any information regarding LID BMPs that have been constructed within the community, existing zoning shapefiles, and planned zoning shapefiles. Each of the communities was contacted via email with several follow up contacts to encourage as much participation as possible.

COLLECTION RESULTS

Table 1 provides a summary of the data collected: The data collected was provided to the State along with this report.

TABLE 1. SUMMARY OF DATA COLLECTED

City	Data Received	Summary of Data Received
Bluffdale	N	N/A
Bountiful	Y	• Stormwater related GIS data • Planning and Zoning • Detention/Retention pond locations
Brigham City	N	N/A
Draper	Y	• Stormwater related GIS data • Planning and Zoning
Heber	N	N/A
Herriman City	Y	• Spreadsheet summary of LID retention volume and associated drainage area • Recent LID Drainage Reports • Planning and Zoning
Kaysville	N	N/A
Layton	N	N/A
Lehi City	Y	• Planning and Zoning • Stormwater infrastructure GIS data
Logan City	N	N/A
Morgan	Y	• Shapefile of existing and future sump locations
Murray City	Y	• Planning and Zoning • Spreadsheet summary of LID retention volume and associated drainage area for recent developments
North Salt Lake	N	N/A
Ogden	N	N/A
Park City	Y	• Zoning
Payson	Y	• Planning and Zoning • Shapefile of existing sump locations
Riverton	Y	• Map of 10 and 100-year retention volumes • Stormwater infrastructure GIS
Salem City	Y	• Planning and Zoning • Stormwater infrastructure GIS data
Salt Lake City	N	N/A
Sandy City	N	N/A
Saratoga Springs	N	N/A
Spanish Fork	Y	• Planning and Zoning • Shapefile of LID locations • Spreadsheet summary of retention volumes (2017-Present)
Springville	N	N/A
Tooele	N	N/A
Tremonton	Y	• Zoning and Population Projections

DATA COLLECTION SUMMARY

The following observations were made based on the collected data.

- Most MS4 communities are complying with the requirements of the permit.
    - Most communities know they have LID infrastructure in place (i.e. where it is located in GIS), but most do not have the details required for engineering analysis readily available.
- The most common LID implementation is retention of at least the runoff volume of the 80th percentile storm through groundwater infiltration basins.
- Based on the data provided, it is assumed that future implementation of LID within the GSL basin will be similar to the typical existing practice of retention of the 80th percentile storm with infiltration to groundwater.

APPENDIX D

Great Salt Lake Stormwater LID Modeling Methodology

MEMORANDUM

DATE: November 8, 2023
TO: James Harris, Jeanne Riley, Ben Holcomb
Utah DEQ, Division of Water Quality
Craig Miller, Krishna Khatri
Utah DNR, Division of Water Resources
FROM: Kayson Shurtz, Lance Nielsen, Josh Hortin
Hansen, Allen & Luce, Inc. (HAL)
Brad Udvardy, Renn Lambert, Volker Janssen
LimnoTech
SUBJECT: Great Salt Lake Stormwater LID Modeling Methodology and Results

PROJECT NO.: 420.03.100

PURPOSE AND AUDIENCE

The purpose of this memo is to describe the modeling components and techniques that are being applied to quantify the potential effects of Low Impact Development (LID) on groundwater recharge in the Great Salt Lake basin. Utah HB429, which mandated this study, requires:

> *As part of the integrated water assessment, the division (Division of Water Resources) shall study the impact of low impact development best management practices associated with post-construction retention stormwater permit requirements on the water budget of the Great Salt Lake.*

To address this mandate, the HAL-LimnoTech team has developed a modeling methodology that incorporates surface water and groundwater models and a final water balance that compares the results from both models to the overall Great Salt Lake (GSL) system. While other aspects of the Great Salt Lake water balance are addressed with this approach, the modeling is primarily concerned with quantifying the relative differences between non-LID and LID development scenarios.

This memo is intended for a technical audience that is familiar with hydrologic and groundwater modeling, and/or the components of Great Salt Lake basin water balance. It provides details about model development, inputs, assumptions, results, analysis, and conclusions.

DOCUMENT CONTENTS

1.0 - MODELING COMPONENTS AND FRAMEWORK

The general modeling methodology for this study is depicted in Figure 1. The diagram shows the connections between a surface water model (modeled with EPA's Surface Water Management Model - SWMM) that simulates surface flows, infiltration, and LID processes, USGS Groundwater models of Great Salt Lake basin aquifers, and a water balance that incorporates components of both models. The groundwater models will incorporate SWMM infiltration estimates to quantify groundwater flows to the Great Salt Lake. The water balance will compare modeled volumes to losses such as evaporation from the Great Salt Lake and basin flows from areas outside of MS4 communities. **Figure 1** calls out the components that are represented by each piece of the modeling approach (SWMM / Groundwater / Spreadsheet). The diagram also calls out what is *not* represented explicitly in the models: the surface water channels and flows to the Great Salt Lake.

Note that the modeling performed for this study should not be considered calibrated. These are broad tools with a high degree of uncertainty and multiple assumptions. They have also been developed to focus on the relative differences between non-LID and LID scenarios. The SWMM model has been developed specifically for this study and represents anticipated conditions under multiple theoretical scenarios. SWMM model results were verified as discussed in Section 2.0. The USGS groundwater models have been calibrated to observed conditions in the past. However, the specific application of those models for this study represents theoretical projections based on multiple scenarios.

This modeling approach also should not be considered a watershed model, because the surface water component is limited to MS4 communities due to the focus on LID implementation. Although there is no modeling of surface flows outside of the MS4 communities, modeling results from the MS4 communities were scaled and projected to non MS4 communities. The results analysis will therefore focus on the relative differences between various scenarios, not on absolute quantities of water, although the surface and sub-surface water volume contributions of the MS4 areas and LID specifically will be put in context of overall watershed volumes.

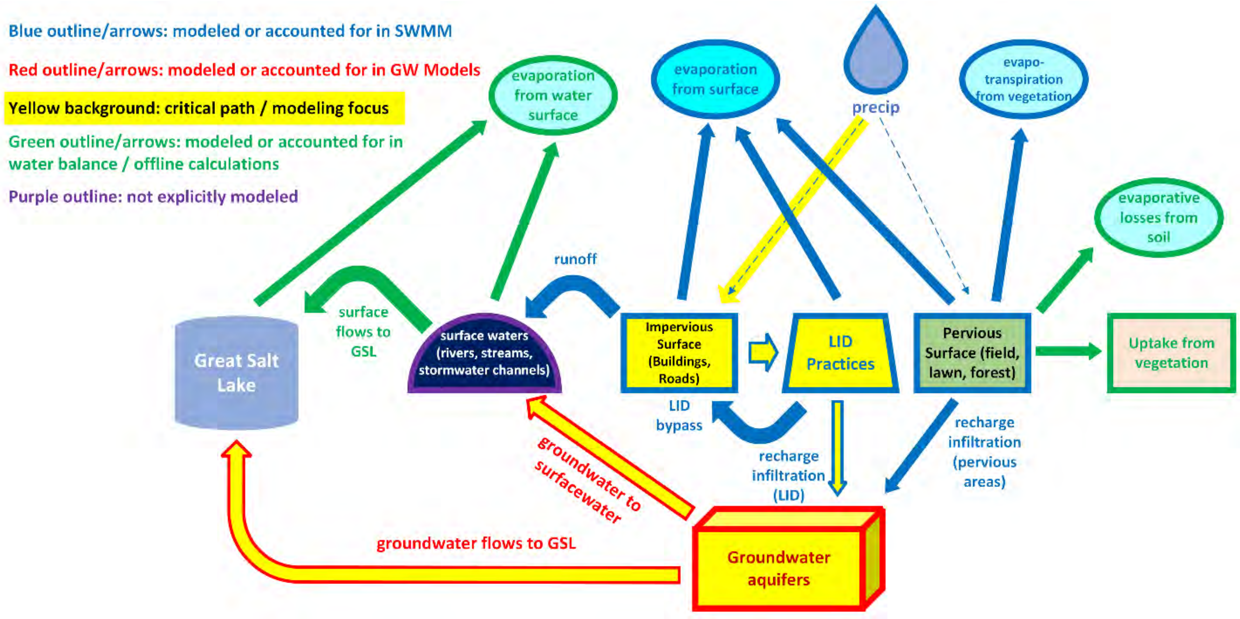


Figure 1. Modeling Methodology Diagram

Varying Model Resolutions

SWMM models typically use precipitation inputs that are hourly or finer in temporal resolution, with model outputs at even finer temporal resolution than the precipitation inputs. Groundwater models usually simulate on a much longer temporal scale, with annualized inputs and annual outputs being typical.

To address this difference in temporal resolution between the surface and groundwater models, SWMM model output infiltration timeseries will be converted into annual volumes before passing along those outputs to be used as inputs to the groundwater models. Likewise, the final water-balance spreadsheet will work with annualized SWMM and groundwater model outputs. Because the ultimate goal of this modeling is to evaluate impacts on the GSL, this level of temporal resolution is reasonable for the overall modeling.

Exclusions from Models

Overall

An assumption of this study is that LID will not be implemented in the aquifer discharge zones of the valleys where development takes place. Aquifers within the basin fill materials generally exist in three zones: primary recharge, secondary recharge, and discharge. In the primary recharge zone, there are no confining layers to inhibit infiltrated water from reaching the aquifer. In the secondary recharge zone, there are confining layers but the potentiometric head of the aquifer is deep enough below the ground surface to allow downward movement of water and contributions to shallow groundwater. In the discharge zone, aquifer pressure forces water upward instead of downward and groundwater is too near the surface to accept additional infiltration. LID in the discharge zone does not result in meaningful infiltration because of the upward movement of water. Therefore, the development in the discharge zone was not evaluated in the surface water or groundwater models.

Surface Water Model

The SWMM model will consist only of a hydrologic model; there will be no routing of flows and no representation of surface flow pathways such as rivers, streams, stormwater channels, or stormwater conduits. Since the models cover MS4 communities throughout the Great Salt Lake Basin, the level of effort to develop a routing model of all communities' surface flow pathways would be considerable and is not within the scope of this study. The inclusion of flow routing would also not enhance the understanding of the water balance or the impact of LID on groundwater.

Groundwater Models

The USGS groundwater models will be used to simulate the downstream effects of added or reduced recharge to the groundwater system on a steady-state basis. We performed a preliminary transient model simulation using the Salt Lake Valley groundwater model [USGS Technical Publication 110B] to determine the effect of increased constant recharge on discharge from the model. A constant annual recharge volume was added to the primary recharge area of the model and the computed additional discharges from the model were monitored for the duration of the transient model. Based on the trends observed in the discharge values, we estimate that it would take about 50 years for the discharge values to approximately equal the constant recharge volume. The balance of the water was received into storage within the aquifer system. This adds unnecessary complications to the groundwater modeling since our objective is to determine average impacts rather than how impacts change over time. Therefore, the steady-state models provide an appropriately simple and reasonable estimate of average downstream impacts from changes in recharge.

2.0 - SWMM SURFACE WATER MODELING AND ASSUMPTIONS

SWMM is a well-established one-dimensional surface flow model which was developed by EPA, with separate model engines for hydrologic and hydraulic processes. For the purposes of this study only the hydrologic model will be used. The developed hydrologic model will provide values for both surface runoff and infiltration, simulate LID practices, and will account for evaporation and evapotranspiration (ET) losses from the surface and account for snow accumulation and snow melt processes. The SWMM model features large subcatchments (average subcatchment size is 1,117 acres) with a single conceptual and “lumped” LID practice representing an infiltration trench for each subcatchment in which LID is applied.

Catchment Delineations and Parameterization

Delineation Process

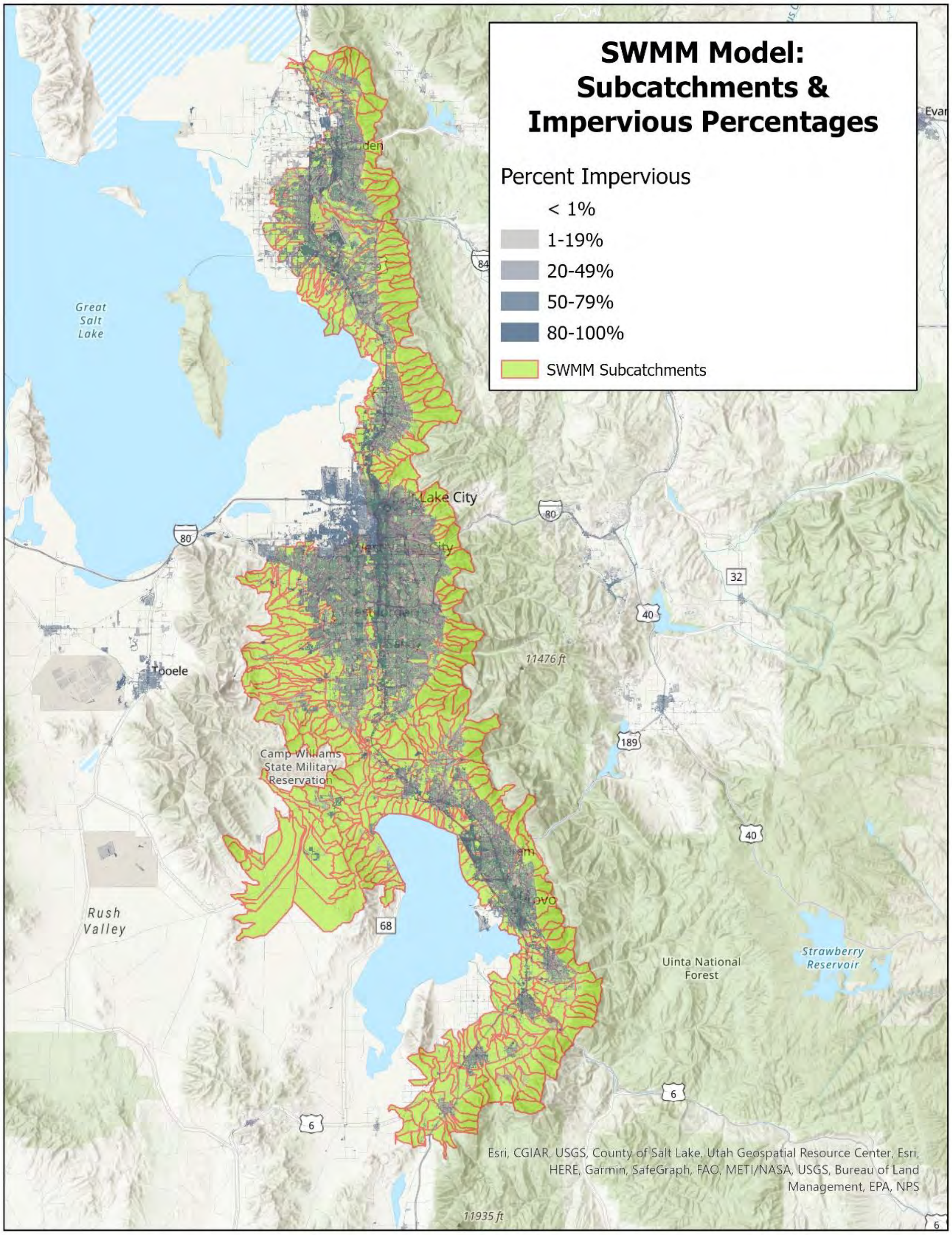
To delineate SWMM model subcatchments, DEM data - developed by the U.S. Geological Survey at 1/3 arc-second resolution - were downloaded from the Utah Geospatial Center. The Watershed Delineation Tool (WDT) in PCSWMM (a third-party software for pre- and postprocessing of EPA SWMM models) was used to create subcatchments across all MS4 areas. The raster was used as the DEM layer at a 1,000 acre target discretization level in the WDT. The resulting hydrologic model contains 659 subcatchments and covers 736,381 acres. The Land Cover Assignment subsection below includes a map of the resulting SWMM subcatchments, with percent impervious as the background layer (see discussion of Figure 2 below).

Land Cover Assignment

The percent impervious area assigned to the SWMM subcatchments is based on the 2019 National Land Cover Database (NLDC) data set for Utah (USGS, MRLCC, 2019). As with catchment delineation, internal PCSWMM tools were applied to assign percent impervious values based on the input dataset. Figure 2 is a map of the SWMM subcatchments with the NLCD percent impervious layer.

Soil/Infiltration Parameters

In the pervious areas, Horton infiltration parameters were assigned to the SWMM model subcatchments based on the USDA SSURGO (Soil Survey Geographic Database) hydrologic soil group data. Hydrologic soil groups are “*determined by the water-transmitting soil layer with the lowest saturated hydraulic conductivity and depth to any layer that is more or less water impermeable or depth to a water table*” (USDA, 2007). As with catchment delineation, internal PCSWMM tools were applied to assign infiltration values by automatically weighting the percentages of each hydrologic soil group per subcatchment. **Figure 3** is a map of the SWMM model subcatchments with SSURGO hydrologic soil group categories as the background layer.



Esri, CGIAR, USGS, County of Salt Lake, Utah Geospatial Resource Center, Esri, HERE, Garmin, SafeGraph, FAO, METI/NASA, USGS, Bureau of Land Management, EPA, NPS

Figure 2. SWMM Model Catchments & Percent impervious

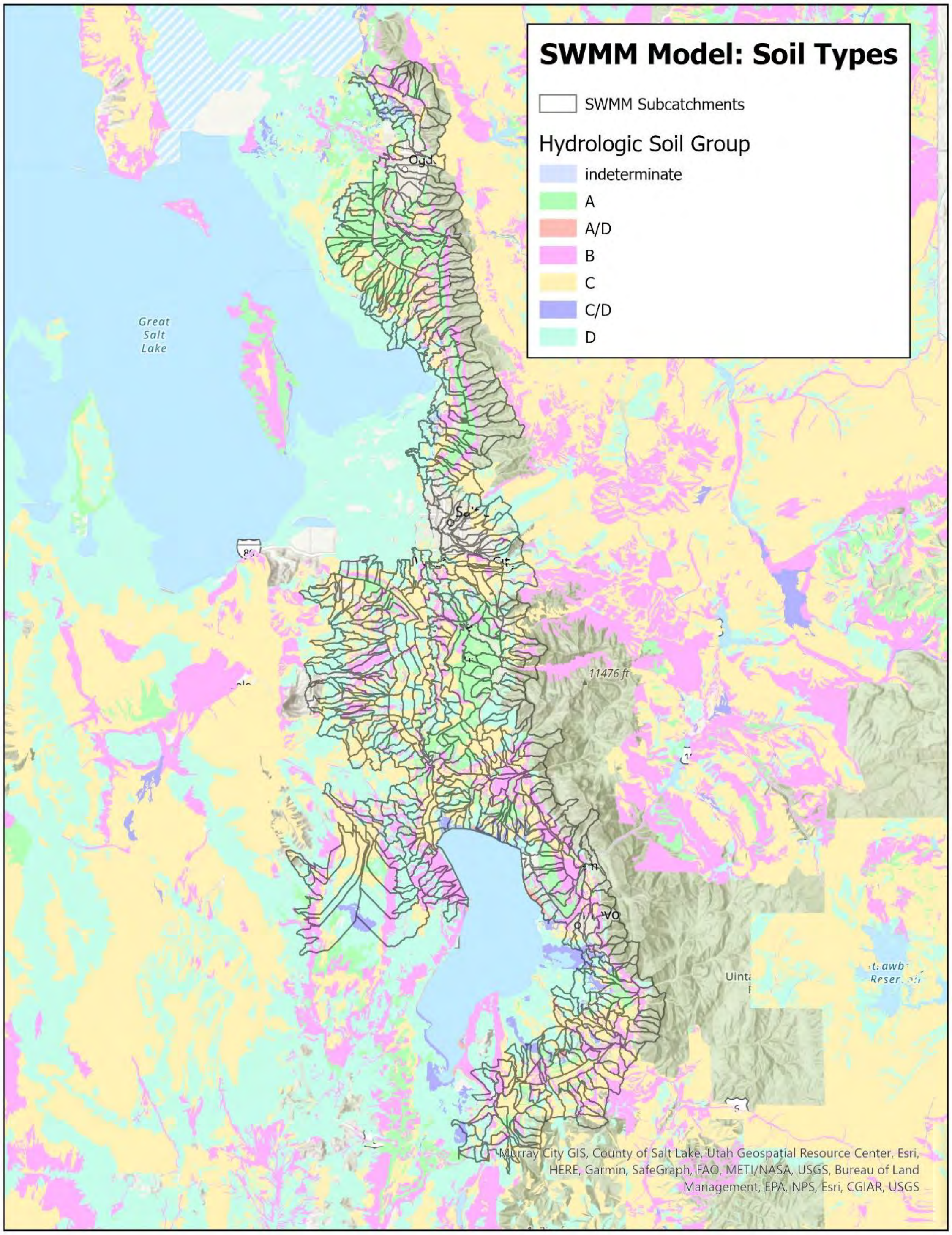


Figure 3. SWMM Model Hydrologic Soil Groups

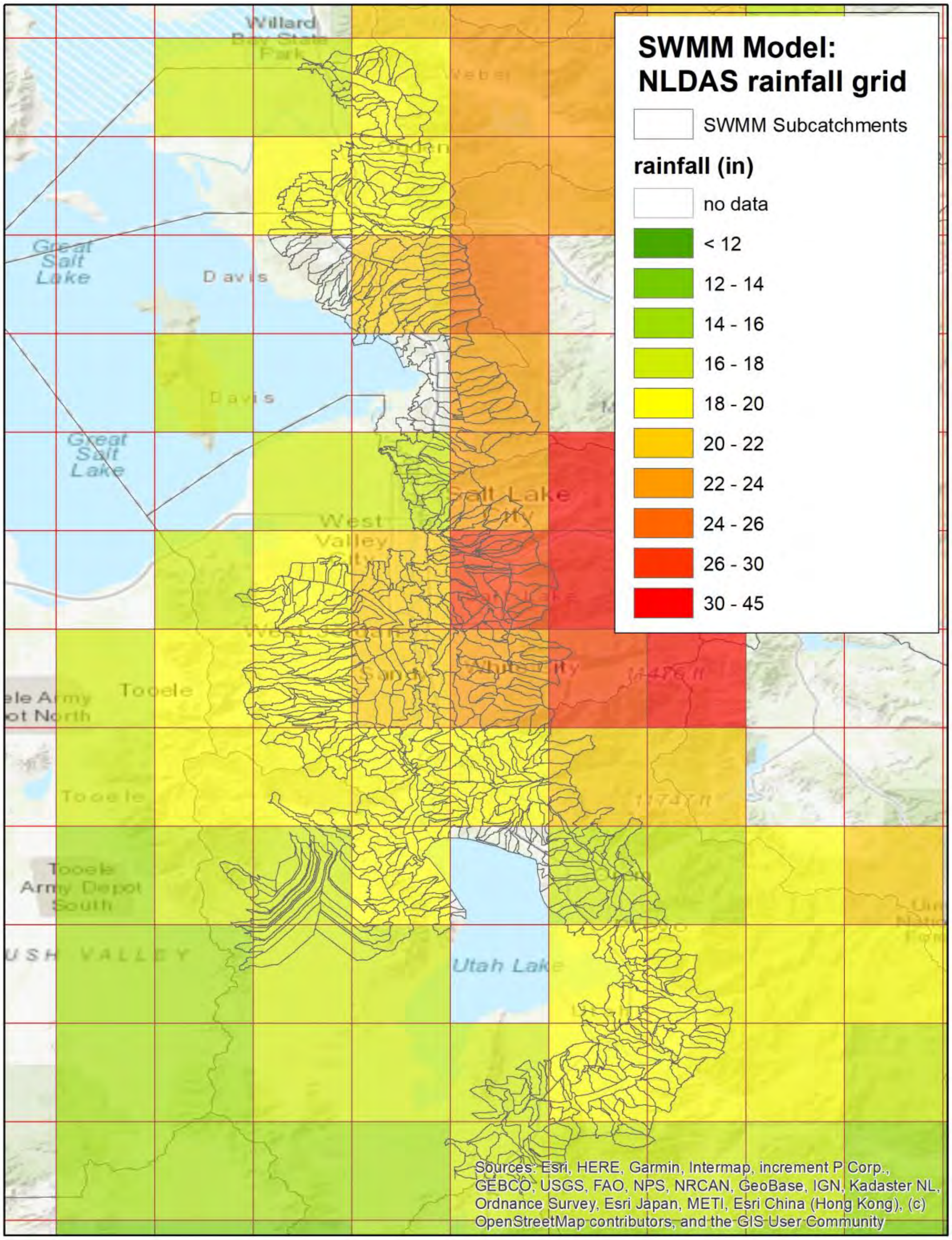
Boundary Inputs

Precipitation

Gridded hourly precipitation data for the period 1980-2022 from NASA NLDAS-2 (Phase 2 of the North American Land Data Assimilation System) data repository was used as a precipitation data source. The NLDAS-2 data set combines multiple sources of observations (such as precipitation gauge data, and satellite imagery as well as radar precipitation information) to produce estimates of climatological data in a gridded dataset. Grid cells are 1/8th of a degree (approximately 8.5 miles) square. Rainfall for individual model subcatchments was assigned from the closest grid cell. Figure 4 shows the analyzed NDLAS-2 grid cells as well as the resulting average annual rainfall for 1980 – 2022.

Climate data

Climate data in SWMM includes temperature, potential evaporation rates (PE) as well as wind speeds. This data is provided as global values and, unlike precipitation, is not spatially variable. Hourly NLDAS-2 data for 1980 – 2022 was downloaded for a grid cell in the center of the model domain (grid-ID x105y126) and converted into the necessary SWMM daily data format.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 4. SWMM Model Gridded Precipitation Data

Implementation of LID Practices

To simplify the implementation of LID in the SWMM model, only infiltration trenches were applied as an analogue for all LID implemented at new developments in a SWMM subcatchment. This practice type was chosen because it is specified in the state design guidance as a practice with the primary function of volume retention (UDEQ 2020), is a practice type option in SWMM, and is the closest analogue to what is commonly implemented in the state. In our review of data provided by the various cities, most practices are not vegetated and often include proprietary underground storage and infiltration solutions. Infiltration trenches are similar to these because they include underground storage and infiltration and do not require vegetation. For these reasons, it was assumed the infiltration trenches were the most representative of LID being implemented or that will be implemented in the basin.

One trench practice type element was assigned to each subcatchment representing all LID practices within that subcatchment. These LID were sized to capture 100% of runoff from the impervious area of a new development during an 80th percentile storm (approximately 0.5 inches of rain). These were sized with design parameters in Appendix C of the Utah LID manual (UDEQ 2020). These LID parameters from the manual designs were translated to SWMM inputs.

SWMM Outputs

Infiltration Volumes

SWMM non-LID infiltration results will be processed to account for soil/sub-surface losses. This is done by utilizing a USGS-published estimate of annual groundwater recharge (USGS, 2003). **Figure 5** shows the USGS annual groundwater recharge grid estimates that were used. Those long-term recharge depths were spatially averaged for every model subcatchment. Long-term (1980-2022) model results were used to determine infiltration as a fraction of rainfall, then the two factors were combined to apply a single factor representing recharge as a fraction of infiltration. This resulted in weighted-average recharge-infiltration from non-LID sources being ~13% of total infiltration and ~11% of precipitation; that is in line with literature values, including a Utah-specific study of Moab that provides a range of 5-25% of precipitation that recharges groundwater (Kolm and van der Heijde, 2020; also see Table 2).

For LID-based infiltration, these factors are not used; rather 80% of model-predicted LID infiltration is assumed to recharge groundwater. The 80% value is near the upper end of broad ranges of estimated LID-to-recharge values from literature (40% to 99%), and thus represents best-case LID performance, from a groundwater recharge perspective (Newcomer et al, 2014).

The resulting “recharge-infiltration” values will be area weighted by subcatchment and further subdivided into discharge, secondary recharge, and primary-recharge components, based on the percentage of each subcatchment that corresponds with each zone type. The primary and secondary recharge and discharge areas were obtained from the USGS groundwater model reports for each aquifer system. Figure 6 shows these aquifer zones along with the SWMM model subcatchments. For each discharge/recharge zone type, the weighted recharge-infiltration values will then be combined into a single annual value per modeled calendar year and can then serve as inputs to the groundwater models.

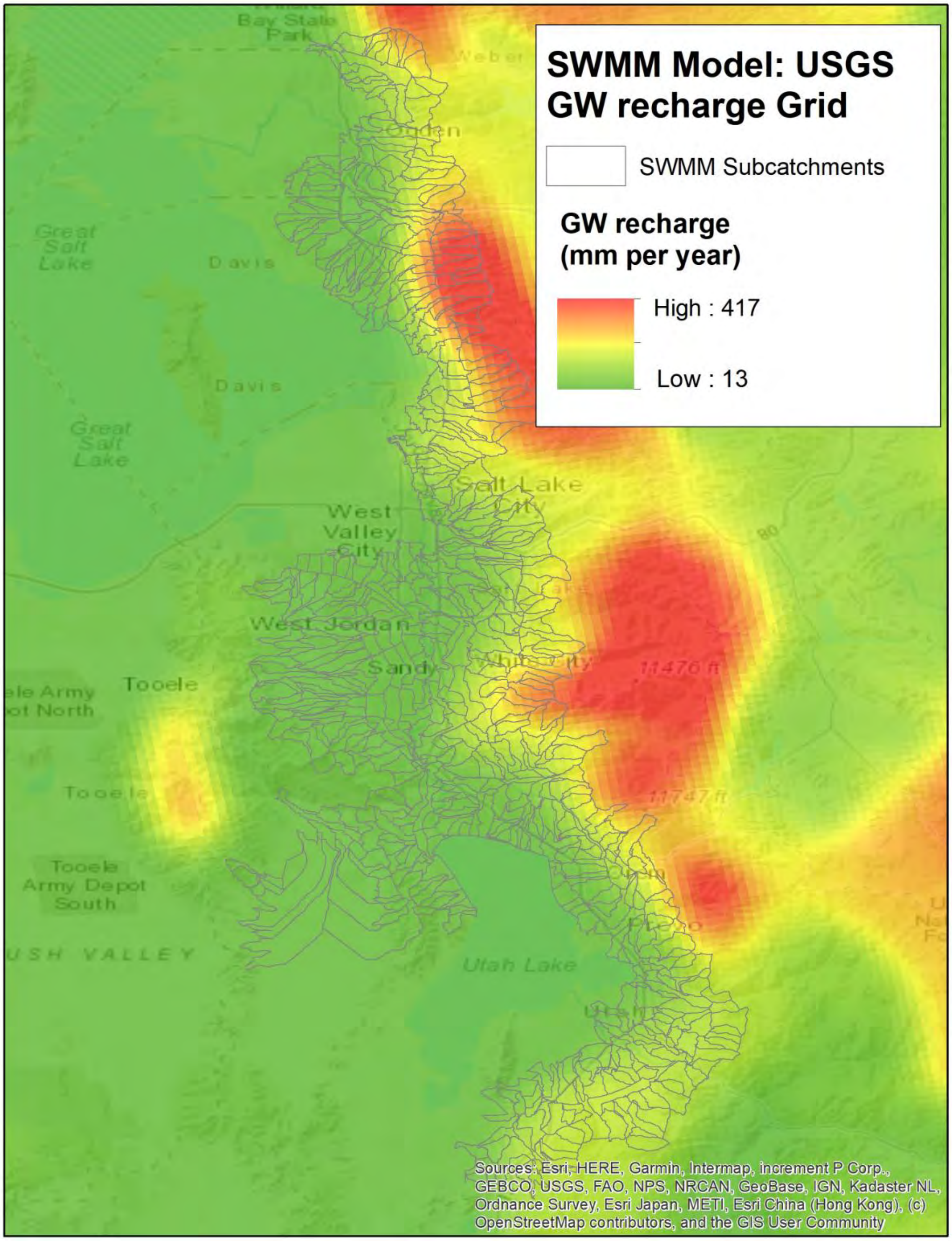
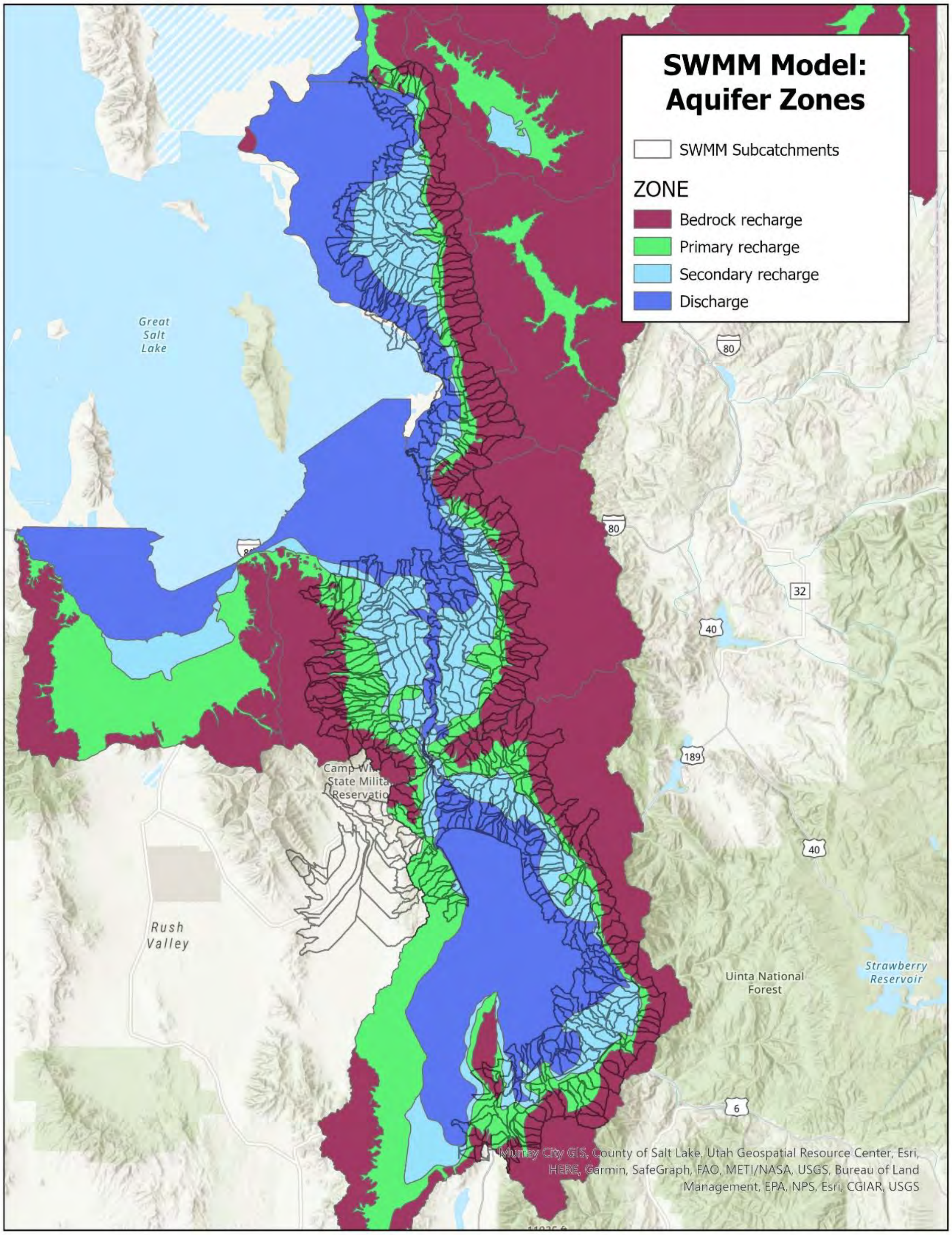


Figure 5: SWMM Model USGS Annual Average Groundwater Recharge Grid



Murray City GIS, County of Salt Lake, Utah Geospatial Resource Center, Esri, HERE, Garmin, SafeGraph, FAO, METI/NASA, USGS, Bureau of Land Management, EPA, NPS, Esri, CGIAR, USGS

Figure 6. SWMM Model Aquifer Zones

Surface Runoff and Infiltration Volumes

SWMM outputs runoff timeseries will be converted to annual volumes and passed on to the spreadsheet water balance. SWMM outputs infiltration timeseries will also be converted to annual volumes and the amounts of infiltration that are lost to evapotranspiration or make their way to the deep aquifer will be calculated in the spreadsheet model. The assumptions for this calculation are described in the Groundwater Models section of this document.

SWMM Output/Processing Example

Below is an example of all the SWMM output processing, applied to a single subcatchment only (for illustrative purposes). The results are values from the initial current-conditions baseline scenario, and represent the entire 1980-2022 simulation. This is for a single model subcatchment, but the process for characterizing every model catchment follows the process below: the subcatchment (or shed) area, percent impervious, and percentage of its area within discharge and recharge areas are determined from GIS analysis. Precipitation timeseries are then assigned via the NLDAS grid overlay and the SWMM model is simulated for surface hydrology. The model results for infiltration are then post-processed to account for the USGS Groundwater Recharge factor, and the resulting value is passed on to the Groundwater Models. In the example below, 101.7 inches of infiltration in the recharge zones (101.1” in primary + 0.6” in secondary) is reduced to 18.3 inches (18.2” from primary + 0.1” from secondary) of infiltration that is estimated to recharge groundwater.

Subcatchment: S1057

- Characteristics:
  - Area = 837 acres **(A)**
    - Discharge % = 48.9% **(B)**
    - Primary recharge % = 50.8% **(C)**
    - Secondary recharge % = 0.3% **(D)**
  - Impervious percentage = 42.2%
- Inputs:
  - Precipitation, via NLDAS (1980-2022 total) = 1603 inches **(E)**
- USGS Factor, recharge as fraction of rainfall = 0.125 **(F)**
- Model results (1980-2022 total):
  - Evaporative losses (ALL) = 126 inches **(G)**
  - Infiltration = 948 inces **(H)**
    - Infiltration/rainfall = **H / E** = 0.59 **(J)**
    - Recharge/infiltration = **F / J** = 0.21 **(K)**
  - Runoff = 528 inches **(L)**
- Recharge Infiltration calculations:
  - Recharge Infiltration = **H * K** = 199.1 inches **(M)**
    - Discharge = **B * M** = 97.4 inches
    - Primary recharge = **C * M** = 101.1 inches
    - Secondary recharge = **D * M** = 0.6 inches
- LID implementation example (100-percent development):
  - Increase in modeled infiltration due to LID = 45 inches (N)
  - Recharge infiltration from LID = N * 0.8 = 35.9 inches
    - Discharge = B * N = 17.6 inches
    - Primary recharge = C * N = 18.2 inches
    - Secondary recharge = D * N = 0.1 inches

Legend
Compiled in Spreadsheet
Water Balance
SWMM-based Inputs to

SWMM Runoff Verification

There is no data to calibrate the surface water model at the full basin scale of the Great Salt Lake, and the project scope did not include a model calibration step. The team relied on best professional judgment and literature values to verify the reasonableness of the results. The primary means of verification was a comparison of the fraction of rainfall runoff between the SWMM surface water model developed for this project and Model My Watershed[1] (MMW).

What is Model My Watershed?

MMW is an online watershed model. It builds model inputs from public datasets on the fly based on the domain the user defines. It utilizes the Generalized Watershed Loading Function Enhanced (GWLF-E) model to simulate long-term hydrology (WikiWatershed, 2023).

MMW Use and Results

The full SWMM surface water model domain was imported to MMW from a shapefile, and an average representative rainfall time series was imported from the NASA-NLDAS inputs[2]. MMW only allows one rainfall time series. A simulation of 1993-2022 in Model My Watershed was completed. (MMW can simulate up to 30 years.)

The results of the comparison were:

- MMW runoff as a percentage of rainfall = 15%
- SWMM runoff as a percentage of rainfall = 14% (also from output from the same time period 1993-2022)

These two model outputs matched closely (within 1%). This demonstrates that the results from SWMM were reasonable and supported by an independent watershed model.

An analysis was also conducted for a typical precipitation year using the SCS curve number methodology (USDA, 1986) as a second check on the reasonableness of the results produced through the SWMM modeling. It was found that for a typical precipitation year, the difference in computed runoff volume between the two methods was found to be within about 10-20%, which is well within acceptable limits for hydrology calculations.

SWMM Output Scalability

Five scenarios were completed with the SWMM model. The results from these are summarized in the main report (Table 2). From these scenarios it was found that the results are scalable. This is because of the strong correlation between the results, (e.g. Surface Runoff volume), and the percentage of future development (50% vs. 100% development). For example, stormwater runoff almost exactly doubled with additional development:

- 50% development – 21,200 acre-ft additional runoff
- 100% -development – 42,000 acre-ft additional runoff

This demonstrated results could be scaled to 100-acre parcels and these values could be applied to other parts of the basin (See Figure 6, the Sankey Diagrams, in the main report).

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[1] https://modelmywatershed.org/

[2] From NASA NLDAS grid-ID x108y121

3.0 - GROUNDWATER MODELING AND ASSUMPTIONS

Model Sources

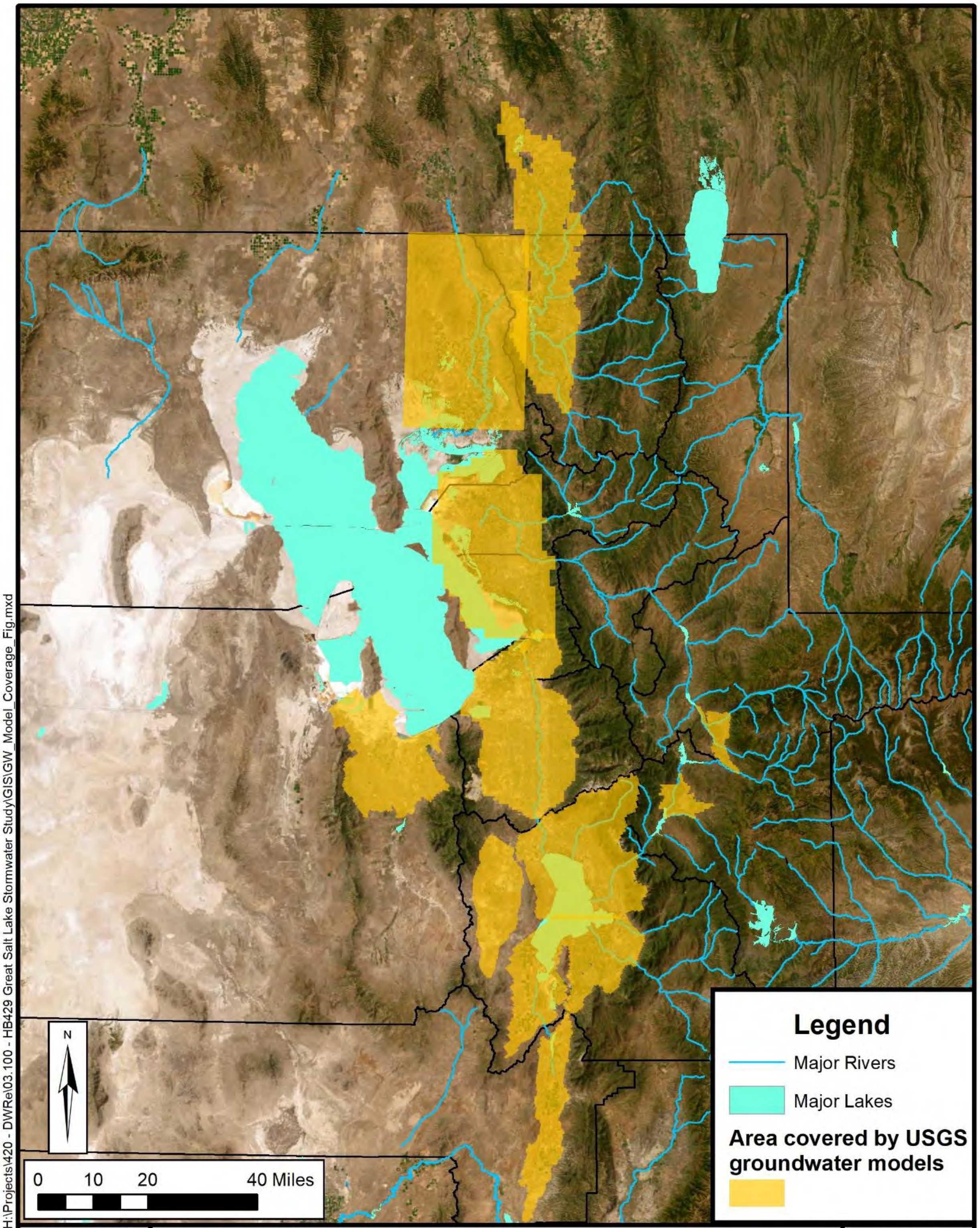
The USGS has invested in groundwater monitoring, studies, and modeling as part of its mission for over a century. This work has resulted in data and numerical models representing groundwater flow conditions for most aquifers present within hydrologic basins tributary to the Great Salt Lake. These models and reports are publicly available directly from the USGS and/or Utah's Division of Water Rights and the references are shown in Table 1.

Table 1. Groundwater Models and Corresponding References

Model	Author, Year
Juab Valley	Thiros et al., 1996
South Utah Valley	Brooks and Stolp, 1995 Brooks, 2013
North Utah Valley	Gardner, 2011 Stolp and Brooks, 2021
Cedar Valley	Jordan and Sabbah, 2012
Heber Valley	Roark et al., 1991
Kamas Valley	Brooks et al., 1995
Salt Lake Valley	Lambert, 1995
Tooele/Rush Valley	Lambert and Stolp, 1999 Stolp and Brooks, 2009
Bountiful	Clark, 1991
East Shore (Davis/Weber)	Clark et al., 1990
Malad-Lower Bear	Stolp et al. 2017
Cache Valley	Kariya et al., 1994

Each of the USGS groundwater models have been calibrated to observed conditions making them a valuable resource for determination of aquifer response to changes in groundwater recharge or withdrawals. Figure 7 shows the area which these models cover.

The USGS is currently developing a basin-wide model of the Great Salt Lake groundwater system. An objective of this model is to quantify groundwater contributions from the aquifer system directly to the Great Salt Lake. Completion of the model is anticipated in 2024.



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Area in Great Salt Lake Basin with a constructed groundwater model

FIGURE 7

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Model Inputs

General Background

The software which runs the USGS-developed groundwater models is called MODFLOW and was also developed by the USGS. MODFLOW uses a modular approach to numerically solve 3-dimensional groundwater flow scenarios.

MODFLOW requires discretization of the modeled area into a 3-dimensional block-centered grid of cells. MODFLOW input parameters include aquifer flow characteristics, recharge to the aquifer (precipitation, irrigation, seepage from canals and streams, etc.), and discharges from the aquifer (well discharge, evapotranspiration, canals, streams, drains, reservoirs, lakes, etc.). Each of the USGS models have been developed and calibrated to existing observed conditions. Detailed descriptions of the USGS groundwater models and the calibration parameters can be found in the USGS model reports referenced in Table 1.

For this study, recharge within developing areas in the primary and secondary recharge areas was modified to simulate the effects of differing stormwater management strategies. Recharge to the groundwater system is generally decreased by development when impervious areas are built resulting in an increase in runoff. Not all precipitation which initially infiltrates into the ground becomes groundwater recharge due to evapotranspiration, soil moisture, and/or soil temperature conditions. The portion of infiltration which does reach the aquifer is sometimes called “effective” recharge. A literature review was performed to determine what portion of precipitation becomes effective recharge. The resulting values were used in the spreadsheet model to translate SWMM infiltration to MODFLOW recharge.

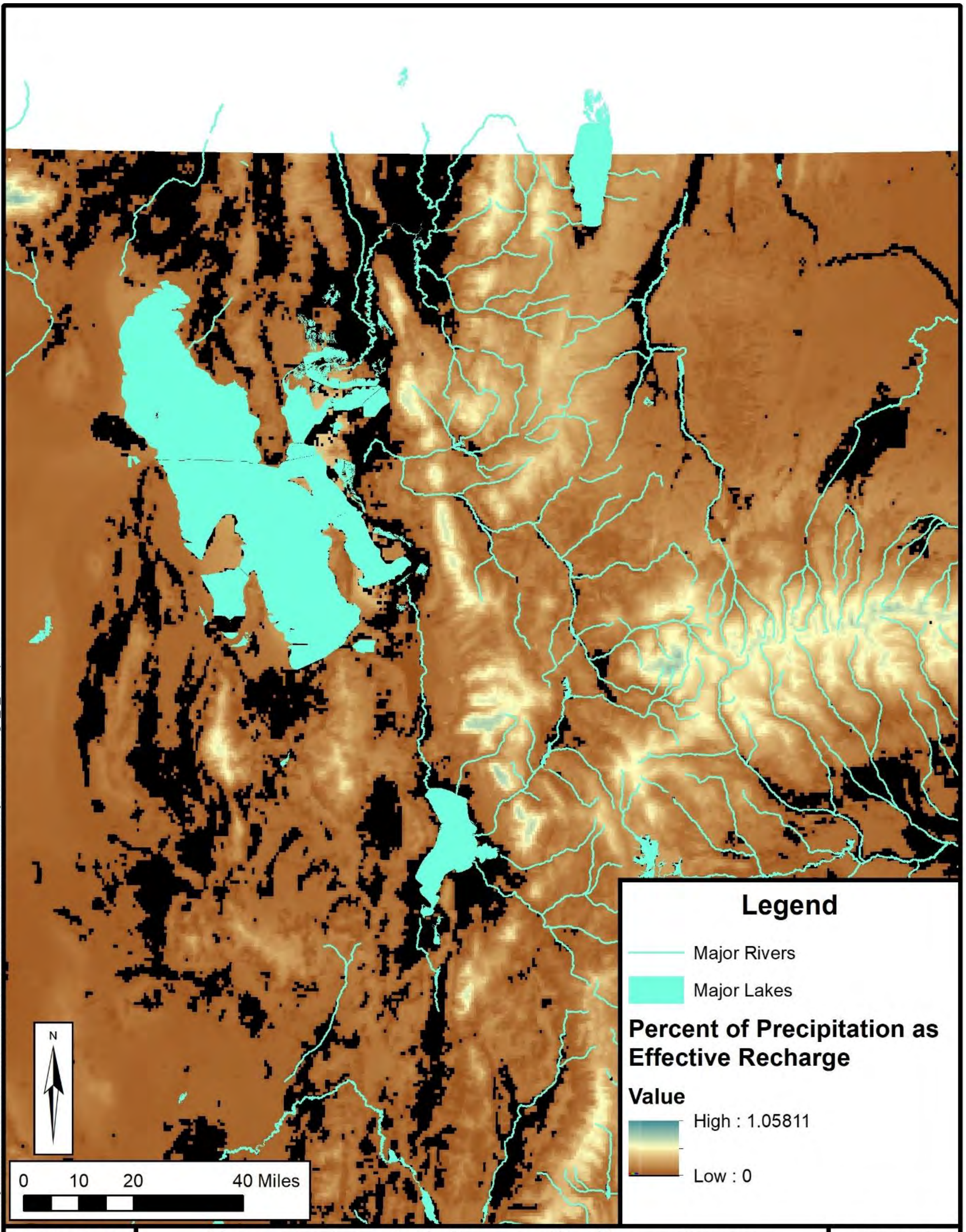
Portion of annual precipitation becoming recharge

The USGS models, which are among the most Utah-specific publications, generally place the portion of total annual precipitation within the primary and secondary recharge areas becoming recharge in the general range of 5-20%. Table 2 summarizes these values.

Table 2. Percent of annual precipitation on the valley floor that becomes recharge from USGS models

Model	Percent of annual precipitation on the valley floor that becomes recharge
South Utah Valley	5 or 10%, depending on distance from the mountains
North Utah Valley	3-10%
Salt Lake Valley	About 15-16%
Tooele/Rush Valley	1-8%, increasing recharge assumed with increasing annual precipitation up to 20 inches
Bountiful	10 or 20%, depending on recharge zone
East Shore (Davis/Weber)	10 or 20%, depending on recharge zone

The USGS also studied recharge in the years 2000-2013 on a gridded, national scale (Reitz et al., 2017). The effective recharge average of years 2005-2013 was divided by the PRISM 30-year precipitation averages (1991-2020) to obtain the percent of annual precipitation becoming recharge. Figure 8 shows the results. These results verify that recharge is lower in the valleys than the mountains. Within the primary and secondary recharge zones, the average effective recharge value was 13.9% for Weber County, 11.9% for Davis County, 7.4% for Salt Lake County, and 5.0% for Utah County.



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Percent of precipitation as effective recharge
Effective Recharge: 2000-2013
Precipitation: 1991-2020

FIGURE 8

However, individual USGS models treat the exact calculation of recharge slightly differently and do not differentiate between rain or snow. The national study also does not differentiate rain or snow. Questions about differences in recharge potential of rain and snow, and whether redistribution of snow from impervious to pervious surfaces influences recharge, were examined by a literature review.

Portion of (spring, summer, fall) rainfall becoming effective recharge

In general, answering the question of what portion of rainfall becomes effective recharge in Utah was challenging to review from literature because of the specificity of the question. A review of 98 studies of groundwater recharge in semiarid and arid regions from around the world (Scanlon et al., 2006) found high potential variability in effective recharge dependent on soils, fracturing, faulting, and area. However, based on long-term annual precipitation averages, effective recharge in semiarid/arid regions varied from 0.1-5% on average. It is noted that many of the more recent studies in semiarid and arid regions of the southwestern United States tend to fall at or slightly above this range (Green et al. 2012, Thomas et al. 2016, Manna et al. 2016, Ketchum et al. 2016). One study in the Chihuahua Desert, northern Mexico, had a much higher estimated recharge rate at 37-55% (Ochoa et al., 2023). Finally, a study specific to Moab, Utah estimated a recharge rate of 5-25% (Kolm and van der Heijde, 2020).

Portion of (winter) snow becoming effective recharge

Answering the question of what portion of snow becomes effective recharge was equally, if not more, challenging than answering the same question for rainfall. The USGS models suggest that there is potential for snow to provide more effective recharge than rain. For example, the Tooele Valley model assumes that the amount of recharge is positively related to the annual precipitation, and it is known that annual precipitation is higher in the mountains where it is dominated by snow. The northern Utah Valley model, which includes mountainous terrain in the boundaries, assumes recharge of 17-33% in the mountain block where snow dominates the annual precipitation.

The scant literature addressing this topic in semiarid regions with a seasonal cold period seems to support the USGS model assumptions. A study in the west Canadian prairie determined that about 35-43% of the spring snowmelt infiltrated (removing an outlier site; Mohammed et al., 2019). It is possible that not all this water became effective recharge due to the water holding capacity of the soil allowing for evapotranspiration in later spring or summer. A study in the Spring Mountains of Nevada found that summer convective storms provide 1/3 of annual effective recharge but only 10% of annual precipitation (Winograd et al., 1998). These values can be back-calculated to show that for a range of 10-20% of annual precipitation becoming effective recharge, the effective recharge from the snow portion is 14-27%. Another study in the southwestern US (primarily Arizona and New Mexico) similarly found that snowmelt provides 40-70% of annual groundwater recharge, although only 25-50% of annual precipitation falls as snow (Earman et al., 2006). Back-calculating the mid-range of these values shows that, again assuming a range of 10-20% of annual precipitation becoming effective recharge, the effective recharge from the snow portion is generally within the range of 15-30%.

Portion of total annual precipitation becoming effective recharge

The USGS studies (USGS, 2003) provided spatially varying percentages of annual precipitation that results in groundwater recharge. Based on these studies, the average approximate percentage of annual precipitation that ends up as groundwater recharge within the study area was 11%. This value is consistent with the data identified in our literature review.

Methods of modifying recharge in the USGS groundwater models

The USGS groundwater models were used in their unaltered condition to simulate the previous, less-developed condition. The models were altered in two separate scenarios to simulate new development with LID and without LID. Based on our hydrological experience, development without LID will increase impervious surface area and thus decrease the groundwater recharge input. Development with LID will also increase impervious surface but will induce some extra recharge due to concentration of infiltration to a smaller area specifically designed to promote groundwater infiltration (Newcomer et al, 2014).

The procedure for adding or subtracting recharge from the models is described below and shown in Figure 9.

- The layers of recharge zone (primary, secondary, or discharge) and municipality borders were overlaid.
- The centroids of the resulting polygons, for only the primary and secondary recharge zones, were determined.
- The polygons were overlaid with relevant land use data (see section heading "Estimation of Future Development") to determine the additional recharge or loss of recharge for the area.
- The USGS model cell coinciding with the centroid of each polygon was modified to add or subtract the volume of recharge expected, divided evenly across the cell area. In the case of subtracting recharge, the USGS model cell may have less recharge than the amount that needs to be subtracted. In this case, the subtraction was expanded to neighboring adjoining cells until the required amount was subtracted (as shown in diagram below).

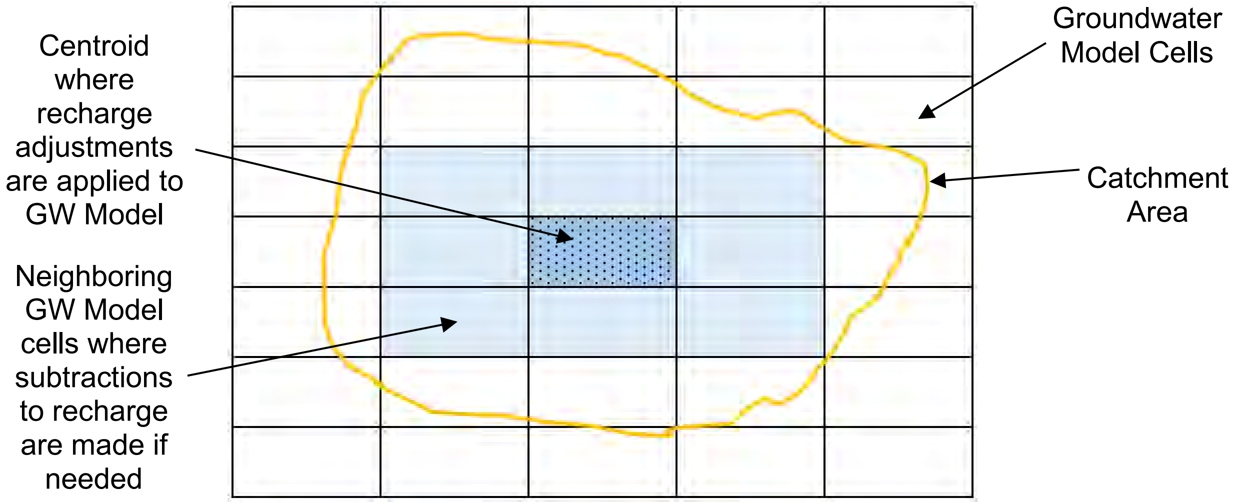

Figure 9. SWMM Model Aquifer Zones

4.0 - WATER BALANCE

The total stormwater volumes of surface runoff from the SWMM model and the groundwater discharges from the groundwater models were quantified together. Volumes from each modeling scenario were tabulated and used to quantify the differences in the volume of water that reaches the Great Salt Lake. In addition, the water balance includes (from DWR, 2023):

- Surface water evaporation from lakes, rivers and streams
- Total surface water volume to the Great Salt Lake

These literature volumes were compared to put the LID volumes in context of the other inputs to the lake. All these volumes together help show how LID volumes compare to the other water inputs and outputs to the Great Salt Lake and the watershed. These were summarized in in the final report.

5.0 - ESTIMATION OF FUTURE DEVELOPMENT

For the purposes of this study, it is necessary to produce a reasonable estimate for the drainage area of future development in the primary and secondary recharge zones. These data can then be used to estimate relative differences between the scenarios we are analyzing as part of this project (undeveloped, developed with LID, and developed without LID). The 2019 National Land Cover Database (NLCD) was used to define areas not yet developed within the primary and secondary recharge areas in the various municipalities located within the extents covered by both the surface and groundwater models.

The shapefiles that defined the extents of the primary and secondary recharge areas were joined with the municipal boundary polygons to create a new shapefile that defined primary and secondary recharges areas for each municipality. GIS tools were then used to determine the number of NLCD pixels by type in each of the polygons. The pixel size and count were used to estimate areas for each of the various NLCD types found within each polygon. Table 3 defines the different land cover types with their corresponding codes and descriptions that are available in the NLCD.

Table 3. 2019 NLCD Codes and Descriptions

NLCD Code	Description
11	Open Water
21	Developed, Open Space
22	Developed, Low Intensity
23	Developed, Medium Intensity
24	Developed, High Intensity
52	Shrub/Scrub
71	Grassland/Herbaceous
81	Pasture/Hay
82	Cultivated Crops
90	Woody Wetlands
95	Emergent Herbaceous Wetlands

Our analysis assumed that any land cover code that was within the range of 11-24 or 90-95 was to be developed already or not developable. The resulting dataset was compared with aerial imagery for several communities to verify that the approach provided a reasonable estimate for remaining area to be developed. The estimated area for the classifications within the code range of 52-82 were compared with the total area of each polygon to calculate the remaining area that could be developed. This data was used as a basis for the total drainage area that could be developed in the future within each municipality. Estimates were also made for unincorporated areas and areas where recharge area delineations were not available based on data from the following sources.

- Wasatch Front Regional Council (Regionally Significant Centers and Land Use, TAZ population projections)
- Cache County General Plan (this plan provided estimated population densities that for the

purposes of this study were assumed to be similar for other rural areas)
- Population projections from the Kem C. Gardner Institute.

The locations of the modeled developable areas along the Wasatch Front were used to spatially correlate the changes in groundwater recharge to the corresponding groundwater model cells.

Estimates for future impervious surface ranged from 20%-50% of total projected development in the recharge area. Typical developments for each county, zoning and planning data, and Table 2-2a from TR-55 was used to estimate the projected impervious surface percentage.

Table 4 summarizes our projections for future growth and impervious surface in the primary and secondary recharge areas through 2060. Table 4 also provides a range of plus or minus 10% on the area to be developed along with a reasonable range on the assumed percent impervious area for future development in each of the counties. The estimated high and low are provided in parentheses under the estimated value.

The estimated depth of recharge from the SWMM modeling was applied to the calculated acreage available for all modeled areas. Recharge was added or subtracted from the baseline groundwater model to simulate future development scenarios.

Table 4. Summary of Projected Development in Recharge Areas and Resulting Impervious Surface Through 2060

County		Projected Recharge Area Development (acres)		Impervious Assumption	Impervious Surface (acres)
		Incorporated	Unincorporated		
MS4 Counties	Cache	**10,941** (9,847-12,035)	**4,057** (3,651-4463)	**30%** (20%-40%)	**4,499** (2,700 – 6,599)
	Davis	**5,369** (4,832-5,906)	**1,486** (1,337-1,635)	**50%** (40%-60%)	**3,428** (2,468-4,524)
	Salt Lake	**23,062** (20,756-25,368)	**3,320** (2,988-3,652)	**50%** (40%-60%)	**13,191** (9,498-17,412)
	Summit	**6,779** (6,101-7,457)	**1,694** (1,525-1,863)	**20%** (15%-25%)	**1,695** (1,144-2,330)
	Utah	**39,174** (35,257-43,091)	**294** (265-323)	**50%** (40%-60%)	**19,734** (14,208-26,049)
	Weber	**4,092** (3,683-4,501)	**1,282** (1,154-1,863)	**50%** (40%-60%)	**2,687** (1.935-3.547)
Non-MS4 Counties	Box Elder	**15,955** (14,360-17,551)	**254** (22-279)	**20%** (15%-25%)	**3,242** (2,188-4,457)
	Juab	**4,010** (3,609-4,411)	**900** (810-990)	**20%** (15%-25%)	**982** (663-1,350)
	Morgan	**2,771** (2,494-3,048)	**609** (548-670)	**20%** **(15%-25%)**	**676** (456-930)
	Rich	**250** (225-275)	**30** (27-33)	**20%** **(15%-25%)**	**56** (38-77)
	Tooele	**17,203** (15,483-18,923)	**1,297** (1,167-1,427)	**50%** (40%-60%)	**9,250** (6,660-12,210)
	Wasatch	**11,098** (9,988-12,208)	**2,775** (2,498-3,053)	**20%** (15%-25%)	**2,775** 1,873-3,815)
				MS4 Subtotal	**45,234** (31,952-60,461)
				Non-MS4 Subtotal	**16,980** (11,878-22,839)
				Total	**62,214** (43,830-83,301)

6.0 - MODELING SCENARIOS

Modeling scenarios established an existing-conditions baseline that serves as the basis for all other scenarios including future-development scenarios that evaluated increases in impervious land cover that come with development, and LID scenarios that examined the effects of low-impact development on the capture of impervious surface from future development. The list below describes model scenarios:

1. Baseline (existing conditions): primarily serves to put all predicted values in context.
2. Future-development without implementation of LID.
    a. Future development assumes a percent impervious area of 50%.
    b. Development was assumed for 100% of estimated potential development acres within the primary and secondary recharge areas.
    c. Sensitivity analyses were performed by varying the developed area and the percent impervious area.
3. Future-development with LID.
    a. LID was assumed to capture 100% of 80th-percentile storm, for all impervious area added by future development.

7.0 - PROJECTED IMPACTS TO GSL WATER BALANCE CONCLUSIONS

With the models and scenarios in place, the model results were combined and applied to the projected development (Table 4). Table 5 summarizes the general trends in the results when compared to Baseline conditions. The Baseline scenario represents a completely undeveloped condition with essentially zero impervious area. The full results are described in greater detail in the final study report.

Table 5. Percent Change in Flow Compared to Baseline Condition

Scenario	Surface Runoff	Total ET	Groundwater Recharge to GSL	GSL Inflows	Water Quality Impacts
100% Future Development No LID	3,933% ⬆	30% ⬇	36% ⇩	292% ⬆	Water quality degrades as development occurs (Hertzman 2016). Alternative treatment is required.
100% Future Development with LID	33% ⇧	13% ⇩	138% ⬆	129% ⇧	Water quality degrades as development occurs. LID filters runoff through the soil (Gautam et al. 2010, See Appendix B).

Note: Comparisons are to the undeveloped conditions that become developed with 50% impervious cover.

The assumptions for the future developed area and the percentage of that area that is impervious (i.e. roads, driveways, parking lots) are major factors in the reported results. A sensitivity analysis of the modeling results showed that reasonable estimates can be made by scaling the results to a smaller unit area. SWMM and groundwater modeling results were scaled to represent a 100-acre development with 50% impervious area. This allows for the results to be more easily applied to various future development scenarios outside of the modeled area by applying the results in 100-acre increments or units. Figure 10 provides 3 Sankey diagrams (Baseline, LID, and No LID) to help visualize the magnitude and pathway of stormwater assuming average precipitation over 100-acres. The Baseline scenario for the 100-acre development represents a completely undeveloped condition with essentially zero impervious area.

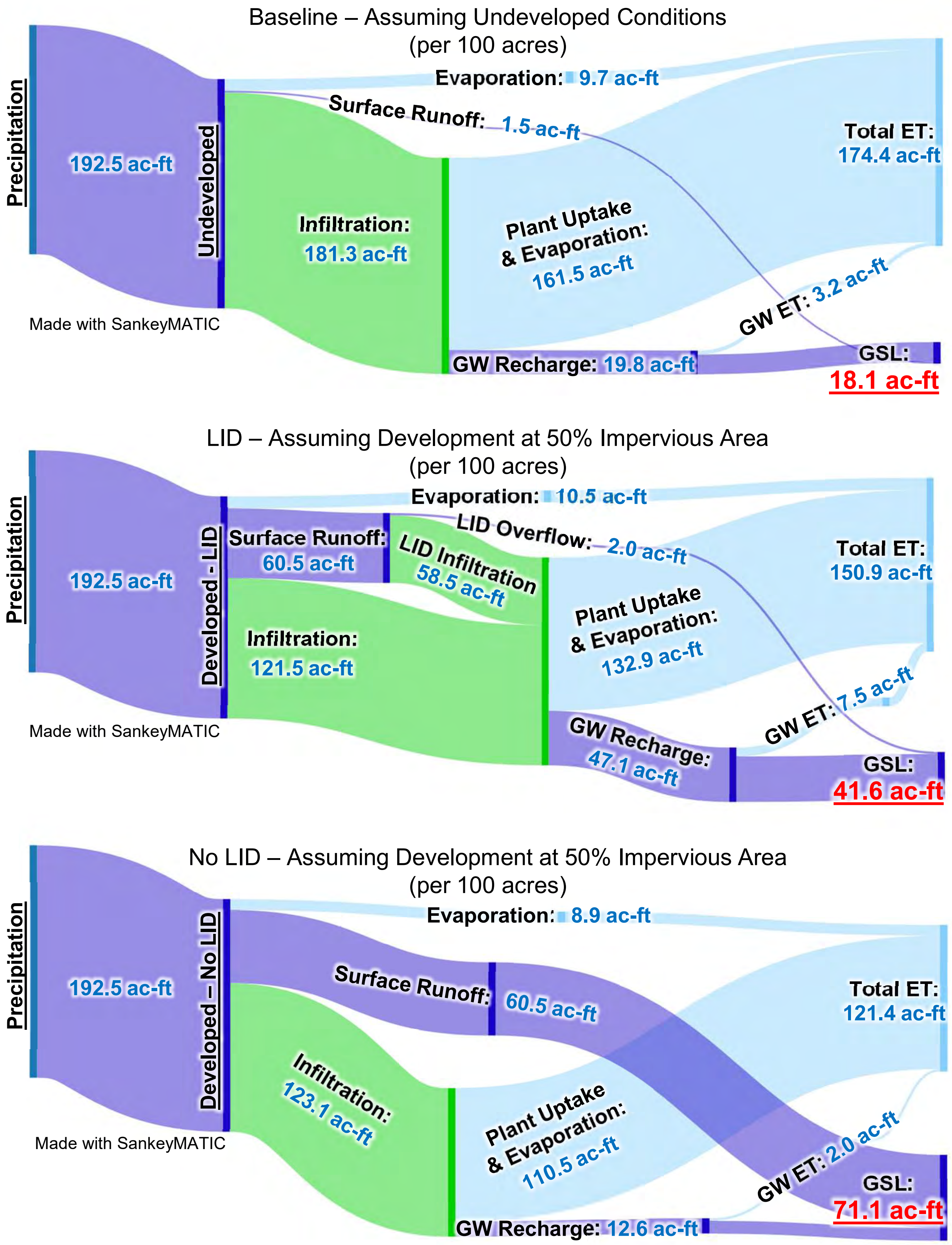

Figure 10. Sankey Diagrams showing Baseline, LID, and No LID Scenarios for 100 acres of Development

Table 6 summarizes the total area modeled, total area where projections were used, and the resulting runoff increases compared to the Baseline condition for LID and No LID through our 2060 development projections. High and low range estimates are provided in parentheses.

It should be noted that the results from this study are estimates and the uncertainty involved in these types of predictions is high. The results from our analysis can help guide decision-making, as they should help to explain the complex physical processes and connections between LID and groundwater flow to the Great Salt Lake.

Table 6. Summary of Additional Volume to the GSL Compared to Baseline through 2060

Description	Modeled Areas[1]	Areas Not Modeled[1]	Totals[1]
Developed Area (acres)	**71,200** (64,100-78,300)	**62,100** (55,900-68,300)	**133,300** (120,000-146.600)
Impervious Surface (acres)	**35,600** (25,800-49,900)	**17,400** (11,400-21,200)	**53,000** (37,200-,71,100)
Additional Volume to GSL (LID) (acre-ft)	**16,700** (12,100-23,400)	**8,200** (5,400-10,000)	**24,900** (17,500-33,400)
Additional Volume to GSL (No LID) (acre-ft)	**37,700** (27,300-52,800)	**18,400** (12,100-22,400)	**56,100** (39,400-75,200)

1.Tooele County has been excluded from these numbers based on findings from the Stolp & Brooks (2009) study that shows little to no water from Tooele County enters the GSL.

8.0 - ASSUMPTIONS AND UNCERTAINTY

With the speculative nature of this study, and without data to conduct model calibration, many broad assumptions were necessary in parameterizing the models used in this study. Those assumptions were based on literature values and guidance documents whenever possible, but they do lead to uncertainty in model predictions. Table 7 below summarizes the assumptions used for this study's models (assumptions were stated in earlier memo sections and are merely summarized here). Future studies and data collection could potentially minimize the need for some assumptions, reducing uncertainty and leading to increased confidence in model predictions.

Table 7. Model Assumptions Summary

Parameter	Assumed Value	Source	Uncertainty
Groundwater recharge from (non-LID) infiltration	Average of ~11% of precipitation	USGS groundwater recharge grid	Low: Within range of literature values (5-25%)
LID-based groundwater recharge	80% of LID infiltration recharges groundwater	Upper bound of literature values	High: literature value ranges are broad
General LID performance	No degradation in LID over time	Professional judgment, use of low-maintenance LID practice (infiltration trenches)	Medium: infiltration trenches are low-maintenance, maintenance issues can occur w/LID
LID bottom infiltration rate	1.5 inches/hour	Utah State LID guidance	High: Literature has wide range of LID infiltration values, and this value is at/near the upper end of those ranges
Future Development locations	Constrained to MS4 communities	Professional judgment of where development is likely	Low: could be slightly under-representing future added runoff, should development occur in remote areas
Percent Impervious for future development	Assumed 50%	Literature/professional judgment, based on SLC impervious % (50%)	Low: upper bound of % impervious is likely ~70% (NYC is ~72%), 50% is reasonable for region

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