FINAL REPORT
Groundwater banking for the Little Bear River immersive model

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ABSTRACT

Groundwater, often overlooked in water management, holds significant potential for enhancing resilience and sustainability, especially as the Great Salt Lake faces severe declines from reduced inflows and rising demands. This study explores groundwater banking—storing surplus water in aquifers for future use—as a solution. Using immersive modeling, it develops a groundwater banking model for the Little Bear River watershed, simulating surface-groundwater interactions and human activities. Incorporating strategies like managed aquifer recharge, conjunctive use, and water trading, the model aims to improve water allocation while balancing ecological and human needs, offering a tool to address groundwater system complexities in Utah.

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1 INTRODUCTION

Groundwater is frequently overlooked in water management, despite its significant potential as a dependable and sustainable resource, particularly in the face of climate change and rising water demands (Sahuquillo et al., 2022). Historically, regions like Utah have prioritized surface water allocation and conservation, relegating groundwater to a secondary role due to its intrinsic complexity.

The Great Salt Lake, a critical ecological and economic resource, exemplifies the urgent need for innovative water management solutions. Declining water levels, driven by reduced inflows and increasing demands (Mohammed & Tarboton, 2011), require comprehensive strategies that integrate both groundwater and surface water. Groundwater banking offers a promising solution by storing surplus water in aquifers for later use, enhancing resilience and sustainability in water management (Maliva, 2020). Despite its potential, groundwater banking remains underutilized in Utah, where water management efforts have primarily focused on surface water solutions under the Water Banking Act of 2020.

Researching groundwater banking through immersive modeling to address the declining water levels of the Great Salt Lake presents a highly valuable opportunity. Historically, groundwater has been neglected in water management strategies due to challenges such as the complexity of groundwater systems, uncertainty in management, and the extensive data collection required. Immersive modeling, with its capacity to simulate complex hydrological systems, offers a way to deepen our understanding of interactions between surface water, groundwater, and human activities. This approach can help optimize water use, recharge aquifers, and balance ecological and human demands more effectively.

This report outlines the progress in developing a groundwater banking model for the Little Bear River watershed. The report is structured to provide insights into the literature review, model formulation, data collection, and future steps necessary to successfully develop a immersive groundwater banking model for the Little Bear River.

2 LITERATURE REVIEW

Groundwater is frequently overlooked in water management, even though it holds significant potential as a dependable and sustainable resource, particularly in the face of climate change and rising water demands (Sahuquillo et al., 2022). In that sense, groundwater banking, despite its transformative potential, has long been overlooked in water management strategies, particularly in regions like Utah, where surface water has traditionally been the focus. This oversight arises from the intrinsic complexity of groundwater systems, characterized by their slower flow dynamics, substantial storage capacities, and the difficulties involved in accurately measuring and managing them but also the dynamics of these systems are inextricably linked to many other physical and social systems (Tidwell & Van Den Brink, 2008).

The Great Salt Lake, a critical ecological and economic resource, exemplifies the need for innovative water management solutions. As its water levels decline due to reduced inflows and increasing demands (Mohammed & Tarboton, 2011), integrating groundwater banking into the region's water strategies might support mitigating these challenges. In a nutshell, groundwater banking involves storing water in aquifers during periods of surplus for later use, making it a resilient and sustainable solution for long-term water management (Maliva, 2020).

In Utah, the Water Banking Act of 2020 marked a pivotal step toward recognizing the potential of water reallocation mechanisms, particularly for instream flow benefits and ecosystem conservation. However, the act's focus has largely been on surface water, leaving groundwater banking underexplored. Groundwater storage could play a vital role in replenishing the Great Salt Lake, however, there has been minimal analysis at the detailed resolution required to estimate recharge processes in complex terrain and to connect these contributions to land surface processes (Carroll et al., 2024). As an example, for a headwater basin of the Colorado River it has been determined an stable groundwater contribution to stream water of approximately 26 ± 3% and flows are directly responsive to groundwater storage (Carroll et al., 2024). For the Great Salt Lake it has been estimated that approximately 66 percent of its water comes from streamflow contributions, 31 percent from direct precipitation, and an estimated 3 percent from groundwater (Null, 2022). However, the mentioned research results for the Colorado River show that groundwater plays a key role in stream water availability that still require further specific research for the Great Salt Lake basin.

The principles of groundwater banking rely on Managed Aquifer Recharge (MAR) and in-lieu recharge methods. MAR intentionally recharges aquifers through wells or surface spreading, while in-lieu recharge allows users to earn credits by substituting groundwater use with surface water (Maliva, 2020). Conjunctive use strategies, which balance surface and groundwater use depending on seasonal availability, further enhance the flexibility and effectiveness of these systems (Sahuquillo et al., 2022). Successful examples include California's Kern Water Bank, which stores surplus water during wet years for extraction in dry periods, and Arizona's Water Banking Authority, which mitigates Colorado River shortages through recharge schemes (Page et al., 2023). Internationally, Australia's Murray-Darling Basin demonstrates how MAR enhances drought resilience, while Spain's Mijares Basin showcases the effectiveness of conjunctive use in optimizing water storage and availability (Sahuquillo et al., 2022). These cases highlight the importance of robust governance, stakeholder collaboration, and advanced hydrological modeling in ensuring the success of groundwater banking systems.

Despite its potential, groundwater banking faces significant barriers, including legal and institutional challenges rooted in the "first in time, first in right" water rights doctrine, which complicates equitable reallocation (Leonard et al., 2019). Technical issues such as estimating recharge rates, preventing saline intrusion, and managing aquifer impacts add further complexity (Maliva, 2020). Social and economic concerns, such as balancing agricultural and urban water demands with ecological priorities, also hinder implementation (Carney et al., 2021). Addressing these barriers requires adaptive policies, stakeholder engagement, and investment in hydrological research and monitoring systems. However, until nowadays conventional modeling tools like MODFLOW and AQUATOOL have been successfully applied in other regions to optimize water allocation and predict aquifer responses (Sahuquillo et al., 2022).

In the context of the Great Salt Lake, immersive modeling offers a promising approach to integrate groundwater banking into regional water management strategies that still require further research. By simulating the interactions between surface water, groundwater, and human activities, immersive models might provide critical insights into the impacts of groundwater use, recharge rates, and aquifer sustainability (Tidwell & Van Den Brink, 2008). The feedback provided by users in the application of an immersive water bank model for Cache Valley Utah has shown the potentialities of this type of tool for water banking (Akbar & Rosenberg, 2023) and shows its feasibility to expand its application through the inclusion of the groundwater component.

Groundwater banking, by integrating surface and groundwater systems into a cohesive management framework, can enhance water use, increase resilience, and balance competing demands (Carney et al., 2021). Local initiatives, such as the Cache Valley water banking pilot, demonstrate the feasibility of streamflow enhancement through water leasing, which could be expanded to include groundwater banking with the aid of modeling tools (Null, 2022). The success of such strategies hinges on the development of innovative recharge techniques, robust governance structures, and adaptive management practices.

As water scarcity challenges intensify under climate change, the need for comprehensive and integrated solutions becomes ever more urgent. Groundwater banking offers a path forward, enabling regions like Utah to move beyond traditional surface water dependency and embrace a more sustainable and resilient approach to water management. For the Great Salt Lake, this strategy could provide a lifeline, securing its ecological integrity and ensuring its continued role as a vital resource for the region.

3 MODEL FORMULATION

- *System boundaries*

Based on the existing Cache Valley Water Bank model (Akbar & Rosenberg, 2023), this project focuses mainly on the spatial space of the Little Bear River watershed (HEC 10) as shown in the figure below. The temporal scale for the model will be from 2000 to 2023 (thirteen years). The model will consider yearly data.

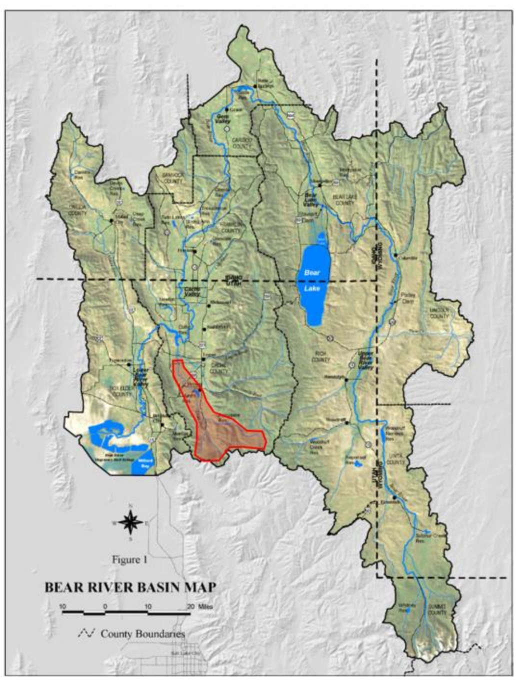

Figure 1. Bear River watershed, notice in red the spatial area that the model will cover considering the Little Bear River affluent before its confluence with the Logan River

- *Assumptions*
  1. The aquifer extent corresponds with the Little Bear River watershed.
  2. The groundwater use will be calculated based on water rights register information.
  3. If a well is in the Little Bear River watershed, we assume that it is being used within that boundary and its source is only from that watershed (no interconnection with surrounding aquifers)
  4. No spring creeks will be considered for the computation.
  5. The estimated recharge to groundwater area for Cache Valley is equal to 215 cfs based on the study developed by Robinson (1999).
  6. The estimated volume of groundwater available for Cache Valley is equal to 40 million acft (Bjorhund and Mc. Greevy, 1971). It is assumed that the available groundwater volume for the first year of the computation is proportional to the area corresponding to the Little Bear River watershed.

- *Decision variables*

  The model incorporates decisions that are taken either joined or individually. The join decisions are described in the following table, and as it can be seen the decision variables are mostly related to the physical characteristics of the system and the interchange rate between surface water and groundwater.

Table 1. Joint decision variables for the Little Bear River immersive groundwater banking model

Decision	**Description**
Surface inflow percentile	This variable provides the inflow of surface water that the model will have for every year
Percentage of extractable groundwater	Not all groundwater available can be extracted, this variable represents the percentage that can be extracted through wells. The value ranges from 20 to 50%.
Recharge percentage of surface water to groundwater	Percentage of surface water that will recharge groundwater, including unconsumed irrigation water, seepage from streams and canals.
Recharge percentage of groundwater to surface water	The percentage of groundwater that will recharge surface water, mainly as baseflow.
Groundwater percentage that influences the Great Salt Lake volume	The percentage of groundwater that influences the Great Salt Lake available volume.

The individual decisions vary according to the role type that the model user can take (see Table 2 for further detail). Currently, the model considers four users. Three of them related to the use and source of water (Tier A, Tier B and Tier C) and the last one (Tier D), responsible for defining the value at which water will be acquired.

Table 2. Individual decision variables for the Little Bear River immersive groundwater banking model

Tier	Role Type	Decision
A	Surface water agricultural users	• Crop type to be planted • Percentage of area to be cropped • Volume of water to sell or buy from/to reservoir storage • Volume of water to sell for groundwater recharge • Economic compensation to buy or sell of water
B	Groundwater agricultural users	• Crop type to be planted • Percentage of area to be cropped • Volume of water to sell for groundwater recharge • Economic compensation to sell water
C	Domestic water users	• Volume of water to sell for groundwater recharge • Economic compensation to sell water
D	Bank	• Economic value to buy water

- *Constraints*
  - Water available for use from the aquifer:
    Twenty to fifty percent of the available water in the Little Bear River can be extracted for different uses.
  - Recharge rate of surface water to groundwater:
    Five to fifty percent of the available surface water after allocation and trades in the Little Bear River will recharge the aquifer.
  - Recharge rate of groundwater to surface water:
    Five to fifty percent of the available groundwater after allocation and trades in the Little Bear River will become surface water in the form of baseflow.
  - Available crops and area to crop:
    The crop pattern is either hay-alfalfa, wheat irrigated, corn or barley. The maximum area to crop per in Tier A is equal to 27656 acres and in Tier B is 56949 acres, respectively.

- *Computations*
  For the following computations surface water and groundwater are considered as independent storage:

  1. End of Year Surface Water Storage (SWS):

$$SWS = (Inflows - Water\_Crop_{TierA} - Bank_{SW} - Bank_{GW}) * (1 - R_{SW-GW}) \qquad \textit{Eq. 1}$$

Where:
SWS = Surface Water Storage (acft) at the end of the year
Inflows = Surface water inflow for the year (acft)
$Water\_Crop_{TierA}$ = Volume of water used for the selected crop in Tier A (acft)
$Bank_{SW}$ = Volume of surface water stored in the reservoir (acft)
$Bank_{GW}$ = Volume of surface water for aquifer recharge (acft)
R_{SW-GW} = Recharge of surface water that gets into the aquifer (%)

2. Groundwater Volume (GWV) after allocation and trades:

$$GWV = (GWV_{t-1} - Water\_Crop_{TierB} - Water\_Urban_{TierC} + Bank_{GW}) * (1 - R_{GW-SW}) \quad Eq.2$$

Where:
GWV = Groundwater Volume (acft) after allocation and trades
GWV_{t-1} = Groundwater Volume (acft) from previous time steps. For time step one the value is computed based on an assumed volume.
$Water\_Crop_{TierB}$ = Volume of water used for the selected crop in Tier B (acft)
$Water\_Urban_{Tier\_C}$ = Volume of water used for urban users in Tier C (acft)
$Bank_{GW}$ = Volume of surface water for aquifer recharge (acft)
R_{GW-SW} = Recharge of groundwater that gets into the streamflow (%)

3. End of Year Groundwater Storage (GWS):

$$GWS = GWV + (SWS * R_{SW-GW}) \quad Eq.\ 3$$

Where:
GWS = Groundwater Storage (acft) at the end of the year
GWV = Groundwater Volume (acft) after allocation and trades
R_{SW-GW} = Recharge of surface water that gets into the aquifer (%)

- *State Variables*

  State variables describe the system's status each year.

  1. Groundwater Storage: The volume of water in the aquifer at the beginning of each time step. This is updated based on recharge and withdrawals from previous time step except for the first year where it is computed based on an assumed value.
  2. Reservoir Storage: Water stored in reservoirs, updated annually based on inflows and outflows (including water trading).
  3. Surface Banked Water Volume: Amount of water stored in the reservoir, held by the water bank.
  4. Groundwater Banked Water Volume: Amount of water stored in the aquifer, held by the water bank.
  5. User Water Demand: For each water user (agriculture, domestic, etc.), the amount of water demanded from the system, which drives withdrawals.
  6. Great Salt Lake Contribution: The volume of water allocated to the Great Salt Lake each year either from surface or groundwater.

- *Outputs*
  - Water Allocation: How much water is allocated to each user (agriculture, domestic, reservoir, Great Salt Lake) annually.
  - Groundwater Levels: The updated groundwater storage after each year's recharge and withdrawals.
  - Reservoir Levels: Updated water storage in reservoirs, based on inflows and withdrawals.
  - Economic Benefits: The monetary outcomes of water trading, including how much water is sold and at what price.
  - Water Banking Transactions: Quantities of water banked or withdrawn from the aquifer or reservoir each year.

- *Feedback to Next Time Step*
    - Storage Updates: Groundwater storage values at the end of one time step become the starting values for the next step.
    - Water Demand Adjustment: Water demand for the next year could be adjusted based on changes in use patterns. For example, for agriculture the area varies.

4 DATA AVAILABILITY

One of the main challenges in implementing the model has been defining the key components of the groundwater balance equations and the interchange between surface water and groundwater. To address this, a literature review was conducted to identify the recharge and discharge processes governing groundwater in the study area. Table 3 presents the estimated water budget for the entire Cache Valley aquifer, based on the parameterization used in the MODFLOW model developed for the region.

Table 3. Water balance for Cache Valley (Myers, 2003)

Recharge	**Flow (cfs)**
Net recharge of precipitation	140
Net recharge of unconsumed irrigation water	75
Seepage from canals	116
Seepage from streams	1
Total	*332*
Discharge	**Flow (cfs)**
Seepage to streams	55
Spring discharge	138
Evapotranspiration	87
Withdrawal from wells	52
Total	*332*

For this project, which focuses primarily on the Little Bear River, further discretization of the values presented in the row withdrawals from wells from Table 3 was required. To refine the estimates, data from the Division of Water Rights has been collected to assess the amount and the water use that groundwater has. Specifically, water rights categorized as "approved" or "perfected" and classified as "groundwater" have been used. It is important to note that these data reflect the maximum allowable usage for each water user rather than the actual volume of water pumped. The following table summarizes the acres irrigated, the volume of domestic and stock water used in both the headwaters of Little Bear River and the Outlet Little Bear River HUC 10 watersheds. The complete database regarding the groundwater use is available at https://github.com/Pamela-Claure/CEE_6410_Claure/tree/main/Final_Project.

Table 4. Summary of irrigated area, domestic water use and stock water use for the Little Bear River Watershed

HUC 10 CODE	HUC 10 NAME	Irrigation (Acres)	Domestic (EDU)	Stockwater (ELU)	Domestic (ACFT)	Stockwater (ACFT)
1601020301	Headwaters Little Bear River	837.8	540.8	12935.9	5821.2	362.2
1601020304	Outlet Little Bear River	56110.8	1587.2	125750.7	714.2	3521.0

For the Little Bear River system, recharge primarily originates from shallow unconfined aquifers (Myers, 2003). Infiltration from streams, canals, ditches, and irrigated fields contributes significantly to groundwater recharge. However, due to the lack of specific data for the area of interest, the listed processes have been simplified into two parameters, the first one that considers the recharge rate of groundwater to surface water and the second one, the recharge rate from surface water to groundwater. In that sense, most of the groundwater representation variables (see Table 1) were designed as decision variables that will be determined jointly by model users.

5 MODEL DEVELOPMENT

The development of the Little Bear River Groundwater Banking model has been developed based on the model developed by Akbar and Rosenberg (2024). Collaborative Model for Water Bank in Cache Valley, UT. The model has been developed on Excel platform and it consists of three spreadsheets. The first spreadsheet, denominated directions, provides the basic instructions to operate the model. The second spreadsheet called model (see Figure 2) is where the user inputs their choices and computations are performed. Finally, the last spreadsheet called GW_Use provides the information used by the model to compute the water use per Tier. The Little Bear River Groundwater Bank model is available at https://github.com/Pamela-Claure/CEE_6410_Claure/tree/main/Final_Project.

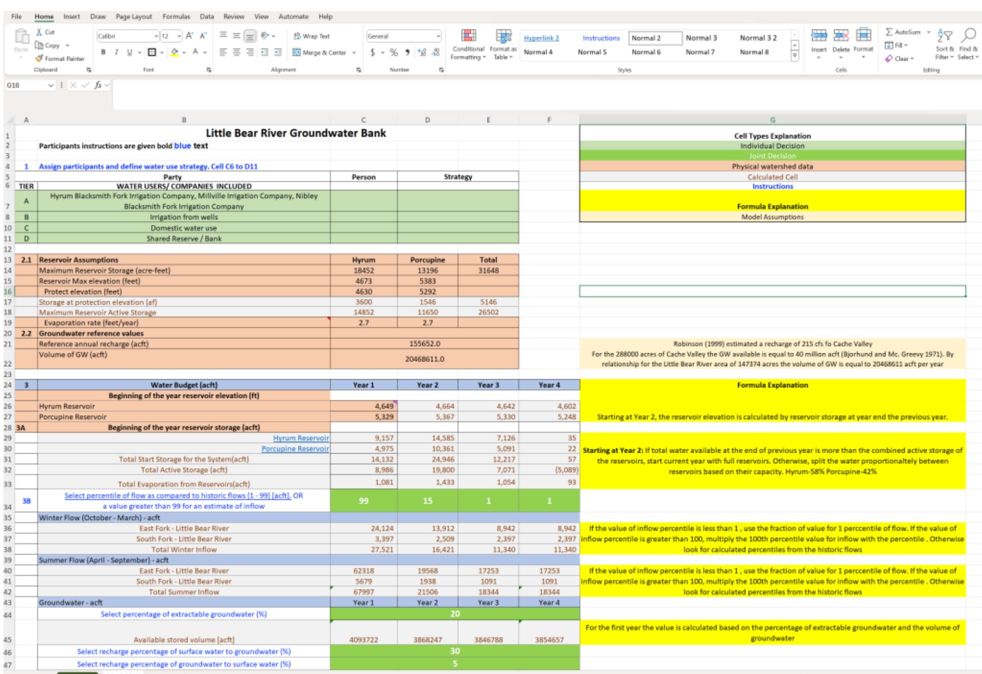

Figure 2. Screenshot of the Little Bear River Groundwater Banking Model spreadsheet

It is worth mentioning that the current model development structure is directly related to the data availability regarding groundwater characteristics, groundwater uses and surface-groundwater interaction. The selected Excel platform provides sufficient flexibility to update the model based on user feedback and further data availability.

6 CONCLUSIONS AND RECOMMENDATIONS

This report underscores the critical role of groundwater banking as a sustainable solution to address the declining water levels of the Great Salt Lake. By integrating immersive modeling techniques, the research provides a feasible framework for simulating interactions between surface water, groundwater, and human activities within the Little Bear River watershed. The model highlights strategies such as managed aquifer recharge, conjunctive use, and water trading, illustrating their potential to improve water allocation and support ecological balance.

Groundwater banking offers significant benefits, including increased resilience to water scarcity, reduced dependence on surface water, and enhanced ecological outcomes. However, its implementation is challenged by technical uncertainties in recharge estimation, surface-groundwater interactions, and the need to balance competing water demands. The immersive modeling approach shows promise in addressing these challenges by fostering collaboration, stakeholder engagement, and adaptive management, though further testing is necessary.

It is important to note that the current model has not yet been tested with users. The following recommendations are based on the model formulation and implementation phases:

1. *Enhance Data Availability and Resolution*
   Prioritize further data collection to refine groundwater recharge and discharge estimates, particularly at the hydrogeological section level in Cache Valley. Improved data resolution will strengthen the model's accuracy and applicability.
2. *Develop a Comprehensive Groundwater Use Database*
   The current groundwater use data is derived from water rights information, which does not necessarily reflect actual annual pumping rates. Develop a detailed database based on observed pumping rates or well levels to improve understanding of the system's dynamics.
3. *Conduct a Pilot Groundwater Banking Modeling Session*
   Organize a pilot modeling session to test and refine the groundwater banking model with user interaction. This will provide valuable insights into the model’s practical applications and potential for scalability.

By implementing these recommendations, the groundwater banking model can be further developed and adjusted to enhance water management strategies, contributing to efforts to stabilize and maintain Great Salt Lake levels.

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